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# semiconductorTODAY

COMPOUNDS & ADVANCED SILICON

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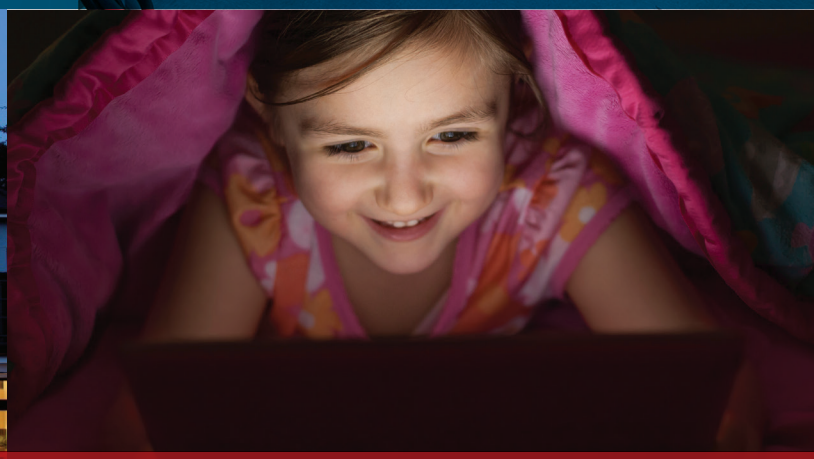
# Wide-bandgap devices for power electronics

# IEDM report


Grand Chip abandons Aixtron deal • Philips sells Lumileds stake
NeoPhotonics sells low-speed transceiver business to APAT


# Lower Cost LEDs



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*Veeco's New TurboDisc EPIK700 GaN MOCVD System*

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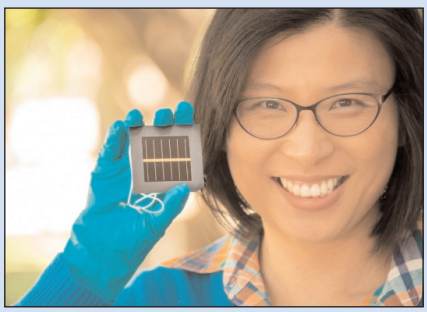
**p19** Infineon has opened its new warehouse and GaN cleanroom at its Epi Services fab in Mesa, AZ, USA.


**p40** Osram has supplied LED lighting for Rinspeed's Oasis concept vehicle, launched at the 2017 Consumer Electronics Show in Las Vegas.



**p56** Australia's University of New South Wales has claimed record efficiency with the largest perovskite solar cells to date: 12.1% for a 16cm$^2$ cell.

Cover: Evatec discusses the advantages of wide-bandgap silicon carbide and gallium nitride power devices on 200mm substrates and some of the development challenges ahead. **p70**

# editorial

## Technologies converge despite widening gap between regional powers

On pages 80–87 we report on December's annual International Electron Devices Meeting (IEDM), focusing on developments in III–V-based high-frequency and high-power electronics device technology. As well as InGaAs MOSFETs, this covers devices using wide-bandgap semiconductors such as gallium nitride and silicon carbide.

In addition, on pages 72–75 epiwafer supplier EpiGaN discusses the benefits of GaN-on-silicon technology for RF power and power switching applications. Meanwhile on pages 70–71 equipment supplier Evatec highlights the advantages of wide-bandgap power devices on 200mm silicon substrates, specifically how the aluminium nitride (AlN) buffer layer can be deposited at lower cost using sputter physical vapor deposition (PVD) rather than metal-organic chemical vapor deposition (MOCVD).

In RF and power electronics, GaN and SiC devices are driving growth, encroaching on more established GaAs and silicon-based technologies, according to ABI Research (see page 9). Similarly, driven by DOCSIS 3.1 deployments in the cable TV/broadband market, GaN is the only RF technology to see revenue growth, reckons Strategy Analytics. Market developments are reflected by Germany's Infineon opening an expansion of its EPI Services Inc fab in Mesa, AZ, USA, focused on GaN (see page 19).

On pages 68–69 Yole Développement report how thermal management materials for both power electronics and LEDs are converging at the module level, detailing the device structures and suppliers where there is cross-over between the two applications, and where the market revenues overlap (30% of revenue in 2015, with 30% more that can be made common by adapting either LED or power electronics technology to suit the other).

Such adaptation is in tune with LED industry trends, where manufacturers — under continuous competitive pressure — need to accelerate their entries into more profitable niche markets such as fine-pitch LED displays, UV LEDs and IR LEDs (see page 8, where LEDinside forecasts an increase in LED market growth from 3.4% in 2016 to 4% in 2017).

In Taiwan, LED epiwafer maker Genesis Photonics Inc expects traditional blue LEDs' share of company revenue to be slashed from 80% in late 2015 to just 30% by early 2017 (selling its fab in Kunshan, China) as it refocuses on higher-end chip-scale-packaged (CSP) LEDs for initially automotive lighting and then smartphone flash light applications (see page 38). Epistar is converting MOCVD systems originally used for making nitride-based blue LED chips to produce AlGaInP-based infrared LED chips (e.g. for security surveillance, virtual reality and iris recognition applications), which should rise from 25–30% of company revenue in Q4/2016 to over 30% in 2017. And, in response to adoption by LCD TV and smartphone makers, it is also expanding production capacity for flip-chip CSP nitride blue LEDs, which should exceed 10% of revenue in 2017.

Driven by industry overcapacity, for full-year 2016 MOCVD system maker Veeco reports that its Lighting, Display & Power Electronics segment has dropped from 61% of company revenue in 2015 to 41% in 2016, with China correspondingly falling from 51% to 26% of revenue (page 30). Regarding MOCVD system maker Aixtron (which is also diversifying), its takeover has been abandoned by China's Fujian Grand Chip (page 32) after it was blocked by US President Barack Obama. President Trump may boost protectionism, but it may also stimulate China's home-grown development.

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***Semiconductor Today* covers the R&D and manufacturing of compound semiconductor and advanced silicon materials and devices** (e.g. GaAs, InP and SiGe wafers, chips and modules for microelectronic and optoelectronic devices such as RFICs, lasers and LEDs in wireless and optical communications, etc).

**Regular issues contain**:
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- conference reports;
- event calendar and event previews;
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HVM: High Volume Manufacturing

# VCSEL market growing at CAGR of 21.3% from $760m in 2015 to $2414.91m in 2021

## Datacoms to remain dominant application, but automotive growing fastest and consumer electronics boosting growth

The global vertical-cavity surface-emitting laser (VCSEL) market is rising at a compound annual growth rate (CAGR) of about 21.3% from $760m in 2015 to $2414.91m in 2021, forecasts Zion Research in its report 'VCSEL Market by Application (Data Communication, Industrial Heating, Infrared Illumination, Pumping and Sensing) for Data Centers, Consumer Electronics, Automotive, Industrial, Healthcare and Others End Users: Global Industry Perspective, Comprehensive Analysis and Forecast, 2015–2021'.

The VCSEL has gained a reputation as a superior technology for short-reach applications such as infrared illumination, fiber-channel and intra-systems links and automotive. VCSELs have become the technology of choice for short-range datacoms, local-area networks (LANs), and are effective in displacing edge-emitter lasers. Usage of VCSEL is mainly due to the VCSEL's lower manufacturing costs and higher reliability compared to edge-emitters.

Advances in automotive electronics, the growing number of data centers and increasing demand from high-end applications such as gesture recognition and 3D imaging are some of the major drivers expected to propel the growth of the VCSEL market in coming years. Ongoing technological advances are enabling the use of VCSELs in huge quantities in infrared illumination. Also, increasing demand for cloud computing is expected to lead to a surge in growth of the VCSEL market in the near future. However, restriction to short-distance communications due to the limited range of VCSELs is expected to have impact the market. Nonetheless, technology such as the laser-assisted hard disk drive is expected to open up new growth opportunities for the VCSEL market in the coming years.

Data communication was the leading application segment in 2015 with over 57% market share, and is expected to maintain its dominance throughout the forecast period owing to the construction of new data centers for data analytics coupled with cloud computing. The sensing application segment is expected to see high growth in the China market. Technical advances in VCSELs and greater use in infrared illumination is expected to fuel demand for infrared illumination applications in the coming years.

By application, the data-center and automotive end-user segments are expected to be the most attractive in the forecast period. The automotive end-user segment is expected to grow at the highest CAGR of 25.11%, while rising demand for VCSELs in consumer electronics is expected to boost the growth of the consumer electronics application segment.

North America was the largest geographical market for VCSEL in 2015 and is expected to continue its dominance throughout the forecast period. Europe is expected to show remarkable growth, driven mainly by rising use of VCSELs in consumer electronics. Asia Pacific is considered to be the fastest-growing regional market for VCSELs, and growth in this region is mainly attributed to the growing number of data centers, paired with significant growth of the automotive sector in China and India.

The report lists some of the key players in the VCSEL market as JDS Uniphase Corp, Philips Photonics, Princeton Optronics Inc, Avago Technologies, II-VI Inc, Vixar Inc, and Ultra Communications Inc.

**www.zionmarketresearch.com/report/vcsel-market**

# LED makers to benefit from growing gaming demand

Global demand for gaming hardware, software and services is projected to rise at a compound annual growth rate (CAGR) of 6.6% from US$99.6bn in 2016 to US$118.6bn in 2019 and, because gaming notebooks, desktops, monitors and even keyboards and mice are offering visual effects lit by LEDs, LED makers are expected to benefit from the growing demand, according to Digitimes Research.

In addition to gaming, the global market value for e-sports in 2016 is estimated to be US$891m, for which, Asia, North America and Europe together account for over 90%, Digitimes Research indicates.

In addition to gaming, demand for LED chips used in sensing is increasing along with the rapid growth in demand for virtual reality (VR), as 20–40 LED chips (including infrared models) are used in a single VR system, it is noted.

**www.digitimes.com/reports**

# HB-LED market to grow at 10% CAGR to $29bn in 2022

The global high-brightness light-emitting diode (HB-LED) market is rising at a compound annual growth rate (CAGR) of 10% from $15bn in 2015 to $29bn in 2022, forecasts a report 'HB-LED Market by Application and Geography — Global Opportunity Analysis and Industry Forecast, 2014–2022' by Allied Market Research.

In 2014, Asia-Pacific dominated the market, contributing more than 50% share of overall market revenue, followed by North America. The presence of key market players in Asia-Pacific and rising HB-LED application (primarily in signs, display and large-screen backlighting) have fueled growth.

Increasing HB-LED applications in general lighting, cars, mobile, and large-scale replacements of traditional lighting (as LED lights are more cost-effective, energy-efficient and offer longer life-span) are driving market growth. However, high initial investment could restrict growth. Moreover, it is anticipated that the rise in demand for lighting, coupled with increasing government focus on energy conservation on photovoltaic technology, would spur the global market.

In 2014, the general lighting application segment dominated the HB-LED market (with over 46% share) and is expected to maintain this lead in future. However, the mobile application segment should grow significantly (at a CAGR of 10.8% during the forecast period), due to various applications of HB-LEDs in mobile devices, since they produce bright light with minimal use of electricity and instant responsiveness.

Among various geographical regions, Asia-Pacific contributed the most revenue share in 2014 (led by Japan, with about a quarter of the region's market). Asia–Pacific is expected to maintain its lead throughout the forecast period, due to factors such as outdoor lighting installations and policies related to installation receiving importance mainly in emerging markets like India, Russia and Southeast Asia (Vietnam, Malaysia, Indonesia, and Thailand). Moreover, improvement in government expenditure in LED orders has boosted HB-LED growth in Asian countries, particularly India.

"The ability of HB-LEDs to provide longer lifespan, low power consumption and enhanced illumination features are expected to promote demand globally," says Preeti Bisht, senior research associate, Semiconductor & Electronics Research at AMR. "Moreover, the swift rise in the usage of the HB-LED technology in various applications (for instance, backlighting, street lighting, automotive, mobiles, signs and signals) has witnessed the remarkable growth in the global HB-LED market, which would in turn fuel the market growth."

However, North America is projected to be the fastest-growing region throughout the analysis period. Increasing shipments of mobile devices and reduction in the cost of LED components are major driving forces for HB-LED markets in the region. Moreover, rising demand for brighter LEDs in commercial applications, automobiles and displays is also contributing to growth.

Key players have adopted product launch as their key developmental strategy to expand their services and businesses in different geographies, notes the report. The major players profiled include Epistar Corp, Cree Inc, Philips Lumileds, Moritex Corp, Samsung Electronics Co Ltd, Seoul Semiconductor, Osram Opto Semiconductor, American Bright Optoelectronics Corp, Nichia Corp, and Toyoda Gosei.

**www.alliedmarketresearch.com/high-brightness-hb-led-market**

# LED suppliers to accelerate expansion into niche markets

## Growth of 3.4% in 2016 to be followed by 4% in 2017

The value of the global LED market is estimated to grow 3.4% annually to $14.8bn in 2016, according to LEDinside (a division of TrendForce). Although the LED industry will again be under tremendous competitive pressure in 2017, and participants will need to accelerate their entries into more profitable niche markets such as fine-pitch LED displays, UV LEDs and IR LEDs, the market will grow 4% from 2016 to $15.4bn in 2017, forecasts LEDinside.

"The projected growth in LED market value for this year is marginal, but the industry has witness some major changes," says LEDinside's research director Roger Chu. "The surge in demand for fine-pitch LED displays has caused a general tightening of chip supply. As a result, some chip and package products have seen price hikes for the first time in five years," he adds.

Rising prices for hard commodities such as copper and aluminum during second-half 2016 have also led to significant price hikes for LED lighting products. "LED lighting vendors have adjusted their prices to reflect the increase in material costs," says Chu. "The actual contribution of this wave of price increases to the vendors' profits is limited," he adds. Since the general state of the LED lighting market remains weak, LED suppliers are actively developing strategies to transform their businesses and accelerate their entries into the blue-ocean niche markets.

**Fine-pitch LED displays to be contested application in next few years**

Traditional LED display makers shifted much of their development efforts towards fine-pitch LED displays through 2016 as consumers demand better image quality from these products. "LED display makers' focus on fine-pitch LED displays has resulted in a several-fold increase in LED usage volume," says Chu. "And many Chinese LED package suppliers have undertaken capacity expansion just to capture a share of this market."

However, this scramble has also generated intense pricing competition. To avoid getting trapped in a price war, suppliers will have to improve their product specifications and make packages more compact. Currently, fine-pitch LED displays with pitches measuring 1.5mm and less constitute a market segment where LED suppliers are not under pressure to lower their prices.

**UV-C LEDs to find more applications as efficiency improves**

UV-C LEDs are another emerging market with a lot of blue-ocean opportunities, reckons LEDinside. "Deep UV has sterilization and purification features that would be useful in many application areas, including home appliances, water treatment, air purification and so on," says Chu.

While there is high demand for UV-C LEDs, there are challenges in developing this market. UV-C LED chips are currently very expensive and have low external quantum efficiency. Also, application development for UV-C LEDs used to be led mainly by research institutions based in Japan, Europe and the USA. These organizations came up with solutions that could not achieve economies of scales. Nonetheless, more LED suppliers are starting to see the importance of UV-C LED products and investing more in developing related applications. The industry's contribution therefore will speed up growth of the UV-C LED market in the near future, forecasts LEDinside.

**Applications for IR LED components to become more diverse**

IR LEDs comprise a relatively mature technology and offer inexpensive solutions in many applications. Iris recognition sensors and motion sensors for virtual reality (VR) devices, for example, are two of many newly emerged applications that provide lucrative opportunities for IR LED suppliers. The vertical-cavity surface-emitting laser (VCSEL) is another related technology that has attracted greater market interest in recent years. VCSELs now features in handheld devices and sensor equipment related to the Internet of Vehicles. "The expansion of applications for IR LEDs depends on the willingness of end-system integrators to adopt them," says Chu. "Successful adoption of IR LEDs in turn is based on the values that they can add to different devices and equipment."

**Micro-LED displays may arrive on the market as early as next year**

The micro-LED constitutes a next-generation display technology that has the potential to overtake organic light-emitting diodes (OLED) in the future. While major branded companies in various industries have begun to invest in this technology, it will be some time before micro-LEDs can supplant TFT LCD and OLED solutions currently on the market. Meanwhile, there are many other advanced display technologies that are in the race with micro-LEDs to achieve commercialization and mass production.

Branded companies that intend to launch micro-LED products have developed market-positioning plans and applications that would set this technology apart from LCD or OLED. Furthermore, they are working to find the right trade-off between pixel volume and pixel density (as expressed in pixel per inch, or PPI) so they can begin mass production as quickly as possible. Therefore, micro-LED displays that will soon hit the market can either have high pixel volume or high PPI but not both together. LEDinside anticipates that devices featuring micro-LED displays will arrive on the market in 2017 at the earliest.

**www.ledinside.com**

# Pulsed RF power device markets up to 4GHz to exceed $250m by 2021

## GaN to drive growth, encroaching on silicon and GaAs

Markets for pulsed RF power devices up to 4GHz will show continued growth over the next five years to more than $250m by 2021, despite current economic and political turmoil, forecasts a report 'Pulsed RF Power Semiconductors' by ABI Research.

While their association with consumer spending fuels the volatility of many global electronics markets, pulsed RF power device markets are supported by quite different priorities, notes the report. Pulsed RF power transmitters generate tremendous amounts of power in small bursts that are useful for radar, airborne collision avoidance systems, and military IFF equipment.

"Many RF power semiconductor manufacturers are on a quest to find markets unrelated to mobile wireless infrastructure," says research director Lance Wilson. "Device prices in wireless infrastructure are falling, and the total available market is flattening out."

The airborne transportation safety market and military market are both experiencing solid growth in pulsed RF power device shipments. The markets use the devices for military radar, weather and marine applications, and in the current worldwide upgrade of the air traffic control system. The avionics transponder and air navigation market segment is also seeing growth, which is further lifted by the overall worldwide air traffic control upgrade. Intrinsically less 'optional' than many consumer markets, these segments are therefore less sensitive to economic upheavals than consumer-driven markets, although they are not totally immune to the macro economy.

Understanding this, many semiconductor manufacturers are attempting to enter this market space. However, some factors may complicate their efforts, says ABI. Pulsed RF power device markets are becoming very competitive technologically: gallium nitride (GaN) and, to a certain extent, silicon carbide (SiC) devices are vying for market share along with the more established silicon- and gallium arsenide (GaAs)-based technologies. With many companies rushing into these markets, ABI Research speculates that there may not be the market size to support them all.

"Undoubtedly, some consolidation will continue to occur beyond what already happened," concludes Wilson. "While not guaranteed success, those companies that have track records working with government agencies and defense contractors will have an advantage over those that are new entrants."

Leaders for high-power RF pulsed semiconductor devices include Ampleon, Integra Technologies, M/A-COM Technology Solutions, Microsemi, Qorvo, Sumitomo Electric Device Innovations, and Wolfspeed.

**www.abiresearch.com**

# CATV/broadband market boosted by DOCSIS 3.1 deployments, but RF revenue to remain flat

## GaN the only RF technology to see revenue growth

DOCSIS 3.1 (Data Over Cable Service Interface Specification) networks will provide obvious benefits for operators and consumers, but the advantages for the RF portion of the network are not as clear, notes the Strategy Analytics Advanced Semiconductor Applications (ASA) service report 'CATV/Broadband Infrastructure Amplifier Forecast and Outlook: 2015–2021'.

DOCSIS 3.1 networks will usher in a new era for CATV/broadband service providers, says the market research firm. This specification allows cable operators to provide services and data speeds competitive with current fiber offerings, while providing a clear path for network evolution.

The report concludes that RF revenue peaked in 2016 in response to DOCSIS 3.1 network deployments, but then decline over the rest of the forecast period as fiber pushes deeper into the networks. It also extrapolates that gallium nitride (GaN) technology will be the only RF technology to see revenue growth in this market application.

"DOCSIS 3.1 is a significant accomplishment for the CATV/broadband industry," says Eric Higham, service director, Advanced Semiconductor Applications service. "It provides an evolution path for the networks that allows operators to add capacity and services as consumer needs dictate, while remaining competitive with fiber alternatives. The challenge for the RF industry will be to expand device opportunities as fiber moves deeper into the HFC (hybrid fiber coax) networks in response to the increasing data traffic enabled by DOCSIS 3.1 networks," he adds.

"The performance advantages of GaN make it the preferred technology for the power amplifiers in the CATV/broadband infrastructure network," says Asif Anwar, service director, Advanced Defense Systems service. "This will enable a small revenue increase over the forecast period."

**www.strategyanalytics.com**

# DoD extends Qorvo's Trusted Source accreditation through 2018, adding design services

Qorvo Inc of Greensboro, NC, USA (which provides core technologies and RF solutions for mobile, infrastructure and defense applications) has earned continued Trusted Source Category 1A accreditation through 2018 from the Department of Defense (DoD). Accreditation was originally gained in 2008, followed by renewals in 2012 (adding post-processing, packaging/assembly and RF test services) and 2016 (expanded now to include design services). The firm is one of only five accredited suppliers for both gallium nitride and gallium arsenide.

Accreditation reflects the confidence of the DoD Defense Microelectronics Activity (DMEA) and the National Security Agency's Trusted Access Program Office (TAPO) that Qorvo will continue to deliver Category 1A trusted foundry microelectronic goods and services that meet mission-critical needs today and in future.

"This accreditation milestone signifies that the DoD and DMEA office trust Qorvo with national security technology," notes Roger Hall, general manager of Qorvo's High Performance Solutions business. "It also affirms to our commercial customers and partners that we will maintain the security of their intellectual property."

**www.qorvo.com/defense**

## Qorvo appoints communications industry executive to board

Qorvo has announced the election of Susan L. Spradley to its board of directors, effective 1 January. She also joins the board's governance and nominating committee.

Spradley has senior management experience in the communications industry, most recently as executive VP & general manager—Network and Service Enablement for Viavi Solutions (formerly JDS Uniphase). Previously, she served in leadership positions with global telecoms companies including Nokia Siemens Networks and Nortel, and was a member of the board of directors of EXFO Inc (a provider of test and service assurance solutions for communications network operators and OEMs).

"She brings broad operating experience in sales, product portfolio management and R&D for multiple global communications-related companies," comments president & CEO Bob Bruggeworth.

"Qorvo is recognized globally for advancing innovation and functional integration in the increasingly complex market for RF solutions," says Spradley. "I look forward to working with Bob and my fellow directors in driving Qorvo's growth strategy to create long-term value for its shareholders."

**www.qorvo.com**

# Skyworks adds multi-band LTE front-end modules for IoT

Skyworks Solutions Inc of Woburn, MA, USA has unveiled its next-generation LTE Category M-1 and NB-1 front-end solutions, which target machine-to-machine and Internet of Things (IoT) applications requiring embedded cellular connectivity.

The firm's multi-band modules leverage half-duplex RF operation to deliver a highly integrated, turnkey solution that addresses Release 13 specifications of the 3GPP LTE standard — providing dependable, secure, low-power connectivity in a compact package. The new products are said to allow OEMs to simplify the design process, shorten development time, meet operator requirements worldwide and significantly accelerate time to market.

"With leading cellular network operators announcing plans to enable the latest IoT standards on their networks in 2017, Skyworks is pleased to be pushing the performance envelope and offering our customers a single-SKU, low-cost LTE solution that operates over multiple frequency bands and supports migration from 2G," says VP of sales & marketing Carlos Bori. "Skyworks' modules are powering wireless cellular communications for applications such as wearables, action cameras, smart meters and other consumer IoT devices requiring LTE connectivity as well as paving the way for 5G machine-to-machine communication networks."

According to GSMA, cellular machine-to-machine connections are expected to grow from about 300 million devices today to as many as 2 billion by 2020. More broadly, market research firm IHS forecasts that the IoT market will grow from an installed base of 15 billion devices in 2015 to 31 billion devices in 2020.

Skyworks' portfolio of LTE front-end modules for IoT now comprises:

- the SKY68000 (launched in February 2016) — a hybrid RF front-end (RFFE) module supporting cellular LTE bands 4 and 13 for Category M-1 and NB-1 (half-duplex) transceiver platforms;
- the SKY68001 — a hybrid, universal multi-band RFFE module supporting cellular LTE Category M-1 and NB-1 (half-duplex) transceiver platforms covering more than 15 bands; and
- the SKY68011 — a hybrid, multi-band RFFE module supporting cellular LTE for Category M-1 and NB-1 (half-duplex) transceiver platforms covering more than eight bands.

Engineering samples are available now, for production in first-half 2017.

**www.skyworksinc.com/Products/112/LTE_Front-end_Modules**

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# Microsemi unveils wideband low-noise MMIC amplifiers and GaAs MMIC switches spanning DC–26GHz for defense and industrial markets

Microsemi Corp of Aliso Viejo, CA, USA (which makes chips for the communications, security, aerospace and industrial markets) has launched six monolithic microwave integrated circuit (MMIC) products, including four wideband low-noise MMIC amplifiers (MMA040AA, MMA041AA, MMA043AA and MMA044AA) and two wideband gallium arsenide (GaAs) MMIC switches (MMS006AA and MMS008AA), suitable for test & measurement, electronic warfare and radar applications.

"Our new high-linearity MMIC amplifiers and switches represent Microsemi's significant investment in expanding our Forever MMIC product portfolio as we continue addressing customers' highly specific and complex MMIC requirements with affordable, low-risk solutions that can also reduce end-equipment bill of materials (BoM) costs," says Kevin Harrington, director of strategic marketing for the RF/Microwave Discrete Products business unit.

Microsemi says that the new devices are suitable for applications primarily within the defense and industrial markets, including receiver front-end amplifiers for electronic warfare (EW) and signal intelligence (SigInt); and wideband bench-top and portable measurement equipment up to 26GHz.

The firm claims that, compared with existing market solutions, the new wideband low-noise MMIC amplifiers deliver excellent performance with flat gain over a wide frequency range, and significantly better output third-order intercept point (OIP3) performance. Similarly, the new GaAs MMIC switches provide broad frequency coverage combined with superior insertion loss, isolation and input third-order intercept point (IIP3) performance. Market research firm Strategy Analytics estimates that the market for GaAs MMICs for EW, radar and microwave communications applications will reach $500m by 2019.

**Our new high-linearity MMIC amplifiers and switches represent Microsemi's significant investment in expanding our Forever MMIC product portfolio as we continue addressing customers' highly specific and complex MMIC requirements with affordable, low-risk solutions**

The 3mm x 1.3mm x 0.1mm MMA040AA, a DC–28GHz distributed low-noise amplifier (LNA), features a low noise figure of 2.5dB, flat gain of 16dB and provides 27dBm of OIP3 linearity. The 3mm x 1.3mm x 0.1mm MMA041AA, a DC–26GHz distributed LNA, features 3.2dB noise figure, 18dB gain and 35dBm of OIP3 linearity. The 2.2mm x 1.3mm x 0.1mm MMA043AA, a 0.5–12GHz LNA, offers a 1.4dB noise figure, 16.5dB of gain and 29dBm of OIP3 linearity. The 1.12mm x 1.3mm x 0.1mm MMA044AA LNA operates across the 6–18GHz band and provides a low noise figure of 1.7dB, in combination with 21dB of gain and 30dBm of OIP3 linearity.

The MMS006AA, a DC–20GHz single-pole double-throw (SPDT) non-reflective MMIC switch, features high isolation of 45dB and low insertion loss of 1.5dB at 15GHz. The MMS008AA is a DC–8GHz single-pole four-throw (SP4T) non-reflective MMIC switch that offers over 45dB of isolation and less than 1.7dB insertion loss. Both devices handle up to 30dBm of input power and offer high IIP3 performance of 42dBm and 46dBm, respectively, and have return loss of 15dB.

All six MMIC devices feature RF ports that are internally matched to 50Ω of input/output impedance and are available in bare die, facilitating easy integration into multi-chip modules (MCMs).

**www.microsemi.com/mmics**

# JS Commtech to represent Anokiwave in South Korea

Anokiwave Inc of San Diego, CA, USA, which provides highly integrated silicon core chips and III-V front-end integrated circuits for millimeter-wave (mmW) markets and active electronically scanned array (AESA)-based terminals, has signed a representative agreement for JS Commtech in South Korea to support new customers and opportunities for its highly integrated active antenna core IC solutions in South Korea.

JS Commtech has a highly technical sales and engineering staff and is a representative in Korea for all RF & microwave, commercial, and defense-related markets.

"This agreement strengthens the technical support we can provide to customers in South Korea and increases our ability to promote our 5G active antenna core IC solutions in the region," says Anokiwave's chief operating officer Carl Frank. "With detailed knowledge of the Korean electronics market coupled with excellent technical resources, JS Commtech is ideally positioned to drive the adoption of our IC solutions into the 5G, radar, and SatCom markets," he believes.

**www.jscommtech.com**
**www.anokiwave.com**

# Carbonics introduces carbon-on-silicon wafers for RF components in 5G wireless

## RF devices and integrated amplifiers to be launched in 2017, then RFICs and MMICs in 2018

Carbonics Inc of Marina Del Rey, CA, USA has launched its ZEBRA carbon-on-silicon technology for radio-frequency components and devices in wireless, communications, defense and aerospace markets.

Carbonics was spun out from University of California Los Angeles (UCLA) and University of Southern California (USC) in 2014, funded by university-sponsored research from the Center of Excellence for Green Nanotechnologies at UCLA and King Abdulaziz City for Science and Technology Center (KACST), SRC, DARPA, US Air Force and UCLA's California NanoSystems Institute (CNSI) Technology Incubator. The start-up is backed by $5.5m in venture funding from technology investment and development company TAQNIA International. It aims to revolutionize the billion-dollar RF compound semiconductor market by employing carbon plus CMOS on the road to a single 5G wireless chip.

Specifically, Carbonics is focused on developing and commercializing a carbon-on-wafer single chip solution that improves the power consumption and performance of wireless products — including next-generation smartphone and communication devices.

The ZEBRA product is said to be the first available platform solution for realizing next-generation semiconductor device technologies using semiconducting single-walled carbon nanotubes (CNT). By leveraging the one-dimensional (1D) transport properties of thousands of aligned, gate-controllable conduction pathways, linear current densities exceeding that of gallium arsenide (GaAs) pseudomorphic high-electron-mobility transistor (pHEMT) and silicon technologies have been realized.

Carbonics says that ultra-arrayed carbon nanotubes represent the enabling technology necessary for a carbon-on-wafer single-chip solution, and the launch of ZEBRA wafers remains in step with Carbonics' mission to enable design engineers, foundries, integrated device manufacturers (IDMs) and advanced development houses access to the most advanced semiconducting platform for designing next-generation high-speed circuits.

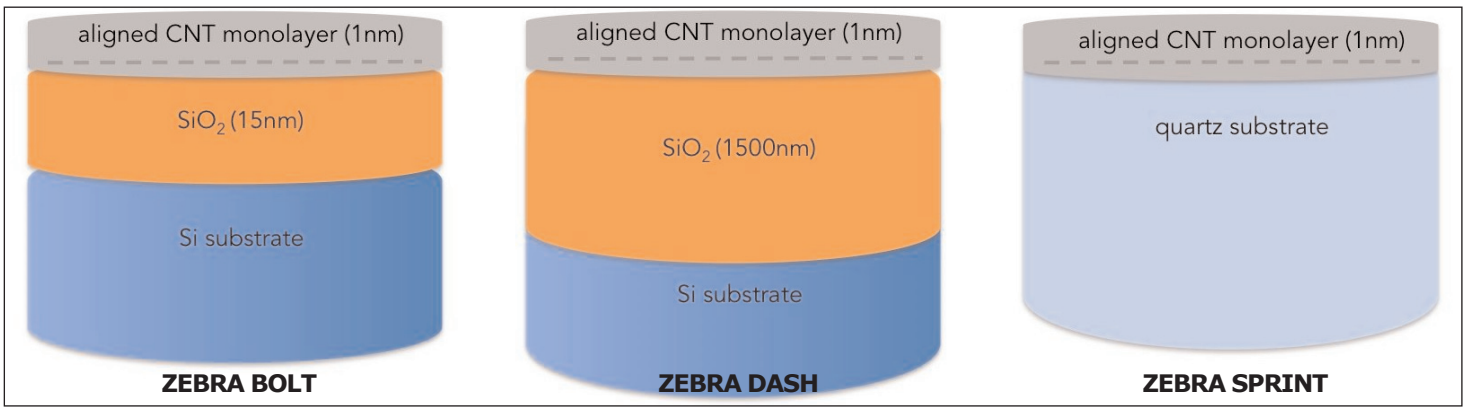
"Carbonics intends to shake up the billion-dollar compound semiconductor market with our superior disruptive carbon technology that is fully CMOS compatible and able to perform in the mmWave spectrum — representing perfect timing for the 5G and Internet of Things (IoT) revolution," says CEO Kos Galatsis.

"Carbonics has achieved a unique milestone in the evolution of carbon electronics," comments Ken Hansen, president & CEO of Semiconductor Research Corporation (SRC). "This is a crucial first step from Carbonics toward high performance, next-generation RF electronics using next-generation nanotechnology for high-performance mmWave RF and CMOS compatibility," he adds. "It's exciting to see the progress from the fundamental material and device research sponsored by SRC and DARPA develop into the launch of a groundbreaking product technology."

The ZEBRA wafer product line includes the ZEBRA BOLT with aligned semiconducting CNT on 15nm $SiO_2$ for back-gated device applications such as sensors and detectors; the ZEBRA DASH with aligned semiconducting CNT on 1500nm for top-gated devices such as memory, switch, logic and RF applications covering L-band to mmWave and 3G, 4G, 4G, WiFi, 802.11ad and WiGig spectrums; and the ZEBRA SPRINT with aligned semiconducting CNT on quartz aimed for RF applications up to 100GHz.

Carbonics also plans to launch its VIPER product line — comprising high-performance RF devices and integrated amplifiers — in 2017, and its STINGRAY product line of RFICs and MMICs — which will include high-performance mmWave low-noise amplifiers (LNA), power amplifiers (PAs), mixers, switches and front-end modules (FEMs) — in 2018.

**www.carbonicsinc.com**



# EU DEEPEN device modelling project wraps up

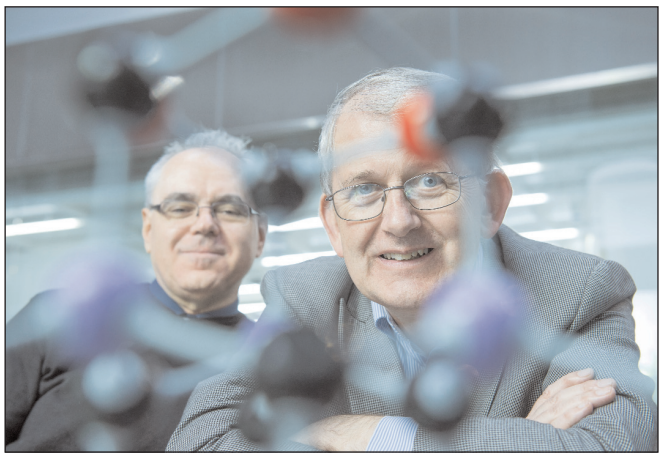
## Semiconductor, electronics, photonics and modelling expertise guiding development of III–V and 2D materials for future devices and quantum computing methods

The Internet's carbon footprint is already larger than the entire aviation industry, as the volume of Internet traffic increases exponentially every year, requiring increasing amounts of energy to fuel communications. From smartphones to electronic devices, the underlying technologies, infrastructure and energy needs will not be sustainable in the medium to long term.

This challenge has been a key focus of scientists involved in the three-year project DEEPEN (from atom-to-Device Explicit simulation Environment for Photonic and Electronic Nanostructures), which comes to an end in December. Findings of the DEEPEN project are being shared at workshops in Cork, Ireland this week.

Funded by a €2.69m contribution under the European Union's Seventh Framework Program (EU FP7), the €3.82m DEEPEN project (from January 2014 to end-2016) was led by Ireland's Tyndall National Institute (based at University College Cork), together with partners including University of Rome 'Tor Vergata' spin-off TiberLab (Italy), Osram Opto Semiconductors (Regensburg, Germany), technology computer-aided design (TCAD) software provider Synopsys (Zurich, Switzerland) and ETH Zürich (Switzerland), UCC (Cork, Ireland) and Paul-Drude-Institut für Festkörperelektronik (Berlin, Germany).

"Each time we ask Google a question, we access a giant data center of highly interconnected computers," notes professor Eoin O'Reilly (DEEPEN project lead and Tyndall chief scientist) in advance of the workshops. "The transistors and interconnects sitting at their core are all consuming so much energy that a major design issue for data centres is how to manage the level of heat created by computer components," he adds. "Through the DEEPEN project, scientists at Tyndall are working with counterparts and industry across Europe, including Osram and Synopsys, to solve these real issues."



**TiberLAB's CEO Dr Fabio Sacconi and professor Eoin O'Reilly, Tyndall's chief scientist and DEEPEN project lead, pictured at Tyndall National Institute.**

The focus of O'Reilly, his colleagues at Tyndall and partners in the project is to develop simulation techniques that not only leverage existing technologies and materials to dramatically enhance the capabilities of incumbent infrastructure, but can also guide the development of new materials like III-V semiconductors and 2D materials to advance future device applications and quantum computing methods.

The critical regions in existing devices can be as little as 20 atoms wide – these regions need to be treated in full detail for accurate simulation without compromising the higher-level simulation of the full device structure.

"We have been looking in DEEPEN at specific device parts at atomistic level, generating multi-scale simulations that link the atomistic behaviour to the overall device performance, and ultimately creating new open-source interfaces for developing products for the future," says O'Reilly. "Within three years, we have advanced our knowledge significantly and the DEEPEN project has had global impact, bringing together leading minds from academia and industry to generate new solutions to our current and future issues," he adds. "In short, the DEEPEN project is driving forward our capability for accurate and reliable device modelling and design, through collaboration and extensive research in modeling and computation methods for semiconductors."

The new tools developed in DEEPEN are finding direct commercial application in the future modelling tools of the project software partners Synopsys and TiberLAB. TiberLAB is hosting the open-source multi-scale software that has been developed. "DEEPEN has been of critical value to us," comments TiberLAB's CEO Dr Fabio Sacconi. "We prize the opportunity that it has given us to build and re-inforce our device simulation capabilities, of benefit not just for our products but also for the wider community through the open-source interfaces that we have developed," Sacconi adds.

Science Foundation Ireland (SFI) has also funded the DEEPEN team in Ireland to build on the work of the project and combine the state-of-the-art existing methods with new methodologies, integrated within a multi-scale framework spanning from first principles to macroscopic continuum models.

**http://cordis.europa.eu/projects/rcn/110555_en.html**
**www.tyndall.ie/content/theory-modelling-design**

# Purdue demonstrates potential of β-$Ga_2O_3$-on-insulator transistor for ultra-efficient switches in power electronics

## Low-cost method developed using adhesive tape to peel off layers of beta gallium oxide from single crystal

Purdue University has demonstrated the high-performance potential of an experimental transistor made of beta gallium oxide, which could bring new ultra-efficient switches for applications such as the power grid, military ships and aircraft (Hong Zhou et al, 'High Performance Depletion/Enhancement-Mode β-$Ga_2O_3$ on Insulator (GOOI) Field-effect Transistors with Record Drain Currents of 600/450mA/mm', IEEE Electron Device Letters, vol38 (2017), no1, p103).

The semiconductor is promising for the next generation of power electronic devices needed to control the flow of electrical energy in circuits. Such a technology could help to reduce global energy use and greenhouse-gas emissions by replacing less efficient and bulky power electronics switches now in use.

The gallium oxide on insulator (GOOI) field-effect transistor is especially promising because it has an ultra-wide bandgap (needed for switches in high-voltage applications). Compared with other semiconductors, devices made from β-$Ga_2O_3$ have a higher breakdown voltage, says Peide Ye, Purdue University's Richard J. and Mary Jo Schwartz Professor of Electrical and Computer Engineering.

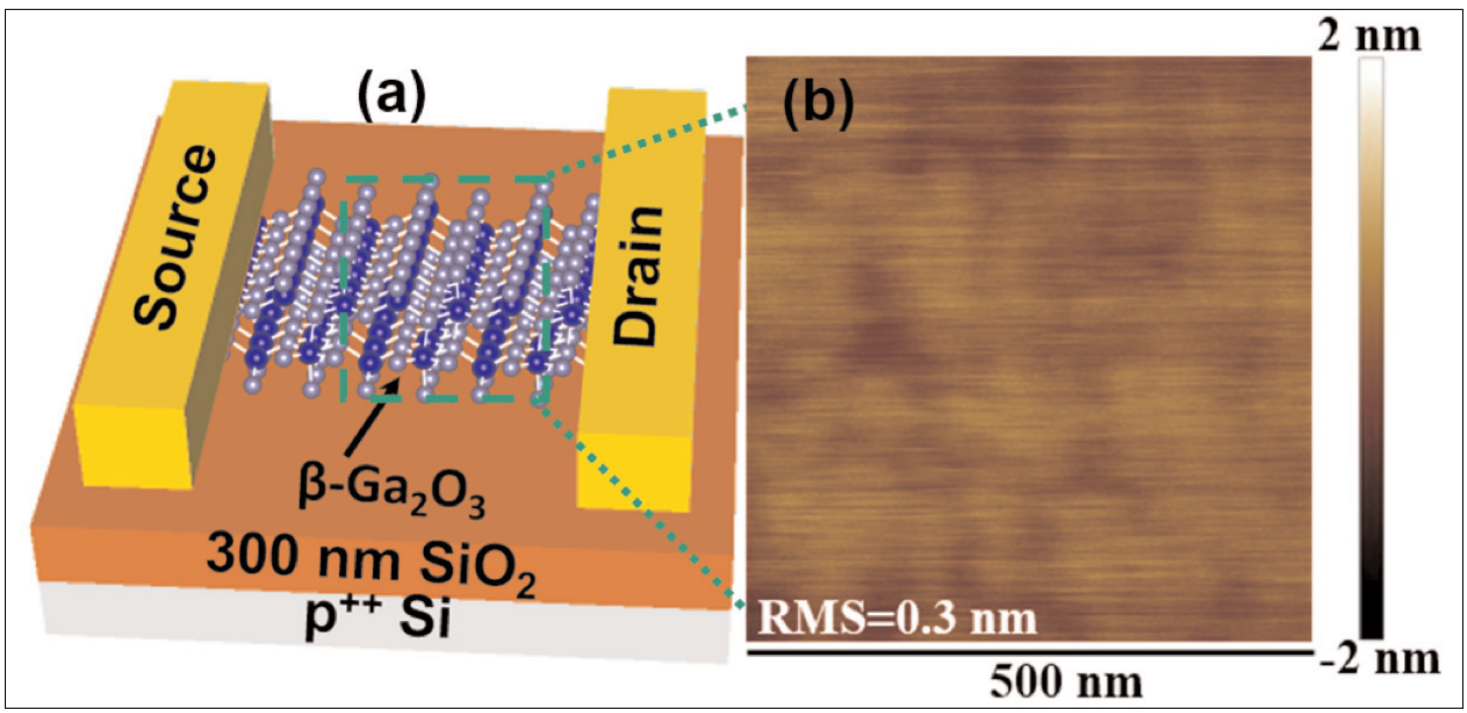
The team also developed a new low-cost method using adhesive tape to peel off layers of β-$Ga_2O_3$ from a single crystal, representing a far less expensive alternative to epitaxy. The market price for a 1cm x 1.5cm piece of β-$Ga_2O_3$ produced using epitaxy is about $6000. In comparison, the Scotch-tape approach costs pennies and can be used to cut films of β-$Ga_2O_3$ into belts or nano-membranes, which can then be transferred to a conventional silicon disc and manufactured into devices, Ye says.

The technique was found to yield extremely smooth films, with a surface roughness of 0.3nm. This is another factor that bodes well for its use in electronic devices, says Ye, who is affiliated with the NEPTUNE Center for Power and Energy Research, funded by the US Office of Naval Research and based at Purdue's Discovery Park (in the Birck Nanotechnology Center). Related research was supported by the center.

The Purdue team achieved electrical currents 10–100 times greater than other research groups working with β-$Ga_2O_3$, Ye reckons.

One drawback of the material is that it has poor thermal properties. To help solve the problem, future research may include work to attach the material to a substrate of diamond or aluminum nitride (AlN).

**http://ieeexplore.ieee.org/document/7765124**
**www.purdue.edu/discoverypark/energy/programs/navy-programs/power-and-energy-research.php**




**Left: Schematic showing the design for an experimental transistor made of beta gallium oxide. Right: an atomic force microscope image of the semiconductor. (Purdue University image/Peide Ye).**

# Wolfspeed launches 900V, 10mΩ SiC MOSFET for electric vehicle drive-trains

Wolfspeed of Research Triangle Park, NC, USA — a Cree Company that makes silicon carbide (SiC) power products including MOSFETs, Schottky diodes, and modules — has launched a 900V, 10mΩ MOSFET rated for 196A of continuous drain current at a case temperature of 25°C. The device enables the reduction of electric vehicle (EV) drive-train inverter losses by 78% based on EPA combined city/highway mileage standards. This efficiency improvement offers designers new options in terms of range, battery usage and vehicle design, says the firm.

Recently — in a collaboration with the US Department of Energy (DoE) — Wolfspeed supplied Ford Motor Company with a full-SiC, 400A power module designed around the 900V, 10mΩ chip. Designed and produced by Wolfspeed, the module contains four MOSFETs connected in parallel to achieve an on-resistance ($R_{ds(on)}$) of 2.5mΩ. Wolfspeed has since demonstrated the capability for using these chips to create an 800A, 1.25mΩ module.

"With the commercial release of the 900V 10mΩ device, electric vehicles can now reap the benefits of SiC in all aspects of their power conversion," says Wolfspeed's chief technology officer John Palmour. "With the continued expansion of our Gen3 MOSFET portfolio in new package options, our devices can now support significant efficiency improvements in on-board chargers, off-board chargers, and now EV drive trains," he adds.

Commercially qualified and rated for a maximum operating temperature of 175ºC, the new chip offers high reliability in harsh environments, such as those found in vehicle drive-trains, says Wolfspeed.

The new 900V, 10mΩ MOSFET is available in bare die form (listed as part number CPM3-0900-0010A) from SemiDice.

Wolfspeed expects to release the associated discrete device in a 4L-TO247 package (C3M0010090K) in the coming weeks. The package has a Kelvin-source connection that allows engineers to create designs that maximize the benefits of SiC's superior speed and efficiency, adds Wolfspeed.

**www.wolfspeed.com/cpm3-0900-0010a**

# Mouser signs global distribution agreement with United Silicon Carbide

Mouser Electronics Inc has announced a global distribution agreement with device maker United Silicon Carbide Inc (USCi) of Monmouth Junction, NJ, USA. USCi technology and products enable affordable power efficiency in key markets, including wind and solar power, transportation, smart grid technology, and motor control.

The USCi product line available from Mouser Electronics includes 650V and 1200V SiC Schottky diodes. USCi's 650V Schottky diodes are available in a TO-220 package with forward currents ranging from 4A to 10A, or in a TO-247 package with forward currents of 16A or 20A. The 650V diodes in the TO-220 package are also available with either enhanced surge capabilities or a surge bypass silicon diode that is suitable for AC/DC boost and power factor correction (PFC) converters. USCi's 1200V Schottky diodes are available in a TO-220 package in forward currents of 5A to 15A, or in a TO-247 package with a current of 20A or 30A.

With zero reverse recovery charge and a maximum junction temperature of 175ºC, USCi's RoHS-compliant diodes are suitable for high-frequency and high-efficiency power systems with minimum cooling requirements.

**www.mouser.com/usci**
**www.unitedsic.com**

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# Infineon refutes statement by MACOM on lawsuit

## Impression that MACOM's case is settled is false, asserts Infineon

Infineon Technologies AG of Munich, Germany has commented that the lawsuit between it, its subsidiary Infineon Technologies Americas Corp of Milpitas, CA, USA, and MACOM Technology Solutions Holdings Inc of Lowell, MA, USA (which makes semiconductors, components and subassemblies for analog RF, microwave, millimeter-wave and photonic applications) is still in its early stages, that the court has made no decision on the merits, and that MACOM has neither won the case nor is settlement imminent.

MACOM's dispute originates from irreconcilable business philosophies, states Infineon, adding that, whereas it generally welcomes competition and has entered into license agreements with many of its competitors allowing broad freedom to operate, MACOM prefers exclusion. However, whether MACOM or Infineon ultimately prevails in the lawsuit, the outcome should determine whether MACOM continues to be licensed to certain Infineon Americas patents. Infineon Americas owns the patents at issue and has the rights it needs for its own operations.

Origins of the lawsuit

Infineon claims that MACOM had been willfully infringing patents owned by Infineon Americas by operating outside the scope of a license agreement. MACOM admitted to the infringement but rejected Infineon America's offer to broaden the license agreement to cover the infringement, the firm adds. Infineon Americas therefore terminated MACOM's license in March. MACOM then filed a complaint in the US District Court for the Central District of California in Los Angeles. While no decision has been made on the merits, the court dismissed claims in MACOM's second attempt at a complaint in October (MACOM had voluntarily amended its first one). It has recently filed a third version. Infineon believes that the third complaint is still flawed and will move to dismiss this week. Once the lawsuit eventually proceeds, Infineon expects a decision within 1–2 years.

**Injunction aims to preserve status quo until judgement made**

To preserve the status quo until the court reaches a decision, the court issued a preliminary injunction that serves to shield MACOM from irreparable harm should it ultimately succeed in its lawsuit, while Infineon can seek to recover damages from MACOM later if Infineon prevails. Infineon says that the preliminary injunction is not a threat to its business plans.

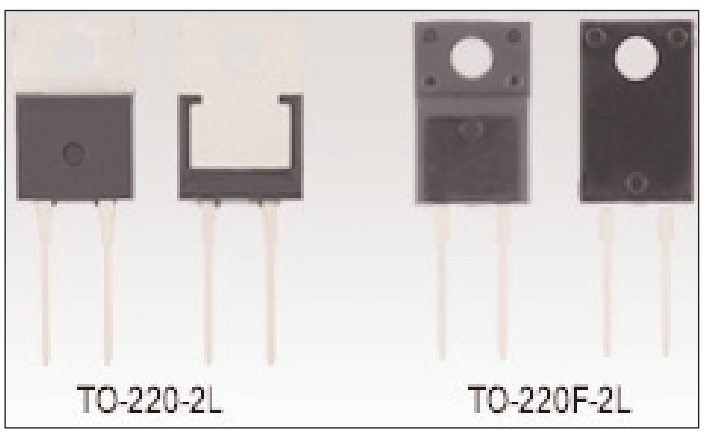
Specifically, and contrary to statements by MACOM, the court has made no decision that Infineon has "acted improperly in trying to operate in MACOM's exclusive field", says Infineon. To the extent that MACOM has given the impression through press releases, analyst calls and customer communication that it has won the case or that settlement is imminent, such impressions are false, asserts Infineon.

**www.infineon.com**

# Toshiba begins shipping second-generation 650V SiC Schottky diodes with 70% greater surge forward current

Toshiba Corp's Storage & Electronic Devices Solutions Company has begun shipping a new line-up of eight second-generation 650V silicon carbide (SiC) Schottky barrier diodes (SBDs) that improve on the surge forward current (IFSM) offered by the firm's existing products by about 70%.

Fabricated with Toshiba's second-generation SiC process, the new SiC Schottky barrier diodes deliver about 70% better surge forward current than its first-generation products, while reducing the switching loss index $R_{ON}$ x $Q_c$ (anode-cathode on-resistance times total capacitive charge) by about 30%, making them suitable for use in efficient power factor correction (PFC) schemes.




**Toshiba's second-generation 650V SiC Schottky barrier diodes with improved surge forward current.**

Available in four current ratings of 4A, 6A, 8A and 10A — either in a non-isolated TO-220-2L package or an isolated TO-220F-2L package — the new products can contribute to improving the efficiency of power supplies in devices including 4K large screen LCD TVs, projectors and multi-function copiers, and in industrial devices such as telecom base-stations and PC servers, says Toshiba.

**www.toshiba.co.jp**

# Infineon opens GaN expansion of Mesa Epi Services fab

Infineon Technologies AG of Neubiberg, Germany has celebrated the grand opening of its new warehouse and gallium nitride (GaN) cleanroom at its facility at 550 W. Juanita Avenue, Mesa, AZ, USA. The multi-million-dollar expansion project added about 11,500ft$^2$ and will create more than 20 new jobs.

"It's wonderful to see a business like Infineon show such a strong commitment to Mesa and District 3," commented vice mayor & District 3 Council member Dennis Kavanaugh at the event.

In attendance at the grand opening were Infineon management and staff from the USA; Villach, Austria; Munich, Germany; and Kulim, Malaysia. The event was hosted by Juergen Woehl, managing director of Infineon EPI Services Inc based in Mesa. Guest speakers included Bob LeFord, president of Infineon Americas; Steffen Metzger, head of Infineon GaN projects based in Munich; and Alex Miehr, head of Materials Management, Munich.

**Left to right: Bob Le Fort, president Infineon Americas; Alex Miehr, senior director Materials Management, Infineon Technologies AG; Jürgen Woehl, managing director, Infineon Epi Services; and Steffen Metzger, senior project director, GaN, Infineon Technologies AG.**

"Our Mesa facility underlines Infineon's commitment to work on advanced materials here in Mesa," stated Dr Jürgen Woehl, managing director, Infineon Epi Services.

**www.infineon.com**

# VisIC raises $11.6m in Series C round of financing

## MISHEMT power conversion device commercialization to accelerate

VisIC Technologies Ltd of Nes Ziona, Israel — a fabless developer of power conversion devices based on gallium nitride (GaN) metal-insulator-semiconductor high-electron-mobility transistors (MISHEMTs) — has closed a $11.6m Series C round of financing led by new investor Birch Investment and joined by existing investors.

VisIC notes that the potential of GaN-based electronics for electrical power delivery systems — from consumer power supplies to solar inverters, UPS (uninterruptible power supplies), power supplies for cloud/data centers and electric motor drives — has been marketed and anticipated for years, especially for high-voltage and high-current-switching applications. In May, VisIC demonstrated the performance of a high-current GaN switching device. This was followed in September by the demonstration of a 1200V GaN power switch.

The new funding is "an important milestone," says founder & CEO Tamara Baksht. "Having achieved the best performance metrics for any GaN devices in the market, this new capital infusion positions us to accelerate commercialization."

**www.visic-tech.com**

# Transphorm's fully packaged GaN FETs available via Digi-Key's global websites

Transphorm Inc of Goleta, near Santa Barbara, CA, USA says that its gallium nitride (GaN) FETs in standard TO-xxx through-hole and PQFN88 surface-mount packaging are available for immediate shipment from global electronic components distributor Digi-Key Electronics of Thief River Falls, MN, USA as part of a new global distribution agreement.

Transphorm designs and manufactures what it claims are the industry's only JEDEC-qualified GaN FETs for high-voltage power conversion applications. The product portfolio includes 600V and 650V discretes for power levels up to 4.5kW.

"The Transphorm team uniquely delivers a vertically integrated approach to GaN development [design, fabrication, device, and application integration]," says Mike White, senior VP, sales & marketing. "Our expertise applies to each layer of production — from the epitaxy tech through to the application development support," he adds. "We're deeply invested in the end-to-end process so that we can deliver the highest-quality, highest-reliability GaN technology available and, ultimately, help GaN achieve its promise as the new solution to power density challenges."

Transphorm pairs its depletion-mode, high-voltage GaN FET with a standard, low-voltage silicon MOSFET, creating a hybrid device (cascode switch) that operates as normally-off and is compatible with off-the-shelf silicon drivers for ease of use. GaN is said to provide higher performance, higher power density, and overall lower system cost.

**www.transphormusa.com**
**www.digikey.com**

# University of Illinois-led team develops GaN-on-Si HEMT technology scalable to 200mm substrates

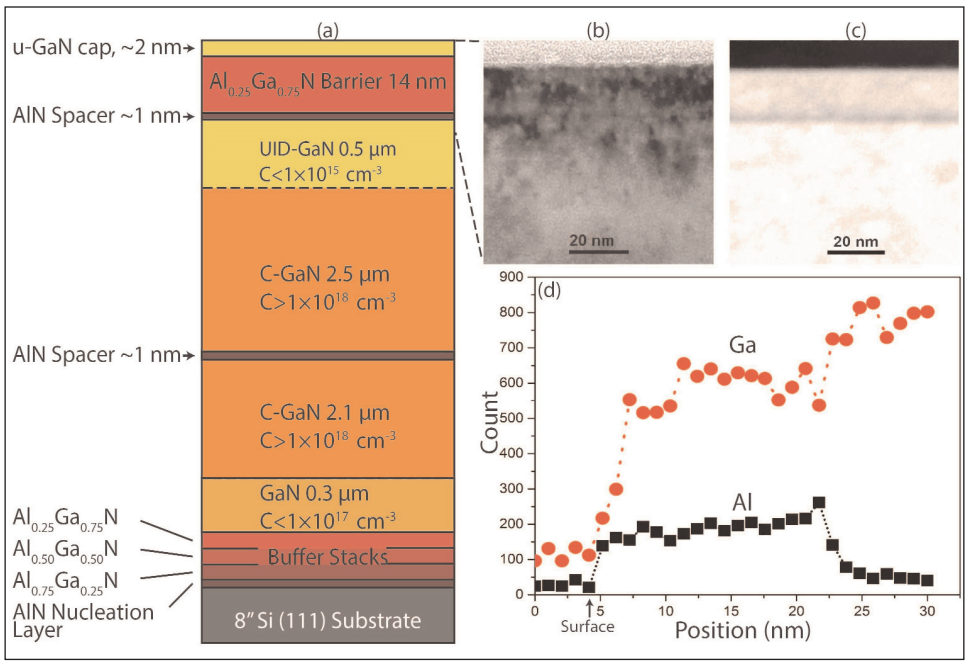
## Next step to fabricate fully functional high-frequency GaN HEMTs on silicon for 5G wireless data networks

University of Illinois at Urbana-Champaign (UIUC) claims to have recently advanced gallium nitride (GaN)-on-silicon transistor technology by optimizing the composition of the device layers. Working at its Micro + Nanotechnology Lab with industry partners Veeco Instruments Inc of Somerset, NJ and IBM Research of Yorktown Heights, NY (with support from the US Air Force Office of Scientific Research), the research team created the high-electron-mobility transistor (HEMT) structure on a 200mm silicon substrate with a process that will scale to larger industry-standard wafer sizes.

According to assistant professor Can Bayram of the Department of Electrical and Computer Engineering (ECE), his team created the GaN HEMT structure on a silicon platform because it is compatible with existing CMOS manufacturing processes and it is less expensive than other substrate options such as sapphire and silicon carbide (SiC).

However, silicon's lattice constant (the space between atoms) does not match up with the atomic structure of the GaN grown on top of it. "When you grow the GaN on top, there's a lot of strain between the layers, so we grew buffer layers [between the silicon and GaN] to help change the lattice constant into the proper size," says the ECE undergraduate lead researcher and lead author J Perozek et al 2017 J. Phys. D: Appl. Phys. 50 055103.

Without these buffer layers, cracks or other defects will form in the GaN material, which would prevent the transistor from operating properly. Specifically, these defects — threading dislocations or holes where atoms should be — ruin the properties of the device's two-dimensional electron gas (2DEG) channel, which is critical to the HEMT's ability to conduct current and function at high frequencies.




**(a) Cross-sectional structure. (b) TEM image of top 80nm of the HEMT structure. The dark gray layer marks the start of the surface. (c) STEM image of top 80nm. The surface starts beneath the black layer and the dark band is the AlN spacer. (d) EDS Chemical Analysis of top 25nm. Data before 4nm are the background values from above the surface.**

"The single most important thing for these GaN [HEMT] devices is to have high 2D electron gas concentration," says Bayram about the accumulation of electrons in a channel at the interface between the silicon and the various GaN-based layers above it. "The problem is you have to control the strain balance among all those layers — from substrate all the way up to the channel — so as to maximize the density of the of the conducting electrons in order to get the fastest transistor with the highest possible power density."

After studying three different buffer layer configurations, Bayram's team discovered that thicker buffer layers made of graded AlGaN reduce threading dislocation, and stacking those layers reduces stress. With this type of configuration, the team achieved an electron mobility of 1800cm$^2$/V-s.

"The less strain there is on the GaN layer, the higher the mobility will be, which ultimately corresponds to higher transistor operating frequencies," says Hsuan-Ping Lee, an ECE graduate student researcher leading the scaling of the devices for 5G applications.

According to Bayram, the next step for his team is to fabricate fully functional high-frequency GaN HEMTs on a silicon platform for use in the 5G wireless data networks.

When it's fully deployed, the 5G network will enable faster data rates for the world's 8 billion mobile phones, and will provide better connectivity and performance for Internet of Things (IoT) devices and driverless cars.

**http://iopscience.iop.org/article/10.1088/1361-6463/aa5208**
**www.mntl.illinois.edu**

# Mitsubishi Electric develops first GaN Doherty power amplifier with 600MHz bandwidth above 3GHz

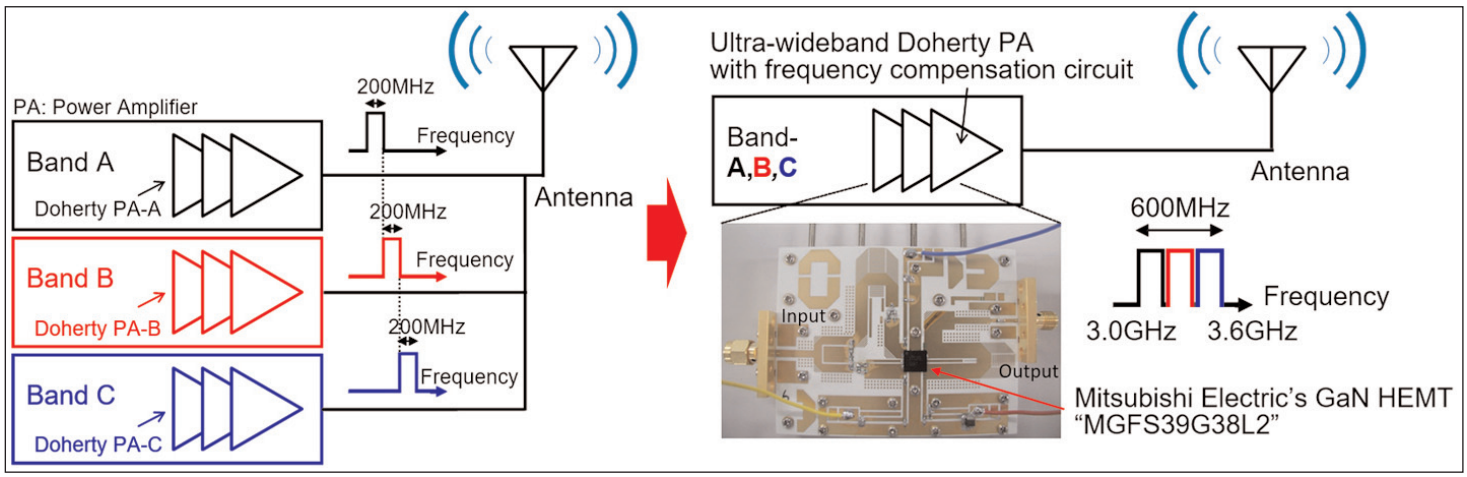
Tokyo-based Mitsubishi Electric Corp and its corporate R&D organization's North American subsidiary Mitsubishi Electric Research Laboratories (MERL) have developed an ultra-wideband gallium nitride (GaN) Doherty power amplifier for next-generation base stations that is compatible with what is claimed to be a record range of frequency bands above 3GHz, covering an operating bandwidth of 600MHz. The technology is expected to help to reduce the size and energy consumption of next-generation wireless base-stations. Details were presented at the IEEE Topical Conference on RF/Microwave Power Amplifiers for Wireless & Radio Applications (PAWR) during Radio & Wireless Week (RWW) in Phoenix, AZ, USA (15–18 January).

To help meet a rapid rise in demand for increasing wireless capacity, mobile technologies are shifting to next-generation systems that raise capacity by allocating new frequency bands above 3GHz and using multiple frequency bands, notes Mitsubishi Electric. Generally, power amplifiers operate with less efficiency at higher frequencies. Also, different power amplifiers are needed for different frequency bands, which can require larger base-stations. As such, extra-efficient power amplifiers compatible with multiple frequencies are in demand.

Mitsubishi Electric says that its new ultra-wideband GaN Doherty power amplifier uses frequency-compensation circuits with a Doherty architecture for enhanced efficiency over a three-fold wider range of frequency bands (spanning 600MHz above 3GHz, which is reckoned to be a record for a Doherty power amplifier).

Wideband, high-efficiency performance for efficient amplification of multiple radio frequencies by just one power amplifier can help to reduce base-station size and cooling needs, notes Mitsubishi Electric. The firm's MGFS39G38L2 high-efficiency GaN device contributes to a drain efficiency of over 45.9% in the 3–3.6GHz frequency range, reducing energy consumption. Also, an adjacent-channel leakage ratio (ACLR) of –50dBc is achieved with a commercial digital pre-distortion (DPD) technique for LTE (long-term evolution) 20MHz signals.

**www.radiowirelessweek.org/pawr-home**
**www.MitsubishiElectric.com**




**Power amplifier units in base stations for next-gen wireless systems: conventional (left) and new (right) Doherty PAs.**

## High-efficiency, wideband Doherty amplifier demonstrated

At Radio & Wireless Week (RWW) in Phoenix (16–17 January), Mitsubishi Electric US Inc presented a hands-on mini lab showcasing its high-efficiency, wideband Doherty amplifier. Also, the firm presented a technical paper describing the wideband Doherty power amplifier design technique for next-generation LTE base stations using Mitsubishi Electric's latest GaN transistor technology.

To break the inherent narrow-band limitation of conventional Doherty design methodology, the paper proposes a frequency dependency compensating circuit and a modified quarter-wavelength inverter incorporating the transistor package parasitic elements.

With improved bandwidth and efficiency compared with earlier design methodologies, this compact design delivers over 2.5W of average power with efficiencies above 45.9% across the full 3–3.6GHz band (20MHz LTE signal). This enables the design of more competitive LTE amplifiers capable of carrier aggregation scenarios in this band. Together with DPD to maintain –50dBc ACLR, use of the wideband efficient GaN Doherty design can reduce the radio's complexity and energy consumption, reducing base-station total cost of ownership.

# EPC and ASD leveraging WiTricity wireless charging reference design on display at CES

Efficient Power Conversion Corp (EPC) of El Segundo, CA, USA — which makes enhancement-mode gallium nitride on silicon (eGaN) power field-effect transistors (FETs) for power management applications — has announced accelerated efforts to build magnetic-resonance-based wireless charging systems based on WiTricity Corp's reference designs that feature GaN-based solutions from ASD Technology Ltd (a design and manufacturing company in Hong Kong). EPC says this ramp-up in activity is in response to growing interest from both customers and end-system manufacturers in wireless charging products using GaN.

WiTricity provides technology to enable wireless power transfer over distance using magnetic resonance, which has emerged as the leading technology for wireless power, says EPC. Meeting the AirFuel Alliance wireless power standard, the WiTricity reference design uses EPC's high-speed, thermally efficient and small-sized eGaN devices. As a licensee of WiTricity technology, ASD designs and produces products incorporating WiTricity's technology. The three-way relationship is said to provide a fast, direct route to introducing high-performance wireless charging products and systems.

"WiTricity has continuously supported business partners and licensees who adopt the AirFuel Alliance wireless charging standard to develop innovative wireless charging solutions," says WiTricity's VP of product management Sanjay Gupta.

**www.asdtech.com**
**www.witricity.com**
**www.epc-co.com**

## EPC showcases eGaN-based applications at CES

At the Consumer Electronics Show (CES) in Las Vegas (5–8 January), EPC showcased end-user application units enabled by eGaN FETs and ICs as well as its GaN products and development boards. EPC staff were available to discuss demonstrations of end-user applications in the home and in the car. For example, wireless power systems embedded in furniture and a free-standing wirelessly powered LED big-screen TV demonstrated the wirelessly powered home of the future; an ingestible pill containing a miniature x-ray system showed how a colonoscopy can be performed without the need for purging or an invasive procedure; and a real-time 3D LiDAR imaging sensor system demonstrating the technology at the core of autonomous vehicles highlighted how the speed of GaN significantly improves image location and resolution.

Also, in the AirFuel Alliance booth, EPC demonstrated the use of eGaN devices in an AirFuel-standard 33W, Class 4/ category 4 wireless-charging system, showing the ability to charge tablets and cell-phone handsets simultaneously. In addition, an eGaN-based multi-mode wireless-charging transfer system capable of charging devices regardless of the standard used in the receiving device was on display.

**www.airfuel.org**
**www.epc-co.com**

# GaN Systems joins AirFuel Alliance

GaN Systems Inc of Ottawa, Ontario, Canada — a fabless developer of gallium nitride (GaN)-based power switching semiconductors for power conversion and control applications — has joined the AirFuel Alliance, a global, non-profit consortium of industry leaders developing wireless charging standards. GaN Systems says it will aid the Alliance by bringing its wireless technology experience, by extending beyond the previously assumed limits of wireless charging, and by assisting the development of global wireless charging standards.

Wireless charging is growing at a CAGR of over 60% (according to MarketsandMarkets.com). Until recently, this market has been dominated by low-power (<15W) applications using silicon-based transistors. Contributing to this growth is the demand for wireless charging systems that operate at power levels greater than 15W.

GaN Systems says its transistors meet this demand by enabling efficient resonant wireless charging at power levels from 25W to 2500W. These high power levels make it possible to rapidly charge multiple phones and tablets simultaneously, as well as larger devices such as laptops, power tools, robotics, drones and 2-wheelers.

As well as enabling efficient higher-power wireless charging, GaN transistors provide two major benefits: reducing system size by 2–3 times, and reducing charging system cost.

"GaN Systems plays a critical leadership role by enabling high-power wireless charging while reducing system size and cost," says GaN Systems' VP of strategic marketing Paul Wiener, who will be active in AirFuel. "By joining the AirFuel Alliance, we will extend our role by contributing our technology, know-how and perspective toward the evolution of resonant wireless charging standards."

**www.gansystems.com**
**www.airfuel.org**

# EPSRC awards £10m to create UK compound semiconductor manufacturing hub

## Hub to focus on applying compound semiconductor expertise to silicon manufacturing techniques

The UK Engineering and Physical Sciences Research Council (EPSRC) has awarded £10m in funding that aims to will bring together UK academics and industry expertise in a compound semiconductor (CS) hub.

The EPSRC Manufacturing Hub in Future Compound Semiconductors will work closely with the Compound Semiconductor Centre (CSC) a joint venture formed in August 2015 between epiwafer foundry and substrate maker IQE plc of Cardiff, Wales, UK and Cardiff University.

The Future Compound Semiconductor Manufacturing Hub (EP/P006973/1) will be led by Cardiff University, together with three other key academic partners: UCL (University College London), the University of Manchester and the University of Sheffield. A further 26 initial companies and organizations allied to the Hub will help Cardiff and Wales capitalize on the £50m CS Applications Catapult unveiled by Innovate UK in January 2016. The Hub's industrial partners are:

- IQE (Drew Nelson);
- CSC (Wyn Meredith);
- CST (Neil Martin);
- Microsemi (Martin McHugh);
- Renishaw (Nick Weston);
- Silverwing (Neil Pearson);
- TWI (Nick Couling);
- Land Instruments (Fiona Turner);
- Amethyst;
- Selex;
- MACOM (Andrew Patterson);
- Diamond Microwave Devices (Richard Lang);
- Linwave (Ian Duke);
- Seren Photonics Ltd (Carl Griffiths);
- Zeta Specialist Lighting (Phil Shadbolt);
- Lux-TSI (Gareth Jones);
- NPL (J.T. Janssen);
- Lockheed Martin (Brent Segal);
- Toshiba Research Cambridge (Stuart Holmes);
- Teratech (Byron Alderman);
- Huawei Technologies Dusseldorf GmbH (Gao Yunhai);
- CIP (David Smith);
- Oclaro (Mike Wale);
- Bristol University (Daniel Whitcomb);
- Philips; and
- Umicore.

Total contribution from all project partners: is £11.23m.

"The Hub will provide Europe-leading facilities that will translate research into large-scale compound semiconductor growth and device fabrication," says professor Peter Smowton, the Hub's director. The central focus of the new venture will be the application of compound semiconductor expertise to silicon manufacturing techniques, yielding integrated compound semiconductors on silicon. "Many advances in our daily lives depend upon compound semiconductor technology," continues Smowton. "The new Hub will allow Cardiff and its partner Universities and companies to continue to develop technology that enables emerging trends, such as self-drive vehicles and 5G communications," he adds.

**The Hub will provide Europe-leading facilities that will translate research into large-scale compound semiconductor growth and device fabrication.**

**The central focus of the new venture will be the application of compound semiconductor expertise to silicon manufacturing techniques**

"We are committed to making strategic interventions to support industrial sectors where Wales already has internationally recognized academic and industrial expertise, where we have businesses capable of exploiting this knowledge and where there is a significant global market potential," says the Welsh Government's Minister for Skills and Science Julie James. "The Hub will shine a global spotlight on Wales and is an exemplar of how the Welsh Government's Smart approach to innovation will benefit the people and businesses of Wales," she adds.

"IQE produced compound semiconductor materials for 10 billion wireless chips last year, underpinning the worldwide mobile communications industry," notes IQE's CEO Drew Nelson. "The Hub will allow us to exploit the highly advantageous electronic, magnetic, optical and power-handling properties of compound semiconductors while utilizing the cost and scaling advantage of silicon technology where it fits best, and generate novel integrated functionality such as sensing, data processing and communications."

Another Hub project partner, the US-based optical components manufacturer Oclaro, saw 50% quarter-on-quarter growth in 100Gb/s transceiver products (developed and manufactured in the UK), supporting Internet communications.

The Hub's goal is to grow long-term future partnerships with UK and international companies and academics. "We are open to interactions with new partner companies and universities, and we can provide opportunities through feasibility project funding calls to kick-start future partnerships," says Smowton.

**www.iqep.com**
**www.compoundsemiconductorcentre.com**

# IQE to report greater-than-expected double-digit growth for 2016, after stronger second half

## Photonics customer qualifications drives rise in capital investment

Epiwafer foundry and substrate maker IQE plc of Cardiff, Wales, UK says that, since announcing its interim results on 13 September, trading has continued to be strong across multiple markets, particularly in the photonics business. The firm is hence on track to deliver 2016 revenue and adjusted operating profit ahead of expectations. It is anticipated that revenue will reflect a double-digit growth rate year-on-year, and that second-half revenue will be up sequentially over first-half 2016.

The wireless business has largely performed as expected through 2016 and remains on track for year-on-year growth. Photonics continues to be the fastest-growing business segment (seeing strong double-digit growth year-on-year), and progress with customer qualifications during 2016 provides a solid platform for continuing strong growth. In response to this opportunity in photonics, IQE has increased its capital investment in second-half 2016. InfraRed business has performed in line with expectations, and license income has reduced from the front-loaded income seen in 2015.

Revenues (which are primarily dollar denominated) also benefitted in second-half 2016 from the devaluation of sterling following the UK's EU membership referendum on 23 June. However, the currency impact on profitability is largely presentational, as most of IQE's costs are also denominated in dollars. The balance sheet impact is also presentational, as both non-sterling assets and liabilities will be translated at the year-end spot rate. This is expected to impact positively the presentation of shareholder funds. Furthermore, although IQE has de-leveraged its balance sheet during 2016 in underlying dollar terms, the presentation of this is expected to be distorted adversely in sterling.

**Photonics continues to be the fastest-growing business segment (seeing strong double-digit growth year-on-year) and progress with customer qualifications during 2016 provides a solid platform for continuing strong growth**

IQE's board is confident that IQE will exceed current full-year 2016 expectations for both revenue and adjusted operating profit. The firm will report its full-year 2016 results on 21 March 2017.

"IQE has made good progress in 2016, and is performing well against its strategic goals," comments IQE's chief executive Dr Drew Nelson. "The breadth of IQE's technologies is a competitive advantage that is enabling its continued growth, and will provide a platform for strong cash generation over the coming years," he adds.

www.iqep.com

## IQE board gains Cisco UK/Ireland veteran as non-executive director

Epiwafer foundry and substrate maker IQE plc of Cardiff, Wales, UK has announced the appointment of Phil Smith BSc, Hon LLD, DUniv. FIET, as a non-executive director.

Smith became chairman of Cisco for the UK and Ireland in August, after eight years as chief executive. Cisco is a provider of networking for the Internet. Smith is also the chairman of UK Government agency Innovate UK (formerly the Technology Strategy Board) and chairman of the Tech Partnership. Additionally, he sits on the board of the National Centre for Universities and Business (NCUB).

Smith has a 35-year track record in the technology industry in companies including Philips Electronics and IBM. As chief executive and now chairman of Cisco, he leads about 5500 people in the UK and Ireland. He created Cisco's British Innovation Gateway (BIG) program, as a legacy of London 2012 to spark nationwide ingenuity, ambition and growth through technology entrepreneurship. He works closely with government ministers, industrial leaders and business leaders and is an advocate on the transformational nature of technology, sustainability, ambition, inclusion and diversity and the critical need for STEM skills in future generations.

In September 2014 Smith was awarded an honorary doctorate by Birmingham City University, cited for his outstanding contribution to the IT industry. In March 2015 he was awarded an honorary degree of Doctor of Laws by the University of Warwick and in 2016 an honorary degree of Doctor of Science by his alma mater Glasgow University.

"He has been hugely successful leading businesses with technologies that bring transformational benefits to many private and public sector organizations in the UK and the wider world," comments Sir David Grant, chairman of IQE's Nominations and Remuneration Committees. "His vision, his energy and his encouragement of leadership in a global high-technology environment are well matched to IQE's future aspirations."

# Veeco to report Q4/2016 revenue of $91–95m, up from Q3's $85.5m

## Full year down from 2015's $477m to $330–334m as China drops from 51% to 26% of total revenue

In preliminary financial results for fourth-quarter 2016, epitaxial deposition and process equipment maker Veeco Instruments Inc of Plainview, NY, USA has announced revenue of $91–95m, down on $106.5m a year ago but up on $85.5m last quarter.

Full-year revenue is $330–334m for 2016, down on $477m for 2015. Specifically, the Lighting, Display & Power Electronics segment has fallen from 61% of total revenue to 41%, while the Advanced Packaging, MEMS & RF segment has risen from 13% to 21%, the Scientific & Industrial segment from 13% to 22%, and the Data Storage segment from 13% to 16%. Correspondingly, by geographical region, the China market has plummeted from 51% to 26% of total revenue, while the USA has risen from 18% to 26%, the Europe, Middle East & Africa (EMEA) from 13% to 25%, and the rest of the world from 18% to 23%.

On a non-GAAP basis, gross margin is 38.5–39.5% for Q4/2016, down from 40.3% last quarter but up from 36.8% a year ago. Full-year gross margin has risen from 38% for 2015 to 41% for 2016.

Operating expenses have been cut further, from $38m a year ago and $34.6m last quarter to $33–34m in Q4/2016 (with R&D expenses cut from $19.3m a year ago to $17–18m, and selling, general & administrative and other expenses cut from $18.7m a year ago to $16m). Full-year operating expenses were cut from $151.6m in 2015 to $144–145m in 2016. This is despite R&D expenses rising from $74.5m to $78–79m, as selling, general & administrative and other expenses were cut from $77.1m to $66m.

Adjusted net income for Q4/2016 is $2–4m ($0.04–0.10 per diluted share), compared with $0.6m ($0.01 per diluted share) a year ago and a net loss of $1.8m ($0.05 per diluted share) last quarter. However, for full-year 2016, Veeco is reporting an adjusted net loss of $12–10m ($0.31–0.25 per diluted share), compared with income of $22.1m ($0.54 per diluted share) in 2015.

Adjusted earnings before interest, taxes, depreciation and amortization (EBITDA) for Q4/2016 is $5–7m, up from $2.9m last quarter and $4.4m a year ago. Full-year adjusted EBITDA is $3–5m, down from $41.7m in 2015.

Cash, cash equivalents and short-term investments is estimated to have risen from $337m to $344m during Q4/2016.

Veeco concludes that it expects to record bookings of about $125m for Q4, up 6% on $118m in Q3.

# Osram Opto orders Veeco GaN MOCVD and PSP systems for new LED production facility in Malaysia

## Multi-year agreement declares Veeco sole provider of MOCVD and PSP manufacturing technology

Epitaxial deposition and process equipment maker Veeco Instruments Inc of Plainview, NY, USA says that Osram Opto Semiconductors GmbH of Regensburg, Germany has completed an agreement naming Veeco as the supplier for metal-organic chemical vapor deposition (MOCVD) and Precision Surface Processing (PSP) systems needed for high-volume LED production at its new facility in Kulim, Malaysia. As part of the agreement, Osram Opto has ordered multiple TurboDisc EPIK700 gallium nitride (GaN) MOCVD systems and WaferStorm 3306 PSP Wet Process systems.

Veeco says that its production-proven TurboDisc and Uniform FlowFlange MOCVD technologies have enabled LED makers to achieve improved cost per wafer savings compared with previous MOCVD systems through enhanced wafer uniformity, reduced operating expenses and increased productivity. The WaferStorm PSP Wet Process System is a solvent-based platform that integrates Veeco's proprietary ImmJET technology for improved yield, higher throughput and lower chemical cost than conventional methods for metal lift-off and other back-end compound semiconductor processes.

"We are pleased that Osram Opto Semiconductors has selected Veeco as a partner in their Diamond initiative, a clear indication that Veeco's LED manufacturing solutions are best-in-class at lowering manufacturing costs and driving high levels of productivity," says Veeco's president William J. Miller, Ph.D. "Veeco's WaferStorm platform provides distinct advantages to the back-end wafer cleaning process," he adds. "As we move forward with this exclusive multi-year partnership, we plan to support Osram's impressive expansion plans with advanced Veeco technology and process expertise."

www.osram-os.com

# Riber's chairman resigns

Etienne Grodard has resigned for personal reasons as a member and chairman of the executive board of Riber S.A. of Bezons, France.

At its meeting on 6 December, the supervisory board thanked Grodard for the results achieved in the firm's commercial and financial development.

Grodard is replaced as chairman by Guillaume de Bélair, who has 17 years' experience in financial roles, particularly in corporate and investment banking with the Natixis Group, in the credit investment sector, in France and internationally. Since 2014, he has specialized in investment consulting and analysis, notably in connection with turnaround strategies focused on consolidating banking relationships and financial communications, as well as identifying and engaging investment funds.

www.riber.com

# TRUMPF orders second Riber MBE system for high-power bar laser production

Riber has received an order for an MBE system (for delivery in 2017) for the production of high-power bar lasers.

TRUMPF Photonics Inc of Cranbury, NJ, USA (part of TRUMPF Inc, the North American subsidiary of TRUMPF GmbH near Stuttgart, Germany), which produces diode chips, optics and electronics as well as pump and direct-diode modules, has ordered a major MBE system to increase its manufacturing capacity for high-power diode lasers for industrial laser applications.

This order of a second system builds on the partnership established four years ago between TRUMPF and Riber.

www.trumpf.com

IN BRIEF

## Riber wins €2m accessories order from Asia

Riber S.A. of Bezons, France, which manufactures molecular beam epitaxy (MBE) systems as well as evaporation sources and effusion cells, has received a major accessories order worth about €2m from an existing customer in Asia in the display industry.

Deliverable in 2017, the new accessories order completes the order for evaporation sources received in October for the same industry.

Riber says that the order confirms its commercial position in a fast-growth market segment, with opportunities for repeat orders over the next three years as customers ramp up their capacities.

www.riber.com

# China's Grand Chip abandons acquisition of Aixtron

## US president's order to bar takeover of Aixtron's US business thwarts conditions of share offer

Grand Chip Investment GmbH (GCI, a German limited liability company set up as a special-purpose investment vehicle) says that its voluntary public takeover offer announced on 29 July to acquire all the shares of deposition equipment maker Aixtron SE of Herzogenrath, Germany has lapsed due to the non-fulfillment of an offer condition.

Aixtron agreed in late May to be acquired by GCI. GCI's China-based parent firm Fujian Grand Chip Investment Fund LP is held 51% by Chinese businessman & private investor Zhendong Liu and 49% by Xiamen Bohao Investment Ltd (an investment entity indirectly controlled by Chinese private investors Zhongyao Wang and Wanming Huang). Fujian Grand Chip (FGC) hence said that it would launch a voluntary public takeover offer to acquire all of the outstanding ordinary shares of Aixtron SE, including all ordinary shares represented by Aixtron ADS (American depositary shares). Shareholders were offered €6 per ordinary share, valuing Aixtron's equity (including net cash) at about €670m and reflecting a 50.7% premium to the three-month volume weighted average share price prior to the announcement.

However, on 21 October the German Federal Ministry of Economics and Energy withdrew the Clearance Certificate issued on 8 September to FGC and reopened review proceedings in connection with the acquisition, citing that Aixtron's know-how comprises security-related technologies (in particular for the defense sector) that could be revealed through the acquisition.

Including its subsidiary Aixtron Inc in California, Aixtron's US business in 2015 comprised nearly 20% of the company's entire staff and accounted for over 20% of global sales. Hence, following advice from the Committee on Foreign Investment in the United States (CFIUS), which is chaired by the US Department of the Treasury, on 2 December US President Barack Obama issued an executive order prohibiting the acquisition of Aixtron's US business by GCI (some of whose investors have Chinese government ownership, it is alleged).

The US Treasury Department says that FGC's proposed acquisition of Aixtron was to have been funded in part by Sino IC Leasing Co Ltd, a financing provider belonging to China IC Industry Investment Fund, a Chinese government-supported industrial investment fund established to promote the development of China's integrated circuit industry.

CFIUS and the President assessed that the transaction posed a risk to the USA's national security that could not be resolved through mitigation. The risk related to the "military applications of the overall technical body of knowledge and experience of Aixtron… and the contribution of Aixtron's US business to that body of knowledge and experience". Aixtron makes metal-organic chemical vapor deposition (MOCVD) systems to grow semiconductors including gallium nitride (GaN), used in the manufacturing of not only light-emitting diodes but also, it is said, defense electronics. Obama's order hence directed the purchasers and Aixtron to permanently abandon the proposed acquisition within 30 days (unless the date was extended by CFIUS for a period of up to 90 days).

**The US Treasury Department says that FGC's proposed acquisition of Aixtron was to have been funded in part by Sino IC Leasing Co Ltd, a financing provider belonging to China IC Industry Investment Fund, a Chinese government-supported industrial investment fund established to promote the development of China's integrated circuit industry.**

**The public takeover process initiated by GCI has hence come to end, says Fujian Grand Chip**

In response to Obama's presidential order, on 2 December China's Foreign Ministry spokesman Geng Shuang commented regarding the acquisition deal: "Since it is a normal commercial activity, it will be carried out following the rule of markets and business," according to a Reuters report. "We hope the external parties will not over-interpret that or make any political intervention," he added.

Also, on 3 December, Aixtron noted that Obama's presidential order was limited to the US business and did not prohibit the acquisition of Aixtron shares and ADSs by GCI.

Now, Aixtron says that, as a consequence of Obama's order, the offer's condition — for clearance of the transaction by either CFIUS or the US President — has not been fulfilled. The public takeover process initiated by GCI has hence come to end, says Fujian Grand Chip.

According to Reuters, at the time of Obama's order Aixtron said that, in response, action would need to be taken to re-balance costs and income, possibly including cutting jobs. At the end of third-quarter 2016, Aixtron had 713 staff worldwide (including 136 in the USA).

**www.aixtron.com**

# Aixtron sells enhanced 5x4-inch CRIUS MOCVD system to Toyoda Gosei for blue and UV LED production

Aixtron SE of Herzogenrath, near Aachen, Germany says that Japan's Toyoda Gosei has bought an enhanced 5x4-inch CRIUS Close Coupled Showerhead (CCS) metal-organic chemical vapor deposition (MOCVD) system — scheduled for delivery in first-half 2017 — to manufacture blue and ultraviolet (UV) LEDs.

Aixtron says that the novel, improved process chamber of the CRIUS tool enables significantly higher process temperatures than previously available III–V MOCVD reactors. It is designed to deliver the process conditions needed for the manufacture of high-performance blue and UV LEDs, used for applications such as high-color-rendering LED lighting, curing or photocatalytic purification.

"The new Aixtron CCS reactor will support us producing various enhanced LED products since we aim to grow our LED business by expanding the sale of products that will promote the use of LED lighting in Southeast Asia and other regions," says Toshihiro Yokoi, managing officer, general manager of Toyoda Gosei's Optoelectronics business unit. "Furthermore, we will increasingly focus on industrial-used LEDs (UV LEDs, glass-encapsulated LEDs) and LEDs for automobiles, where we can take advantage of our strengths as an automotive parts manufacturer," he adds.

**www.toyoda-gosei.com**
**www.aixtron.com**

# Repeat order from Lumentum for AIX 2800G4-TM systems

Lumentum Holdings Inc of Milpitas, CA, USA, which makes photonic devices for communications, industrial and consumer applications, has placed a repeat order for multiple Aixtron AIX 2800G4-TM MOCVD systems to manufacture devices for optoelectronic and laser applications.

"We have a longstanding business relationship with Aixtron, and their local system support teams are excellent and very responsive," comments Lumentum's executive VP & chief operating officer Vince Retort. "Following the successful qualification of the first AIX 2800G4-TM system, we decided to expand our production capacity and ordered additional Aixtron tools. We look forward to a collaborative relationship with Aixtron in the future," he adds.

"Our AIX 2800G4-TM tool supports Lumentum's technology approach by providing excellent on-wafer uniformity control, unique advanced features for wafer-to-wafer temperature control such as AUTOSAT and low precursor consumption," says Aixtron's executive VP & chief operating officer Dr Bernd Schulte. "Furthermore, this highly efficient and flexible system offers various wafer configurations from 2-inch to 6-inch."

**www.lumentum.com/en**

# Aixtron to delist American depositary shares from NASDAQ and deregister with SEC

Aixtron is to voluntarily delist its American depositary shares (ADSs) from The NASDAQ Global Select Market and deregister and terminate its reporting obligations under the Securities Exchange Act of 1934.

Trading over the past 12 months on NASDAQ accounted for less than 5% of the worldwide trading volume of Aixtron's ordinary shares, while nearly all of the rest was conducted through the firm's listing on the Frankfurt Stock Exchange. Given the comparatively low trading volumes on NASDAQ, Aixtron says that the complexity as well as the cost and effort associated with maintaining a dual listing, including reporting obligations with the US Securities and Exchange Commission (SEC), outweigh the benefits of continuing its listing and registration in the USA.

While noting that it is in compliance with all its listing requirements, Aixtron provided written notice to NASDAQ of its intention to delist and to file a Form 25 'Notification of Removal from Listing' and/or registration under Section 12(b) of the Exchange Act with the SEC on 30 December. Aixtron's last day of trading of the ADSs on NASDAQ was on 30 December, since when it has traded on the US over-the-counter market. The firm's ordinary shares continue to trade on all German stock exchanges, including the Frankfurt Stock Exchange under the stock symbol 'AIXA'. Aixtron expects that delisting of the ADSs and deregistration will have no other impact on the ordinary shares' listing on the Frankfurt Stock Exchange.

Aixtron also aimed to file a Form 15F with the SEC on 9 January, in order to deregister and terminate its reporting obligations under the Exchange Act. Other filing requirements terminate upon the effectiveness of deregistration under Section 12(g) of the Exchange Act (90 days after filing Form 15F).

**www.aixtron.com**

# ClassOne reports record sales, driven by wafer-level packaging and More than Moore technologies

ClassOne Technology of Kalispell, MT, USA, which manufactures wet-chemical processing equipment including Solstice electroplating systems (especially for emerging markets and other cost-conscious users of ≤200mm substrates), has reported its best-ever sales quarter and is currently doubling its Kalispell manufacturing capacity to meet the demand. "We've been seeing a steady increase in market interest and sales," says president Kevin Witt. "Most of these users are now focusing on capabilities they couldn't get before, like wafer-level packaging and More than Moore technologies," he adds.

Wafer-level packaging (WLP) has been used for some time with 300mm and larger substrates, but the equipment has not been available for 200mm, notes Witt. "ClassOne focuses specifically on the smaller-wafer markets," he adds. "At a very affordable price, we deliver the new technology and advanced 3D features they're looking for. For example, our Solstice line of multi-functional electroplating systems enables high-efficiency copper (Cu) through-silicon via (TSV), pillar, bump and barrier plating and other capabilities that WLP requires."

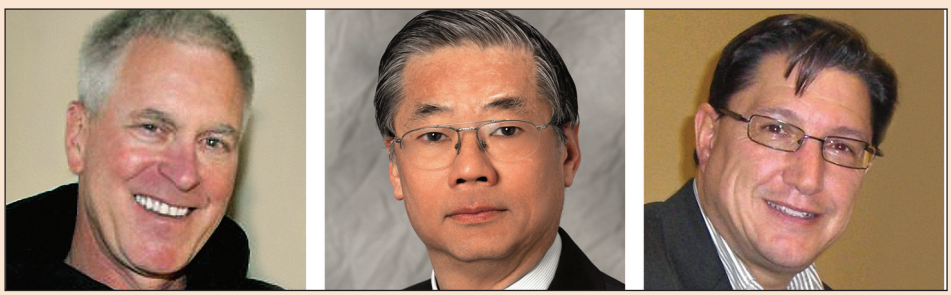
ClassOne says that many of the new buyers are interested in More than Moore (MtM) technologies to increase functionality while reducing cost per device, producing compound semiconductors, LEDs, MEMS, RF, Wi-Fi and a range of Internet of Things (IoT)-related sensors and other devices. The firm cites the combination of ≤200mm-specific tools, advanced capabilities and affordable pricing as the primary driver behind the current equipment-buying surge in emerging markets.

ClassOne Technology offers a selection of new-technology wet processing tools designed for 75–200mm wafer users, including three different models of Solstice electroplating systems for production and development as well as the Trident families of spin-rinse-dryers and spray solvent tools.

**www.classone.com/products**

## ClassOne Technology forms board of advisors

ClassOne Technology has formed a board of advisors consisting of senior executives from the semiconductor industry that will provide their perspective and guidance as ClassOne navigates the expansion of its operations. So far, Larry Murphy, Eric Choh and Tom Pilla have been named to the board.



**From left to right: Larry Murphy, Eric Choh and Tom Pilla, who have been appointed to ClassOne Technology's new board of advisors.**

"ClassOne is experiencing very rapid growth right now, and we wanted to incorporate the broad perspective and deep experience that these gentlemen can bring to our effort," says president Kevin Witt. "Larry, Eric and Tom are long-respected leaders in this industry and have already proven to be a huge asset," he adds.

"We've seen the customer focus and innovative technology that this company is bringing to the industry," comments Murphy. "ClassOne is disrupting the old status quo and delivering much-needed high-performance electroplating and wet process equipment to the smaller-substrate markets — markets that have been generally underserved."

Murphy is currently chief executive officer at PROOF Research. Previously, he has been CEO at Thompson Technology Group, vice president & general manager of North America & Europe SSG Sales at Applied Materials, and VP & general manager of the Semitool Business at Applied Materials. Earlier, Murphy was president & chief operating officer at Semitool for six years and, before that, president & CEO at Tosoh SMD for more than 14 years.

Choh has spent more than 30 years in the semiconductor industry, including extensive experience in wafer fab operations and advanced technology development. Most recently he was the VP/GM of GlobalFoundries' Fab 8. Choh also held senior positions at AMD, including VP of Advanced Process Development and executive managing director of the AMD/UMC Alliance.

Pilla is currently global supply chain director and electronic materials/business manufacturing director of Litho Materials at Dow Chemical. Previously, he was VP of operations at Rohm and Haas Electronic Materials, VP of operations at Rodel, and global supply chain director at Rohm and Haas.

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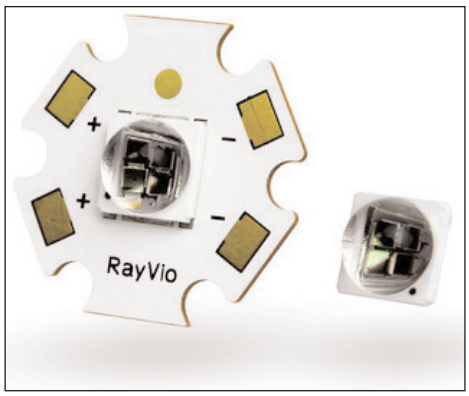
**DISCOVER** PROGRESS

# RayVio launches 60mW UV LED for disinfection and sterilization

Health and hygiene company RayVio Corp of Haywood, CA, USA, which is commercializing deep-ultraviolet (UV) LEDs and consumer disinfection solutions, is delivering what is claimed to be the first 60mW UV LED in volume.

The firm says that, with the XP Series, disinfection of flowing water, whole-room sterilization and purification of household products and medical instruments can be achieved safely and efficiently without the use of fragile and hazardous mercury lamps. Even 'superbugs' like MRSA can be safely and effectively rendered harmless.

"The global need for clean water, sanitary environments and protection against infectious disease is critical," says chief technology officer Dr Doug Collins. "In China, India, Brazil, on the African continent, in the US and elsewhere, people will continue to get sick or die because bacteria and viruses proliferate and, too often, people lack the infrastructure, patience or tools to slow or eliminate the spread of germs." With the 60mW output from the XP Series, it is possible to address some larger-scale infrastructure problems, such as the disinfection of running water with a safe, efficient and long-lasting solution, the firm adds.




**RayVio's XP Series UV LED.**

"The first ever sterilizing pod — Ellie — is just one example of how little time it takes to improve lives with our UV LED technology," says Collins. "Ellie can sterilize baby bottles, purify water and sterilize surfaces on pacifiers, keys and more to keep children safe from germs."

RayVio exhibited at the Consumer Electronics Show (CES 2017) in Las Vegas (5–8 January). Ellie was also on show as part of the BabyTech Summit at CES.

**www.rayvio.com/xpseries**
**http://ellieduv.com**

# AquiSense collaborates with International Light Technologies

AquiSense Technologies LLC of Erlanger, KY, USA (which designs and manufactures water, air and surface disinfection systems based on UV-C LEDs) has entered into a collaboration agreement for the sensors of International Light Technologies Inc (ILT) of Peabody, MA, USA to be offered in combination with its PearlBeam, a bench-scale UV device for research applications.

AquiSense says that advances in UV-C LEDs have led the way to the creation of collimated beam devices whereby researchers can now select multiple discrete UV-C wavelengths, allowing them greater precision in their research to better understand how micro-organisms respond to UV light applications. In unison, as the precision of the wavelength emission increases, more advanced sensors are required to track emission data. ILT provides the needed sensor technology with a handheld light meter.

"AquiSense recognized that an entirely new tool was required to advance UV science to take advantage of the many benefits of UV-C LEDs," says the firm's director of business development Jim Cosman. "The PearlBeam was the first step in this process, and now the incorporation of International Light Technologies' advanced sensors is the next step in our quest to rapidly convert many disinfection applications from mercury-containing UV lamps to more environmentally sound UV-C LEDs."

Collimated beam devices are increasingly critical tools in providing a standardized unit of measurement for UV exposure. Historically these devices, which use mercury lamps, have been expensive, cumbersome and difficult to operate, says AquiSense. The PearlBeam is claimed to be the first UV-C LED collimating beam device, taking advantage of solid-state technology. It is small in size, light-weight and does not contain fragile glass, providing a research tool for the lab but one that is also field-ready. The use of UV-C LEDs offers instant on/off with immediate intensity, allowing for exact exposure times. LEDs also provide variable UV-C wavelengths. The PearlBeam has up to three wavelength options, with an activation switch for each wavelength.

International Light Technologies has been solving the inherent difficulties in light measurement through the design and manufacture of a wide range of light measuring instruments. The sensor used with the PearlBeam will allow testing in the 255–300nm range, which prevents the need for several sensors to test a variety of wavelengths. The hand-held unit from ILT provides data, trends and averages in a portable setting, making the combination of the PearlBeam and ILT products truly field-ready, says AquiSense.

**www.aquisense.com**
**www.intl-lighttech.com**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# Taiwan's Genesis Photonics transitioning to CSP LEDs for automotive lighting

## Kunshan, China fab to be sold as blue LEDs falls from 80% of revenue in late 2015 to 30% by early 2017

Taiwan-based LED epiwafer maker Genesis Photonics Inc (GPI) of Tainan Science Park outlined its future roadmap, stating that it was re-directing its focus to CSP LEDs for automotive lighting, according to Money DJ.com, reports LEDinside.

Genesis Photonics says that its CSP LED products have successfully entered the Taiwan and US markets. It is also accelerating its Chinese automotive luminaire certification process, with the aim of entering China's supply chain by first-half 2017, and estimates that it will profit from this strategic transition.

GPI has entered high-end automotive headlights and other lighting markets. The capacity of CSP LEDs to be driven at high voltage and to deliver high brightness makes them suitable for consumer electronics. The firm is still developing CSP LEDs for smartphone flash light applications, which should yield revenue in first-quarter 2017.

Based on GPI's business transition plans, traditional blue LEDs' share of revenue will be slashed from 80% in late 2015 to just 30% by early 2017. The firm has announced its intention of selling its LED manufacturing facility in Kunshan, Jiangsu, China to further lower its traditional blue LED production, and is seeking a potential buyer.

To strengthen its future product portfolio and gross margin, GPI officially exited the low-end LED lighting market in October.

**www.gpiled.com**
**www.ledinside.com**

# Epistar expanding capacity for both AlGaInP LED chips and flip-chip CSP blue LEDs

## AlGaInP LED chips to rise from 25–30% of revenue in Q4/2016 to over 30% in 2017 and flip-chip blue LEDs rise to 10%

LED epitaxial wafer and chip maker Epistar Corp of Hsinchu Science-based Industrial Park, Taiwan is expanding production capacity for aluminum gallium indium phosphide (AlGaInP) LED chips and nitride-based blue-light LED flip-chips, reports Digitimes. The first quarter of the year is an off-season period and the capacity expansion is preparing for demand in the second quarter, according to Epistar's president Jou Ming-jiunn.

Epistar continues to modify metal-organic chemical vapor deposition (MOCVD) systems — originally used to make blue LED chips — for producing AlGaInP LED chips, Jou notes. Epistar aims to extend its AlGaInP-based infrared LED chip applications from security surveillance to VR (virtual reality), AR (augmented reality) and iris recognition in 2017, he adds. AlGaInP LED chips are hence expected to rise from 25–30% of company revenue in fourth-quarter 2016 to over 30% in 2017, Jou says.

In addition, Epistar has improved yield rates for flip-chip chip scale package (FC CSP) blue LED and will expand production capacity in 2017, Jou notes. Epistar expects Samsung Electronics, LG Electronics and China-based LCD TV vendors to increase adoption of flip-chip blue LED for backlighting, he adds. In addition, after Apple adopted FC CSP LEDs for the iPhone 7 camera flash, other smartphone vendors are expected to follow suit in 2017, Jou says. The flip-chip blue LEDs is expected to rise to more than 10% of revenue in 2017.

Despite suffered a net operating loss in 2016, Epistar hopes to return to profitability in 2017 by adjusting production capacity and product mix, Jou states.

**www.digitimes.com/news/a20170115PD202.html**
**www.epistar.com.tw**

# VP Europe made CEO of Seoul Semiconductor Europe

South Korean LED maker Seoul Semiconductor (SSC) says that its former VP Europe Andreas Weisl has assumed role of CEO at its subsidiary Seoul Semiconductor Europe GmbH based in Munich, Germany. The firm's European headquarters was established in 2010.

In his role as general manager for Central and Northern Europe from 2010 and as VP Europe since 2014, Weisl is an SSC executive and is responsible for business development in Europe.

Before joining SSC in 2010, he had more than 11 years of experience in LEDs, including serving as a manager, among other roles, at Osram Opto Semiconductors GmbH of Regensburg, Germany.

**www.SeoulSemicon.com**

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# Philips sells majority stake in Lumileds to US firm Apollo

The world's largest lighting producer Royal Philips NV of Amsterdam, The Netherlands has agreed to sell an 80.1% stake in its California-based LED component and automotive lighting company Lumileds to certain funds managed by affiliates of Apollo Global Management LLC. Philips will retain the remaining 19.9% interest in Lumileds for a minimum of three years following completion of the transaction.

With operations in more than 30 countries and about 9000 staff worldwide, Lumileds manufactures LED-based lighting components for the general illumination, automotive and consumer electronics markets, generating sales of $2bn in 2015.

The deal values Lumileds at about $2bn. Philips expects to receive cash proceeds (before tax and transaction-related costs) of about $1.5bn and participating preferred equity (entitling it to an incremental share of future value creation, depending on the achievement of certain returns by Apollo managed funds). The transaction is expected to be completed in first-half 2017, subject to customary closing conditions (including the relevant regulatory approvals).

Previously, in January, Philips terminated an agreement to sell an 80.1% stake in Lumileds to a consortium led by GO Scale Capital (an investment fund sponsored by China-based GSR Ventures and US-based Oak Investment Partners) in a deal that valued Lumileds at about $3.3bn. This was after US regulatory clearance was thwarted by concerns of the Committee on Foreign Investment in the United States (CFIUS), as GSR Ventures had existing investments in China-based Lattice Power (one of few firms to manufacture gallium nitride based LEDs on silicon substrates rather than on sapphire or silicon carbide).

"With this transaction, we will be completing an important phase of the transformation of our portfolio and I am satisfied that in the Apollo-managed funds we have found the right owner for Lumileds," says Philips' CEO Frans van Houten. "In line with our strategic focus on health technology, Lumileds has been operating as a standalone company within Philips since early 2015. With Apollo managed funds acquiring a majority interest in Lumileds and partnering with Philips, Lumileds is now well-positioned for further growth and value creation, building on its robust innovation pipeline, technology leadership and strong customer base," he adds.

Apollo is a global alternative investment manager with assets under management of about $189bn in private equity, credit and real-estate funds, invested across a core group of nine industries. Apollo-managed funds have a track record of acquiring and growing businesses in partnership models of co-ownership with former parent companies, Philips says.

"We look forward to partnering with Philips and the outstanding management team and employee base at Lumileds, and bringing in Apollo's resources to support the continued growth and innovation," says Apollo senior partner Robert Seminara.

"Together with the Apollo-managed funds, Lumileds will sharpen its focus and accelerate innovation in its leading product portfolio of lighting components," says Lumileds' CEO Pierre-Yves Lesaicherre. "With our strong R&D programs and intellectual property, we are ready to address the current and future needs of our customers. Lumileds will work closely with its industry partners and customers and capture growth opportunities," he adds.

# Lumileds' third-gen LUXEON UV LED doubles irradiance power of smallest UV emitter at 380–390nm

Lumileds has launched the LUXEON UV U1 LED for UV curing, counterfeit detection, analytical instrumentation, inspections and other UVA and violet (380–420nm) applications.

This third generation of UV LEDs maintains the same micro package size as the LUXEON Z UV, but enables a higher power density. The LUXEON UV U1 also features a robust design that eliminates materials like silicone over mold (which tends to yellow and crack upon UV exposure) and wire bonds (which can lead to catastrophic connection failures). "UV LED customers are reliability driven," says Yan Chai, product line director of Lumileds UV LEDs. "They tend to run their equipment 24/7 and demand a proven product that will perform as expected for over 20,000 hours."

The LUXEON UV U1 LED is nominally tested at 500mA but can be driven at up to 1A to achieve higher irradiances. For UV curing at 395nm, it achieves 700mW at 500mA and >1300mW at 1A under 25ºC.

Compared with the 3.5mm x 3.5mm package size of most UV LEDs, LUXEON UV U1's 2.2mm$^2$ micro SMD package size delivers greater packing density as well as over five-fold greater power density, it is reckoned. The LUXEON UV U1's footprint is a drop-in replacement for the LUXEON Z UV, while providing twice the typical radiometric power as its predecessor at 380–390nm (a popular wavelength range for UV curing applications).

The surface-mount LEDs can be tightly assembled with spacing as small as 200µm for high system flux density. With a wall-plug efficiency exceeding 45+% and thermal management aided by an AlN package, users can avoid the use of more expensive water cooling at the system level, adds Lumileds.

**www.lumileds.com/LUXEONUVU1**

# Soraa launches Helia smart LED lighting

Soraa Inc of Fremont, CA, USA, which develops solid-state lighting technology fabricated on 'GaN on GaN' (gallium nitride on gallium nitride) substrates, is entering the consumer market with Helia, providing a healthy light environment for homes.

Positioned at the intersection of health and smart home, Helia — which has been named a CES 2017 Innovations Award Honoree at the Consumer Electronics Show in Las Vegas (5–8 January) — combines full-spectrum LED lighting with a secure, expandable network of smart home sensors. The result is claimed to be an intuitive, energy-efficient lighting system that brings the benefits of dynamic, natural sunlight indoors.

Recent advances have revealed the crucial impact of light on sleep patterns and health. Specialized cells in the human eye respond to sunlight's blue light wavelengths to synchronize our internal clocks and set a circadian rhythm. Natural sunlight is bright and filled with blue light in the morning. As the sun sets, blue light recedes, signaling our bodies to prepare for sleep. However, people now live under artificial lights and in front of LED screens — which are often packed with blue light content. Many studies now conclude that even common levels of blue light exposure in the evening, primarily from artificial lighting sources, can negatively impact sleep and longer-term health. More than 60% of Americans now report sleep problems.

Helia tackles these concerns with what is claimed to be a unique approach — replicating the timing and visible spectrum of natural sunlight. Leveraging Soraa's LED technology coupled with an enterprise-grade networking and sensor platform, Helia adapts to an environment automatically, based on a home's sunrise and sunset times. Helia bulbs provide plenty of blue light in the morning, whereas in the evening the firm's patented BlueFree LED technology removes blue light completely while retaining a soft white color.

"More than ever, consumers are becoming aware of the effect artificial lighting and screens are having on their sleep and health," says CEO Jeff Parker. "Helia creates the healthiest lighting system ever introduced, to make homes a place where the efficiency of modern lighting and health can coexist," he claims.

"Paying attention to the amount and quality of the light you expose yourself to during the day and night is probably the single biggest modifiable factor for getting a healthy night of sleep," says Dr W Chris Winter, a sleep specialist and neurologist who consults for several NBA, NFL, MLB and NHL teams.

Other smart bulbs can change color during the day and night, but since they are all made with standard LEDs, they emit up to 20 times more blue light and can make your rooms unnaturally yellow. Instead, Helia emits a tailored spectrum — white light to render vivid colors throughout the day and night.

Soraa claims that Helia can also make smart home lighting simple to install. By just screwing in Helia bulbs and turning them on, they will automatically connect to one another over the existing power lines in your house and start working together, before even opening the app. No wireless hub or Internet connection is required to provide seamless integration with no wireless dead spots. Lighting can then be refined using the Helia app by providing information about where your house is located and when you usually wake up in the morning and go to sleep at night.

For consumers who want to connect their Helia lighting system to popular Internet of Things (IoT) cloud services, Helia has created the Cloud Connect accessory, which can be plugged into an outlet near a home Wi-Fi router. The system will be connected to Helia's secure cloud and ready for Amazon Alexa Voice commands, remote control while away from the home and IFTTT compatibility. Also, Helia lighting systems connect seamlessly to popular IOT ecosystems.

Helia is available initially in North America in Spring at Helia.com, sold as Room Kits allowing consumers to order the precise number of bulbs and Smart SNAPS needed to outfit an entire room or rooms. Dynamic White BR30 bulbs will retail for $49.95 each, Dynamic White + Presence Smart SNAPs (one per room) for $29.95, and the Cloud Connect accessory for $49.95 (optional, one per home).

**www.helia.com**
**www.soraa.com**

## Soraa's lamp line first to receive California's JA8-2016-E certification

Soraa claims it is the first firm to have a complete line of LED lamps from MR16s to PARs certified JA8-2016-E under California's new Title 24 lighting standard. From 1 January, all permitted new and retrofit construction projects require JA8-2016-E certified lamps.

To qualify for California's new lighting standard, LED lamps need to have a color rendering index (CRI) of 90+ and a deep red (R9) rendering greater than 50.They must also feature less than 30% stroboscopic flicker; must dim below 10%; and the color point must be consistent from lamp-to-lamp within a 3McA ellipse.

Meeting and exceeding the JA8 certification requirements, Soraa's LED lamps render colors accurately with a CRI of 95 and R9 of 95; have 3McA color consistency; dim as low as 1%; and feature drivers with very low flicker.

**https://cacertappliances.energy.ca.gov/Pages/ApplianceSearch.aspx**

# Cree and Feit settle patent dispute and reach license agreement

LED chip, lamp and lighting fixture maker Cree Inc of Durham, NC, USA says that it has reached a confidential settlement in its patent infringement and false advertising lawsuit with lighting company Feit Electric Company Inc of Pico Rivera, CA, USA.

The settlement ends US International Trade Commission (ITC) investigation number 337-TA-947 ('Certain Light-Emitting Diode Products and Components Thereof') against Feit and its Asian supplier Unity Opto Technology Co Ltd as well as ending the corresponding lawsuit in the US District Court for the Western District of Wisconsin. The agreement also ends Feit's claims against Cree in litigation filed in the US District Court for the Middle District of North Carolina.

As part of the settlement, Feit and Cree have entered into a royalty-bearing license agreement to the Cree patents asserted in the ITC case and in Wisconsin. Feit will pay Cree a license issue fee and ongoing royalties as part of the license agreement, and Cree will receive a license to the Feit filament panel patents.

"Cree has invested over $1.2bn in R&D over the past 10 years to create fundamental technology that has enabled the LED lighting revolution, and it is our obligation to protect our intellectual property," says chairman & CEO Chuck Swoboda. "This settlement and license agreement recognizes the value of our pioneering technology and ensures we are properly compensated while protecting consumers and Cree shareholders," he adds.

**Feit and Cree have entered into a royalty-bearing license agreement to the Cree patents... Feit will pay Cree a license issue fee and ongoing royalties as part of the license agreement, and Cree will receive a license to the Feit filament panel patents**

Cree says that its licensing program, which includes more than 20 licensing partners, allows other companies to use its proprietary technology, and supports these organizations' pursuit of new markets and products.

As a result of the settlement, for its fiscal second-quarter 2017 (ending 25 December 2016) Cree now expects to exceed its revenue, net income and earnings per share (EPS) targets (announced on 18 October). Cree will report its fiscal second-quarter results and third-quarter business outlook on 24 January.

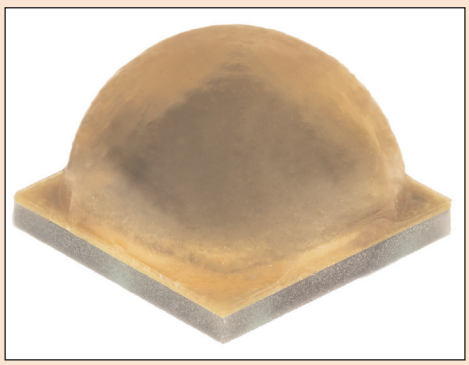
**www.feit.com**
**www.creebulb.com**

# Cree launches XHP50.2 extreme high-power LED, boosting output by 7% and efficiency by 10% over first generation

LED chip, lamp and lighting fixture maker Cree Inc of Durham, NC, USA has introduced the XLamp XHP50.2 LED, which delivers up to 7% more lumens and 10% higher lumens-per-watt (LPW) than the first-generation XHP50 LED in the same 5.0mm x 5.0mm package.

The firm says that the new XHP50.2 LED enables lighting manufacturers to quickly improve the performance of existing XHP50 lighting designs. Capable of producing more than 2500 lumens from its 6mm light-emitting surface (LES), the XHP50.2 can reduce the size and cost of new designs and enable innovative solutions to address applications ranging from spot to street lighting, it adds.

In addition to light output and efficacy enhancements, the XHP50.2 LED provides improvements to optical uniformity through secondary optics, enabling spot and portable lighting manufacturers to deliver better lighting, says Cree. The XHP50.2 LED has LM-80 data available immediately, reducing the time required to receive ENERGY STAR and DesignLights Consortium qualifications.



**Cree's new XLampXHP50 LED.**

"Delivering the industry's best lumen density and reliability, Cree's XHP LED family allows our customers to achieve performance levels not possible with other LEDs at the lowest total system cost in a wide range of applications," claims Dave Emerson, senior VP & general manager for Cree LEDs.

Featuring Cree's EasyWhite technology, which provides high color consistency, the XLamp XHP50.2 LEDs are available in color temperatures of 2700–6500K with high-CRI (color rendering index) options. Product samples are available now, and production quantities are available with standard lead times.

**www.cree.com/xlamp/xhp50_2**

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# Osram launches space-saving package platform for large-area photodiodes in fitness sensors

Osram Opto Semiconductors GmbH of Regensburg, Germany says that its new IR Topled D5140 photodiode requires considerably less printed-circuit board space than before. It enables more compact sensors to be produced for monitoring fitness levels, for example in fitness armbands. The spectral sensitivity of the D5140 has been optimized for visible light and allows precise heart rate measurements using red or green light. The device is also suitable as an ambient light sensor.

The IR Topled D5140 is a further development of the SFH 2440 photodiode that Osram Opto recently introduced for fitness sensors. A pre-molded package soldered to the bottom of the package forms the basis of the new component. Previously offered packages had to be soldered to side legs. Because these legs are no longer there in the new design, the Topled D5140 is around 1.4mm shorter, now measuring 5.1mm.

The electrical and optical properties of the new photodiode are identical to those of its counterpart, the SFH 2440. Along with the short switching rise/fall time of typically 90ns, the spectral sensitivity optimized for visible light is particularly noteworthy, with maximum sensitivity at 620nm. However, in the infrared spectral range the sensitivity of the two photodiodes is suppressed.

Just like the SFH 2440, the IR Topled D5140 is also suitable for optical sensors for pulse rate measurements (e.g. on the wrist). It works by shining visible light on the surface of the skin, some of which is absorbed or reflected to the detector. Because arterial blood absorbs more light than the surrounding tissue, the strength of the detector signal changes with the volume of blood through which the light passes. The periodicity of the signal indicates the heart rate. However, infrared light which shines onto the measuring point from the surroundings and disperses in the body also reaches the photodiode.

The Topled D5140 offers what is claimed to be outstanding signal-to-noise-ratio because it registers the reflected light particularly well while at the same time suppressing the infrared light. Due to its short switching time, the light signal modulated with the heart rate can be time-resolved perfectly. "The IR Topled D5140 allows our customers to design more compact sensors, preserving the high signal quality offered by the SFH 2440 so far," says Dr Chris Goeltner, project manager Infrared at Osram Opto.

Applications that so far have been using large-area photodiodes such as the SFH 2440 or SFH 2430 as ambient light sensors can also be made smaller with the new component. In the near future, Osram wants to offer a photodiode with broadband spectral sensitivity in the new package for its automotive customers too.

# Osram provides LED-based lighting technology for Rinspeed's Oasis concept car

Lighting manufacturer Osram of Munich, Germany (claimed to be the world's top automotive lighting provider) is the exclusive lighting supplier for Oasis, the latest concept vehicle from Switzerland-based think-tank Rinspeed, whose latest concept vehicle is designed to reimagine what the driverless vehicle experience could look and feel like in the future. Rinspeed launched the Oasis at the 2017 Consumer Electronics Show (CES) in Las Vegas, where the vehicle was on display at the Harman exhibit in the Hard Rock Hotel (4–7 January).

With expertise ranging from optoelectronic components to full LED modular solutions, Osram has helped the Oasis team to reach its goal of creating an experience that fully embodies the vehicle's unique character through lighting and technology, inside and out.

Osram supplied five Multi-LED modules for each headlamp, featuring an innovative design that can be used to create a personalized, custom-built headlamp. Depending on the performance desired, low and high beams can be achieved using 6–10 Multi-LED modules, which can also be coupled with an electronic system to offer a broad range of animation sequences, including welcome lights as well as the ability to coordinate the headlights with other light functions of the vehicle.

Oasis features two auxiliary forward lighting LED projection modules for demonstrating how LED technology could be used to welcome the driver to the vehicle, provide a high-quality source of illumination at night to safely guide drivers down the road, and communicate with the outside world. For example, the LED system could indicate to pedestrians that they are seen by the vehicle and aid their decision of when to cross the road. In the future, these same LED-based systems could possibly provide entertainment or functional value when the vehicle is at rest, such as projecting movies, status information, or other video content onto any outside surface.

Osram showcased some of its automotive lighting technologies at CES, demonstrating its range of interior and exterior automotive applications.

**www.osram.com/CES**

# Osram showcases smart LED- and laser-based automotive lighting technologies at CES

Lighting manufacturer Osram of Munich, Germany unveiled its latest automotive applications at the Consumer Electronics Show (CES 2017) in Las Vegas (5–8 January).

"Osram's car lighting technologies are designed to offer drivers smart and stylish design options, but most importantly to significantly enhance road safety," says Olaf Berlien, CEO of Osram Licht AG. "Laser-based car lighting is much brighter and enables a doubled high-beam range," he adds. "The improved down-road visibility and clarity for the drivers increases safety for all on the road." The fatality rate of night-time travel is up to four times that of day-time travel.

"We also will provide the virtual eyes for autonomous driving cars," says Osram's chief technology officer Stefan Kampmann. "A modern car comprises about 200 light sources. Some of them are using invisible light — for example, in systems for smart surroundings analysis and for proximity detection as well as for driver monitoring." Visitors to Osram's CES booth can take part in a virtual reality (VR) tour for them to experience various automotive light sources, ranging from ambience lighting to extra-bright and far-reaching headlights.

As the latest automotive technology using invisible light, LiDAR (light detection and ranging) plays a key role in advanced driver-assistance systems, which are increasingly enabling semi-autonomous to fully autonomous driving capabilities. LiDAR systems generate laser pulses that hit objects and reflect light back onto a detector. The time of travel of the laser beam establishes the distance to the object. Osram's multi-channel laser light source enables vehicles to generate an accurate, three-dimensional image of their surroundings and use this information to initiate the appropriate driving maneuvers. Accurate evaluation of the vehicle's surroundings is crucial for safe autonomous driving, notes Osram.

Headlights using laser technology are the next stage in automotive lighting, states Osram. Due to the high luminance of the laser (about five times higher than the best of other light sources currently available), these headlights double the best high beam range previously available, from 300m to 600m (2000ft). Osram's energy-efficient laser lighting (which includes some of the smallest technology components available, it is claimed) found its way into serial car production with the BMW i8, the BMW 7 series and the Audi R8 und R8 LMX as boosters added to the high beam, providing better visibility for the driver and thus greater road safety.

In addition to laser technology, advanced pixel headlights represent the future of automotive lighting, says Osram. Together with partners, the firm has developed a tiny LED matrix chip with more than 1000 individually controllable pixels. A headlight comprising several such LED chips allows permanent driving with glare-free full beam. An onboard camera recognizes oncoming vehicle and pedestrian traffic, automatically dimming the high-resolution LED chips to ensure that the head areas of oncoming drivers, pedestrians and cyclists are spared from the light beam. This provides the driver with the best possible light at night, with no adverse effects for other traffic users. Osram expects to bring this technology to the commercial market by 2020.

**www.osram.com/CES**

# SemiLEDs shrinks losses as quarterly revenue rebounds and R&D expenses cut further

For fiscal first-quarter 2017 (ended 30 November 2016), LED chip and component maker SemiLEDs Corp of Hsinchu, Taiwan has reported revenue of $2.7m, rebounding by 43% from $1.88m last quarter but still down 10% on $3m a year ago.

Gross margin was +4%, compared with negative 66% last quarter and negative 49% a year ago.

While selling, general & administrative (SG&A) expenses have remained steady at $1.1–1.2m, research & development expenses have been cut from $0.6m a year ago and $0.4m last quarter to $0.2m. Total operating expenses have therefore been cut from $1.7m a year ago to $1.2m.

Operating margin was –41%, cut from –106% a year ago.

On a non-GAAP basis — including $0.5m income from a breach of contract lawsuit payments (a $0.3m advance receipt payment made in March 2015 plus $0.2m settlement payment made in November 2016 — net loss was $0.6m, cut from $2.8m last quarter and $3.3m a year ago.

Net cash used in operating activities was $1.12m, up from $0.53m last quarter. Hence, despite capital expenditure being cut from $154,000 last quarter to just $68,000, total free cash outflow has risen from $0.68m last quarter to $1.19m. During the quarter, cash and cash equivalents therefore fell from $6m to $4.83m.

For fiscal second-quarter 2017 (ending 28 February), SemiLEDs expects revenue to fall back to about $2.1m.

**www.semileds.com**

# VerLASE awarded further patents in US and Japan for use of 2D materials in light sources

VerLASE Technologies LLC of Bridgewater, NJ, USA (which was spun off from technology development firm Versatilis LLC of Shelburne, VT, USA in 2013) says that it has been awarded US Patent No. 9,525,150 by the US Patent Office and Patent No. 6027970 by the Japan Patent Office, further extending its patent portfolio on the use of 2D semiconductor materials as the active light-emitting layer in LEDs, laser diodes and other optoelectronic devices.

The technology enables low-cost, novel electroluminescent devices that can be tailored to directly emit in any color in the visible spectrum, or in a mixed combination for white light at a desired color temperature, without phosphors or other color-converting media. Versatilis says it can challenge organic light-emitting diodes (OLEDs) in applications requiring smaller pixel sizes such as micro-displays for augmented reality (AR) and virtual reality (VR) applications, where OLEDs have difficulty achieving sufficient brightness with small pixels. Other applications include smaller displays of all kinds, ranging from wearables to smartphones and tablets, offering a practical way around some of the technical and cost hurdles pacing broader adoption of OLEDs, claims the firm.

Semiconducting 2D materials like graphene have captured much attention for their potential use in many applications. Such materials can be grown in crystalline layers weakly bound to each other, then be cleaved or exfoliated into extremely thin layers. VerLASE has been investigating photoluminescent quantum wells (QWs) made of 2D materials such as gallium selenide, gallium sulphide and tungsten disulfide, which can be made into highly efficient down-converting phosphors free of cadmium or other heavy metals.

Versatilis previously won a broad patent (US 9,035,344) covering the use of such 2D semiconductor materials as phosphors, analogous to quantum dots (QDs) but as QWs in a 'flat' or 2D aspect, which can also take the form of nano-platelets (NPLs). The firm then extended the work in a second patent (US 9,269,854) to the use of such 2D materials as electroluminescent layers in active devices. VerLASE says that the newly issued patents solidify its IP for 2D materials in such applications.

Independent research worldwide points to the advantages of 2D materials in a wide range of applications, notes the firm. Quantum wells of 2D semiconductor materials offer similar optical advantages to quantum dots (with narrower spectral characteristics, better colors and color saturation) but can be more efficient and offer much better thermal characteristics for better stability in many lighting, projector and display applications.

It can also be easier to work with such 2D materials in depositing the other layers needed to make active devices. The active layers can be exfoliated sheets of controlled thickness, with the other layers necessary to make them into devices added through chemical processes, or grown directly on an appropriate substrate. Depending on the specific chemistries used, such 2D semiconductors can even be grown directly on silicon, enabling the use of available silicon chip manufacturing infrastructure for low cost.

"The unique attributes of 2D materials enable low-cost electroluminescent devices, fulfilling the original QD vision with inorganic QWs," says Ajay Jain, chief technical officer and inventor of the technology. He adds that the same basic 2D semiconductor materials can also be used as gain media in lasers and other high-value electro-optical devices.

**www.verlase.com**

# Alpes Lasers supplying QCLs for SILMARILS program

Alpes Lasers SA of St-Blaise, Switzerland has been selected as a developer and supplier of broadband quantum cascade lasers (QCLs) by several chemical sensing companies working on the program 'Standoff Illuminator for Measuring Absorbance and Reflectance Infrared Light Signatures' (SILMARILS).

The SILMARILS program is part of the Intelligence Advanced Research Projects Activity (IARPA) and is managed by the US Air Force Research Laboratory at Wright-Patterson Air Force Base, Ohio.

Under this project Alpes Lasers will develop new classes of QCLs providing high spectral power density and pulse energy in the fingerprint region of the mid-infrared spectrum, which allows specific identification of a large class of organic and non-organic chemicals such as chemical weapons, explosives, narcotics or biological agents. The lasers will be integrated within portable systems by the prime contractors selected by IARPA.

"These contracts leverage Alpes' know-how as a worldwide leader in broad-gain and high-power QCLs to develop new products," says Alpes Lasers' CEO Dr Antoine Müller. "The laser chips developed have the potential to be integrated into devices that will facilitate safety screenings in airports and can be used by law enforcement agencies worldwide."

Phase 1 of the development is due to be completed by the end of 2017.

**www.alpeslasers.ch**

# TriLumina and Analog Devices collaborate on illuminator module for automotive Flash LiDAR

## High-output VCSEL array and laser driver in small surface-mount package to enable mass deployment of LiDAR

TriLumina Corp of Albuquerque, NM, USA, which manufactures and integrates vertical-cavity surface-emitting laser (VCSEL) array light sources for LiDAR (light detection and ranging) and interior illumination products, is collaborating with Analog Devices Inc (ADI) of Norwood, MA, USA (which designs and manufactures ICs for analog and digital signal processing applications) on a new integrated, solid-state illuminator module for automotive Flash LiDAR systems.

The integration of TriLumina's VCSEL array emitters with ADI's patent-pending high-speed pulse laser driver is said to enable high optical power output in a single, small surface-mount IC package, marking a milestone towards cost-effective, high-performance LiDAR systems.

"TriLumina offers unique illumination devices based on solid-state, back-emitting, flip-chip VCSEL arrays," says TriLumina's CEO Brian Wong. "When coupled with ADI's driver technology, these lasers provide higher optical power, enabling Flash LiDAR systems to achieve greater range," he adds.

"LiDAR is a key pillar of ADI's automotive safety strategy along with radar and inertial sensors," says Chris Jacobs, general manager, Automotive Safety Group, Analog Devices. "It will become a critical element of safety systems as functions such as automatic emergency braking (AEB) and autonomous driving become more common."

Advanced driver assistance systems (ADAS) incorporate a suite of sensors for safety features such as collision avoidance, pedestrian detection, and autonomous driving functions. Future car safety systems rely on the sensor fusion of cameras, radar, and LiDAR (which provides the link between cameras and radar, as it provides both object recognition and distance measurements).

Existing automotive LiDAR solutions have significant drawbacks such as bulky mechanical size, poor reliability and high cost, says TriLumina. The collaboration with automotive supplier ADI is targeted at overcoming these weaknesses to enable mass-market deployment of LiDAR systems.

www.analog.com
www.trilumina.com

# Panasonic acquires US-based industrial direct-diode laser start-up TeraDiode

## Laser processing business to be augmented by integrating direct-diode laser technology

Panasonic Corp of Osaka, Japan has signed a contract to acquire TeraDiode Inc (TDI) of Wilmington, MA, USA, which was founded in 2009 and supplies high-brightness direct-diode lasers (DDL) for industrial use.

Panasonic notes that, recently, high-precision and high-quality laser processing technology has become increasingly important to meet the demand for light-weight and high-rigidity characteristics along with high design flexibility and high productivity in the automobile and other industries. Due to its proprietary wavelength beam combining (WBC) technology, TDI's high-brightness DDL has attracted attention as a next-generation laser that meets such demands from a wide range of industrial markets, the firm adds.

Panasonic and TDI began a strategic alliance in 2013, and in 2014 launched LAPRISS, the first laser welding robot system using TDI's high-brightness DDL technology. Also in 2014, Panasonic obtained from TDI exclusive sales rights for DDL used for welding in major countries in the Asian region. The firms have since collaborated closely on product development, manufacturing, sales and service in order to expand the use of DDL technology worldwide.

**Panasonic and TDI in 2014 launched LAPRISS, the first laser welding robot system using TDI's high-brightness DDL technology**

Panasonic and TDI have agreed to make TDI a 100% subsidiary of Panasonic, so that Panasonic will be able to drive further growth of both companies' laser processing business by integrating TDI's DDL technology and expertise with Panasonic's own technology.

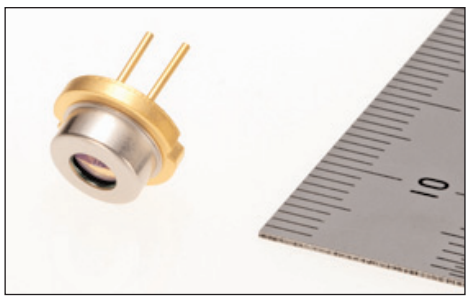
Panasonic and TDI target further joint development of DDL technology, and aim to strengthen laser processing as a new core business of Panasonic in the factory solutions field.

www.teradiode.com

# Mitsubishi Electric launching record 2.1W-output 639nm red laser for projectors

On 1 February, Tokyo-based Mitsubishi Electric Corp is launching the ML562G85 continuous-wave (CW) laser diode (LD), offering a record output power of 2.1W and a brilliant 639nm red light for projectors. The laser diode's pure red color and low power consumption are expected to be adopted for large-venue laser-based projectors requiring high brightness.

It has been a technical challenge to produce red laser diodes offering high output at high temperature using a lasing wavelength not exceeding 640nm (the preferred maximum for achieving necessary luminosity). In 2010, Mitsubishi Electric launched its ML501P73 high-power-red laser diode, which incorporated original epitaxial growth technology and window-mirror structure and offered output of 1.0W (pulse) or 0.5W (CW) at 638nm. In September 2015, the firm launched the ML562G84, which achieves 2.5W of output power at 638nm light in pulsed operation.



**Mitsubishi Electric's ML562G85 639nm-wavelength high-power red laser diode.**

Mitsubishi Electric says that it has now succeeded in developing a new CW high-power red laser diode that operates at high temperature by using original high-power technology, including an optimized laser diode structure.

Product features for the ML562G85 include an optimized epitaxial structure and emitter size, enabling record CW power output of 2.1W (at a case temperature of $T_C$ = 25°C), 4.2 times greater than that of the firm's existing model. The high-luminosity 639nm red laser light and 2.1W output (CW) yield 250 lumens per laser diode. High wall-plug efficiency of 41% at 2.1W (CW) and a low case temperature of 25°C help to reduce projector power consumption.

The large 9.0mm-diameter transistor-outline can (TO-CAN) package improves heat dissipation, yielding what is claimed to be the widest operating temperature range for a red laser diode of 0–45°C at 2.1W (CW). This compares with the existing model's 0–40°C at 0.5W (CW).

www.mitsubishielectric.com/semiconductors/products/opt/laserdevice

# Founding director of Lehigh's Center for Photonics and Nanoelectronics Nelson Tansu elected fellow of National Academy of Inventors

Professor Nelson Tansu of Lehigh University's P.C. Rossin College of Engineering and Applied Science has been named a fellow of the US National Academy of Inventors (NAI).

Election to NAI Fellow status is the "highest professional distinction accorded to academic inventors who have demonstrated a prolific spirit of innovation in creating or facilitating outstanding inventions that have made a tangible impact on quality of life, economic development and the welfare of society."

Tansu, Lehigh's Daniel E. '39 and Patricia M. Smith Endowed Chair Professor in Photonics and Nanoelectronics, is regarded as a leading researchers and inventors in semiconductor optoelectronics materials and devices.

"His inventions in the dilute nitride materials of GaInAsN paved the way for vastly improved lighting emitters and lasers in the infrared and telecommunication wavelengths," comments NAI fellow and National Academy of Engineering member Steven DenBaars, professor of Materials and Electrical & Computer Engineering, University of California Santa Barbara (UCSB). "His innovations in the physics of low-dimensional semiconductor nanostructures, and in metal-organic chemical vapor deposition (MOCVD) of III–arsenide and III–V nitride semiconductor optoelectronics devices, are world-class," he adds.

"My entire professional career has been at Lehigh University, where great support and a team-centered environment allow creative and innovative groups of students, postdoctoral researchers, and faculty to work together to produce some amazing results," says Tansu.

As founding director of Lehigh's Center for Photonics and Nanoelectronics (CPN), Tansu leads a multi-disciplinary research team encompassing electrical engineers, material scientists, applied scientists and physicists to help develop materials, devices and device architectures.

"Our goal is to build a vertically integrated platform of faculty expertise and research capabilities to solve issues that require innovation in materials, devices, systems, and computational aspects," says Tansu. "This integration enables our faculty and students to work on advancing the frontiers of science and technology, with impact in sustainable and energy technologies, healthcare and biotechnologies, communications, and sensors."

Tansu's work has been published in more than 114 refereed journal and 230+ conference publications, and he currently holds 16 US patents, including seven that are licensed and/or used in industry. He has served as a panelist for the US National Science Foundation (NSF), Department of Energy (DoE), and other agencies in the US and abroad. His work has been funded by the NSF, DoE, DARPA, Department of Defense (DoD), and the State of Pennsylvania.

At Lehigh, Tansu targets collaboration opportunities at the intersection of disciplines. He has worked with chemical engineers, material scientists, mechanical engineers, physicists, chemists, applied physicists, and other electrical engineers. For example, a recent chance encounter with Brandon Krick (assistant professor of mechanical engineering) led to research into the mechanical durability of gallium nitride, which his lab has spent time exploring. Another recent partnership with new Lehigh associate professor Jonathan Wierer is yielding insight into improving the efficiency of solid-state lighting by using nanostructure lasers.

"Lehigh's research environment is purpose-built to foster interdisciplinary team science," comments Tansu. "Innovation is often found where disciplines intersect—as are the really fascinating research problems… We build integrated teams that explore larger, more complex problems in a manner that allows us to develop more impactful solutions," he adds.

PhDs minted in Tansu's lab have gone on to technical leadership roles in industry at places like Philips, Apple, Intel, Cree and Veeco, while other graduates have found faculty roles at schools such as Case Western Reserve University, University of Tulsa, Rochester Institute of Technology, Clarkson University, and KAUST (Saudi Arabia).

**The Boy Who Loved to Read**

In Summer 2015, Tansu shared his life story on Kick Andy, the top-rated TV talk show in his native Indonesia. Later that year, that story became an inspirational children's book via 'Nelson: The Boy Who Loved to Read' by author Adela Gozali Yose.

The book details Nelson's early life. At the age of 17 he travelled to the USA to attend The University of Wisconsin at Madison, where he earned undergraduate and doctoral degrees in applied physics and engineering.

Tansu joined the faculty of Lehigh University's Department of Electrical and Computer Engineering at 25. Eleven years later, in 2014 he was named as Lehigh's Daniel E. '39 and Patricia M. Smith Endowed Chair Professor and director of the Center for Photonics and Nanoelectronics.

In late 2015, Indonesia's largest book publisher and distributor Gramedia released an English version of the book. The Indonesian version ranked as one of the bestsellers in the 'children's educational' category.

The book was selected as the highlighted children's book at this year's Indonesian International Book Fair, and as one of the books representing Indonesia in the 2015 Frankfurt Book Fair.

**www.ece.lehigh.edu/~tansu**
**www.academyofinventors.org**

# POET grows revenue in Q3, but operational challenges at DenseLight acquisition in Singapore delay production

POET Technologies Inc of San Jose, CA, USA — which has developed the proprietary planar optoelectronic technology (POET) platform for monolithic fabrication of integrated III-V-based electronic and optical devices on a single semiconductor wafer — has reported revenue of $861,545 for third-quarter 2016 (the first full quarter of revenue from its acquisition of Singapore-based DenseLight Semiconductor Pte Ltd), up on $576,741 last quarter.

Gross margin rose from 28.9% to 47.3%. Net loss has been cut from $3.4m to $2.8m. Cash and cash equivalents were $9,699,899. After quarter-end, POET completed a public offering that generated gross proceeds of $9,349,254.

During the quarter, the firm completed internal qualification and began early production of DenseLight 2.5G DFB (distributed feedback) lasers, winning an initial customer order in China for applications in the passive optical network (PON) broadband access network architecture, which is the dominant Fiber-to-the-X (FTTx) network architecture currently in use. Also, the firm's sensor product roadmap for 2017 includes additional new product introductions for LIDAR (laser imaging, detection & ranging).

Revenue reflects "expanded sales of DenseLight photonic sensors, primarily to existing customers for test & measurement applications," notes CEO Suresh Venkatesan.

"Although we are making solid progress on revenue and product expansion within our DenseLight subsidiary, our integration activities intended to establish a commercial foundation for the consolidated company are not without challenges," Venkatesan comments. "We have uncovered certain deficiencies in the organizational, functional and operational structure of the fab. Importantly, we have already begun to address and remedy these vulnerabilities in order to realize the full value of this business and its related infrastructure. Despite these short-term challenges, we remain highly confident in the potential and unique value proposition that DenseLight represents for its customers and the company alike," he adds.

"In terms of progress on the POET technology, we continue to maintain a strong focus on the development and refinement of the integrated opto-electronics engine, which includes the integrated detector," Venkatesan continues. As a direct result of POET's capital raise, it is now able to pursue parallel development paths for its vertical-cavity surface-emitting laser (VCSEL) design and validation and has taken steps to accelerate its cycles of learning. "Furthermore, we are making selective investments in capital equipment as well as other key capabilities to give us greater control over some of the most time-sensitive aspects of the technology development process," he adds. "The previous delays we encountered — largely related to epitaxial wafer supply and more recently export license controls — were both resolved subsequent to quarter-end, which has enabled us to resume progress toward the production of integrated device prototypes." Specifically, POET has engaged with multiple third-party sources for critical epitaxial wafers, and resumed the development cycles at its 6-inch Taiwan foundry partner Wavetek. "Although this pre-prototype stage of product development has taken longer than we originally anticipated due to various constraints, we believe we are on the right path to achieve commercialization in 2018," Venkatesan says.

POET is currently focused on evaluating multiple paths to improving VCSEL functionality and optimizing the transistor. Ultimately, realizing the commercial potential of the POET technology will require the firm to complete the development of integrated device prototypes, begin product development of integrated single-chip monolithic transceivers for active optical cables (AOCs), demonstrate alpha prototypes, engage potential customers with beta prototypes, demonstrate manufacturability and scalability, and complete qualification of these integrated devices in end-user applications.

During the quarter, POET announced an agreement with Singapore Economic Development Board (EDB) to expand R&D operations in Singapore.

The firm also continues to work on multiple sources of additional NRE (non-recurring engineering) revenue, $154,000 of which was included in sales in third-quarter 2016.

On 8 November, POET was awarded two US patents (#9,490,336 for a fabrication methodology for opto-electronic circuits and #9,490,321 for the design of an integrated optoelectronic circuit). Each represents a significant barrier to entry for potential competitors, the firm reckons. In addition, the '321 patent is fundamental to protecting the firm's design of integrated optical transmitters and detectors using both thyristor and bipolar circuits.

POET says that, due mainly to the unexpected production delays at its Singapore fab, it has lowered its second-half 2016 revenue guidance from $2m to $1.6–1.8m, depending on closing and shipping multiple orders for sensor products, 2.5G DFB lasers and the timely completion of NRE for key clients. However, even considering the reduced revenue guidance, POET says that it has achieved significant quarter-on-quarter revenue increases and expects that the DenseLight business unit will develop into a robust platform for the commercialization of POET technology. The firm anticipates continued revenue growth at DenseLight and targets positive operating cash flow by first-half 2017.

**www.denselight.com**
**www.poet-technologies.com**

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# Finisar's quarterly revenue grows 8.4% to record $370m

## Capacity expansions to include third building in Wuxi

For its second quarter of fiscal 2017 (ended 30 October 2016), fiber-optic communications component and subsystem maker Finisar Corp of Sunnyvale, CA, USA has reported record revenue of $369.9m, up 8.4% on $341.3m last quarter and 15% on $321.1m a year ago.

There were again two 10%-or-greater customers. The top 10 customers comprised 57.9% of revenue (down from 60.2% last quarter).

Telecom product sales were $107.6m, up 9.9% on $97.9m last quarter and up 23% on $87.4m a year ago, due mainly to strong demand for 100G transceivers as well as wavelength-selective switch (WSS) and reconfigurable optical add-drop multiplexer (ROADM) line-card products.

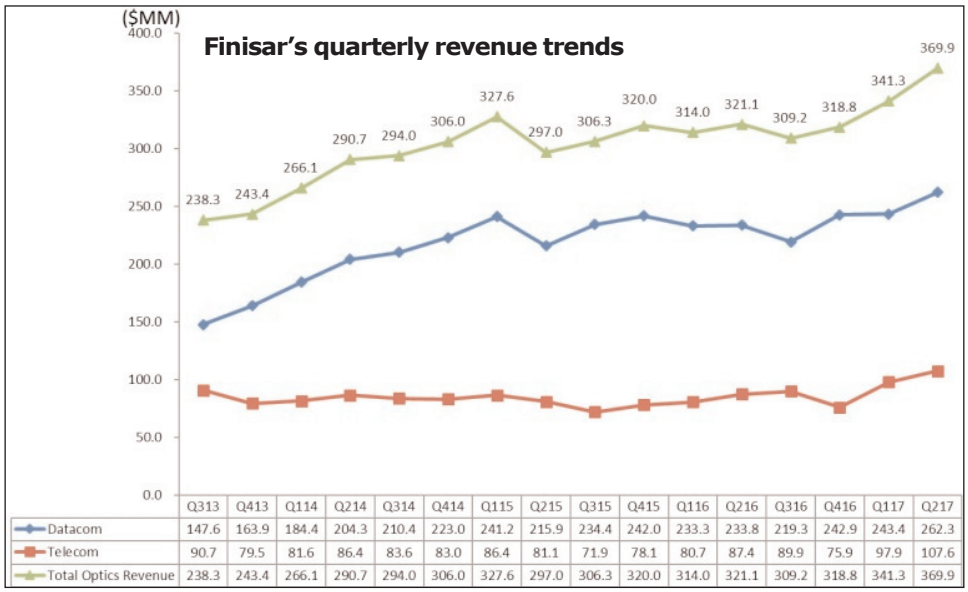
Datacom product sales were $262.3m, up 7.7% on $243.4m last quarter and up 12.2% on $233.8m a year ago, due to growth in demand for 100G transceivers, rising by about 30% on last quarter and over 80% on a year ago to 30–35% of datacom revenue. Sales of 40G datacom transceivers were roughly flat on last quarter.

On a non-GAAP basis, gross margin has risen further, from 30% a year ago and 33.1% last quarter to 37.2% (well above the expected 34%). This is due to a favorable product mix as well as operational leverage achieved through vertical integration with larger production volumes.

Operating expenses were $69.4m, roughly level with $69.3m last quarter but below the expected $71m, and cut from 20.3% of revenue to 18.8% of revenue.

Operating income has risen further, from $28.3m (8.8% of revenue) a year ago and $43.5m (12.8% of revenue) last quarter to $68.3m (18.5% of revenue, well above the guidance range of 14.3–15.3%).

Net income has risen further, from $26.9m ($0.25 per diluted share) and $41.8m ($0.38 per diluted share) last quarter to $65.2m ($0.58 per diluted share, well above the $0.44–0.50 guidance).




| | Q313 | Q413 | Q114 | Q214 | Q314 | Q414 | Q115 | Q215 | Q315 | Q415 | Q116 | Q216 | Q316 | Q416 | Q117 | Q217 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Datacom | 147.6 | 163.9 | 184.4 | 204.3 | 210.4 | 223.0 | 241.2 | 215.9 | 234.4 | 242.0 | 233.3 | 233.8 | 219.3 | 242.9 | 243.4 | 262.3 |
| Telecom | 90.7 | 79.5 | 81.6 | 86.4 | 83.6 | 83.0 | 86.4 | 81.1 | 71.9 | 78.1 | 80.7 | 87.4 | 89.9 | 75.9 | 97.9 | 107.6 |
| Total Optics Revenue | 238.3 | 243.4 | 266.1 | 290.7 | 294.0 | 306.0 | 327.6 | 297.0 | 306.3 | 320.0 | 314.0 | 321.1 | 309.2 | 318.8 | 341.3 | 369.9 |

Capital expenditure (CapEx) was about $30m. During the quarter, cash, cash equivalents and short-term investments hence rose by $32.5m, from $593.8m to $626.3m.

**We are adding capacity over the next couple of quarters in our VCSEL fab in Allen, Texas. This will enable us to pursue several new consumer applications for 3D sensing**

For fiscal third-quarter 2017, Finisar expects 5% revenue growth to a further record of $378–398m, boosted by increased sales of 400G transceivers. Gross margin should rise to 37–38%, due mainly to a favorable product mix plus the operating leverage from vertical integration, despite being offset partially by the impact of one month of annual telecom price reductions that are typically effective from 1 January. Operating expenses are expected to be $72m (down slightly to 18.6% of revenue). Operating margin should improve further to 18.5–19.5%. Driven by the growing revenue and improving margins, earnings per fully diluted share are expected to grow to $0.58–0.64 (another quarterly record). Capital expenditure will rise to about $40m. This elevated level of CapEx should continue in fiscal Q4.

"We continue to add capacity for a number of products," says chairman & CEO Jerry Rawls. "For QSFP28 in particular, we plan to increase capacity significantly in the third quarter and have plans to continue to increase the capacity in the subsequent quarters," he adds. "We are also adding capacity for the 100G and 200G coherent CFP2 ACO transceivers and the ROADM line cards for telecom and long haul and metro. We expect the qualification of these products by key customers in the next few months."

"In addition, we are also adding capacity for our wavelength-selective switches. We believe that China will begin significant domestic deployments of ROADMs in calendar 2017," continues Rawls. "We are still adding a lot of equipment and people in the Wuxi [China] facility… We are going to add a third building, which will increase our capacity there by 50%."

"Finally, we are adding capacity over the next couple of quarters in our VCSEL [vertical-cavity surface-emitting laser] fab in Allen, Texas. This will enable us to pursue several new consumer applications for 3D sensing," concludes Rawls.

**www.finisar.com**

## Finisar raises $575m in private placement of convertible senior notes

On 15 December, fiber-optic communications component and subsystem maker Finisar Corp of Sunnyvale, CA, USA announced an offering of convertible senior notes due 2036 in a private placement, initially amounting to $450m before being upsized to $500m.

Finisar granted the initial purchasers a 30-day option to purchase up to $75m extra notes (upsized from the initial $67.5m) to cover over-allotments.

This led to the issue on 21 December of $575m of notes to initial purchasers Merrill Lynch, Pierce, Fenner & Smith Inc and Goldman, Sachs & Co, for resale to qualified institutional buyers. The notes were issued pursuant to an indenture between Finisar and Wells Fargo Bank, National Association, as trustee.

Interest is payable semi-annually in arrears on 15 June and 15 December commencing 15 June 2017, at 0.5% per annum. Notes will mature on 15 December 2036, unless earlier converted, repurchased or redeemed.

Holders may require Finisar to repurchase the notes for cash on 15 December of 2021, 2026 and 2031 at a repurchase price equal to the principal amount, plus accrued and unpaid interest up to, but excluding, the repurchase date. In addition, holders may require Finisar to repurchase the notes for cash upon the occurrence of a fundamental change.

Finisar may not redeem the notes prior to 22 December 2021, after which it may redeem for cash all or part of the notes at a redemption price equal to the principal amount to be redeemed, plus accrued and unpaid interest up to, but excluding, the redemption date.

Prior to 15 June 2036, the notes will be convertible at the option of the holders only upon the occurrence of specified events. Thereafter until the close of business on the second scheduled trading day immediately preceding the maturity date, the notes will be convertible at any time. Upon conversion, the notes will be settled in cash, shares of Finisar's common stock or any combination (at Finisar's option). The initial conversion rate is 22.6388 shares of common stock per $1000 of notes (equivalent to an initial conversion price of about $44.17 per share), subject to adjustment in certain circumstances. This represents a premium of about 35% relative to Finisar's stock price on 15 December.

Finisar expects to use the net proceeds from the offering for general corporate purposes (including working capital) and perhaps to acquire complementary businesses, products or technologies (although Finisar has no present commitments for acquisitions). Pending such uses, Finisar may invest the net proceeds in highly liquid cash equivalents or US government securities.

## II-VI Suwtech launches GaAs pump laser modules with 20W wavelength-stabilized output for ultrafast fiber lasers

The II-VI Suwtech Division of engineered materials and optoelectronic component maker II-VI Inc of Saxonburg, PA, USA (which provides high-power laser modules) has launched 976nm wavelength-stabilized multimode pump laser modules with output of up to 20W.

Medical, industrial and semiconductor manufacturing applications increasingly employ ultrafast pulsed lasers for precision drilling and marking on a microscopic scale, notes II-VI Suwtech. The new pump lasers feature a wavelength-stabilized optical design that significantly extends their output power stability performance over operating temperature and output power dynamic ranges, says the firm. The pump lasers enable ultrafast fiber lasers to operate with shorter pulses and achieve higher precision drilling and marking, it is claimed. The new wavelength-stabilized optical system also minimizes warm-up time, improving productivity of the fiber lasers.

"This new laser module builds on the proven reliability of II-VI's gallium arsenide (GaAs) technology platform," says II-VI Suwtech's general manager Di Yang. "Beyond ultrafast fiber lasers for precision drilling and marking, our product portfolio will expand to advance pulsed lasers for other applications, including super-continuum lasers for life sciences."

The high output power of the new pump laser is achieved by combining multiple GaAs laser chips into one module. The combined output is coupled to an industry-standard 105µm multimode fiber. The operating wavelength can be adjusted to meet specific customer applications.

II-VI Inc's capabilities are being showcased in booth #1833 (South Hall) at SPIE Photonics West 2017 in San Francisco (31 January – 2 February), highlight the advances that its material science and technology platforms have made possible for users in materials processing, industrial machine tools, biomedical instrumentation and military applications. II-VI is launching several new high-power semiconductor laser chips, modules and bars as well as high-power laser optics for next-generation $CO_2$, fiber and direct-diode lasers.

**http://spie.org/photonics-west.xml**
**www.ii-vi-suwtech.com**

# NeoPhotonics sells low-speed transceiver business to China's APAT for $26.4m

## NeoPhotonics focusing on photonic integration for high-speed 100G-and-beyond networks

NeoPhotonics Corp of San Jose, CA, USA (a vertically integrated designer and manufacturer of hybrid photonic integrated opto-electronic modules and subsystems for high-speed communications networks) has sold its Access and Low Speed transceiver product lines to APAT Optoelectronics Components Co Ltd (APAT OE) of Shenzhen, China, a designer and manufacturer of optical sub-assemblies for telecom and datacom markets, primarily fiber-to-the-home (FTTH) used in telecom client, access and enterprise network applications.

In 2015, and for the first nine months of 2016, the Low Speed Business generated $92.8m and $50.7m in revenue, respectively, and gross profit of $17.1m and $9.7m, respectively. Net assets for the business were about $17m as of end-September 2016.

Assets that have been sold include the intellectual property, inventory and fixed assets for NeoPhotonics' passive optical network (PON) products including GPON and GEPON transceiver products at up to 10G data rates, plus 10G-and-below telecom, bi-directional and specialty transceiver products.

When announced in December, the transaction was valued at about $26.4m (inclusive of post-closing payments under a transition services agreement). This consists of an equivalent of $25m purchase price plus an additional $1.4m to be paid as certain transition services are delivered (not less than the equivalent of $23m to be paid in cash in China Renminbi at close and not more than $2m in a US dollar denominated promissory note).

The secured promissory note is for an initial term of six months with an initial interest rate of 6% per annum. It is renewable at six month intervals with an increase in the interest rate by an additional 4% per annum. The note will be secured by inventory and certain fixed assets being purchased in the transaction.

**This transaction underscores our objective to focus our efforts on growing high-speed optical networking products and solutions based on our advanced hybrid photonic integration technology platform**

In addition, APAT OE will assume outstanding supply chain purchase commitments and will be responsible for the payment of value-added tax obligations.

"This transaction underscores our objective to focus our efforts on growing high-speed optical networking products and solutions based on our advanced hybrid photonic integration technology platform." says NeoPhotonics' CEO Tim Jenks. "This transaction further solidifies our focus on serving the highest-speed, highest-performance and highest-growth segments in the optical communications market, where we believe our vertically integrated advanced hybrid photonic integration technology will have the greatest impact," he ads. "The Low Speed Business will benefit from APAT OE's expertise in Access and PON products while continuing to provide quality products, support and services to customers," Jenks believes.

"We look forward to having more products to sell to our largest customers as well as the opportunity this transaction creates for us to gain many new customers," comments APAT OE's founder & CEO Rex Gu.

**www.apatoe.com**
**www.neophotonics.com**

## NeoPhotonics updates outlook for fourth-quarter 2016

Given recent developments, NeoPhotonics has also announced an updated outlook for fourth-quarter 2016. Demand continues to exceed the firm' capacity to supply high-speed products while production capacities continue to increase. As new capacity has been brought on line, production yields at one fabrication plant have been lower than expected, resulting in delayed shipments and higher-than-expected manufacturing costs during the quarter.

For Q4/2016, NeoPhotonics hence now expects revenue of $105–109m (still up on Q3's $103.3m to a new record). On a non-GAAP basis, gross margin should be 28-31% (up from Q3's 27.6%), operating expenses $27–29m (up from $24.7m) and earnings per share ($0.03–0.11).

The firm's previously outlook anticipated that the Low Speed Business would generate revenue of about $10m in Q4/2016 and $40–45m in 2017. The comparable annual revenue for the Low Speed Business in 2016 is expected to be about $61m. Upon divesting the business, NeoPhotonics' revenue growth rate for continuing business is hence expected to increase.

**www.neophotonics.com**

# NeoPhotonics launches coherent transceiver module platform for single-wavelength 100 and 200Gb/s

NeoPhotonics Corp of San Jose, CA, USA (a vertically integrated designer and manufacturer of hybrid photonic integrated opto-electronic modules and subsystems for high-speed communications networks) has started sampling its coherent CFP-DCO module as part of its ClearLight Coherent Module platform introduction. The ClearLight DCO platform uses the latest advances in 16nm digital signal processors (DSPs) and is capable of achieving single-wavelength 100 and 200Gb/s transmission over data-center interconnect (DCI) through long-haul transmission distances.

The ClearLight CFP-DCO platform is based on optical components with performance capabilities that have already been proven in high-volume production. These include a high-power tunable laser with what is claimed to be the narrowest linewidth and the lowest power consumption in the industry, a low-insertion-loss modulator capable of higher-order modulation, a high-responsivity receiver and a low-power-consumption DSP. These features enable the ClearLight CFP-DCO to deliver performance both high optical performance and low electrical power consumption, says NeoPhotonics, which adds that the 100G CFP-DCO provides a significantly higher transmitter optical signal-to-noise ratio (OSNR) by eliminating a booster erbium-doped fiber amplifier (EDFA) to achieve the necessary output optical power level. This high-transmitter OSNR can enable longer transmission distances and colorless, directionless, contentionless (CDC) reconfigurable optical add/drop multiplexer (ROADM) operation.

The first-release 100Gbps version uses a standard 100GE or OTU-4 interface that can plug directly into existing 100G CFP client-side slots to extend the range and capacity for metro and DCI applications. The module incorporates standard hard-decision staircase forward error correction (FEC) for interoperability, as well 16-QAM (quadrature amplitude modulation) as proprietary soft-decision FEC for high-performance applications. A 200Gbps version is based on the same platform and utilizes the same high-volume, proven coherent optical components.

"Our new ClearLight CFP-DCO 100G pluggable coherent transponder represents a powerful new platform product for NeoPhotonics," says chairman & CEO Tim Jenks. "This exciting new product is made possible by our Advanced Hybrid Photonic Integration technology, coupled with the latest advances in 16nm Coherent DSPs, and provides our customers with a flexible, high-performance pluggable coherent module for their high-speed networks."

**www.neophotonics.com**

## Excellent Core Partner Awards from both FiberHome and Huawei

NeoPhotonics has received the Excellent Core Partner Award for 2016 from telecom network provider FiberHome Telecommunications Technologies.

The award is the highest honor given to a supplier by FiberHome, and was presented at a ceremony at FiberHome's headquarters in the 'Optics Valley' in Wuhan, China. NeoPhotonics was honored for the second consecutive year for its contributions as a supplier of innovative optical technology and products for high-speed communications networks.

"We have served FiberHome with high-speed products for several years, and we have expanded our technology, quality and manufacturing capabilities to support FiberHome's rapid growth during this period," says NeoPhotonics' chairman & CEO Tim Jenks.

FiberHome Telecommunications Technologies is part of the FiberHome Technologies Group, a product manufacturer and solution provider in information technology and telecoms, with annual revenue of about $5bn. As the major high-tech enterprise directly affiliated to the state-owned Assets Supervision and Administration Commission of the State Council, FiberHome Technologies is the core enterprise located in Wuhan Optics Valley of China.

NeoPhotonics has also received, for the sixth consecutive year, the Excellent Core Partner Award for 2016 from telecom network provider Huawei Technologies. At an awards ceremony at Huawei's corporate headquarters in Shenzhen, China, NeoPhotonics was honored for its contributions as a supplier of innovative optical technology and products for high-speed communications networks.

The award is given to companies that consistently deliver innovative technology with the highest performance and quality to meet Huawei's specialized requirements. NeoPhotonics has been recognized annually as a Huawei Excellent Core Partner since 2011.

"We have worked closely with Huawei on their latest-generation 100G-and-beyond products and we strive through continuous improvement to provide both the highest performance and the highest quality in our products, and to leverage our manufacturing and supply chain capabilities to keep pace with Huawei's rapid growth," said Jenks at the awards ceremony.

**www.fiberhomegroup.com**
**www.huawei.com**
**www.neophotonics.com**

# Emcore's quarterly revenue grows 14% to $25.6m, driven by cable TV

## December-quarter revenue to rise to $28–30m

For fiscal fourth-quarter 2016 (ended 30 September), Emcore Corp of Alhambra, CA, USA — which provides indium phosphide (InP)-based optical chips, components, subsystems and systems for the broadband and specialty fiber-optics markets — has reported revenue of $25.6m (above the $23–25m guidance), up 14.4% on $22.4m last quarter and 11.3% on $23m a year ago. Revenue for full-year fiscal 2016 was $92m, up 12.6% on fiscal 2015's $81.7m, driven by continued strength in the cable TV (CATV) product line — which includes RF-over-glass (RFoG) products — offset by a decline in 2.5G GPON (Gigabit passive optical network)-related chip revenue.

Of fiscal Q4 revenue, cable TV comprised 80-85% (up from 75–80% last quarter), chip-level products 5–10%, SatCom and video 5–10%, and fiber-optic gyro 2.5–5%.

SatCom and Fiber Optic Gyro product lines delivered on plan, with flat to slight declines in revenue quarter-on-quarter.

Following the strong growth that began in fiscal Q3, cable TV revenue rose a further 23% quarter-to-quarter (up 49% year-on-year). "The continued strength in this market not only demonstrates the MSOs [multi-service operators] commitment to deploying DOCSIS 3.1 fiber deep networks, but also highlights Emcore's leadership position within the space," says president & CEO Jeff Rittichier. "Demand for our products based on LEML [linear externally modulated laser] technology continues to increase both for DOCSIS 3.1 and several new products that will be announced in the coming months."

Chip revenue remains relatively flat (on about $2.2m last quarter) as Emcore continues to de-emphasize its presence in the 2.5G GPON space. "We see continued weakness in the 2.5G market and intend to only supply our multi-generational customers with 2.5G GPON products as they begin to transition to 10G," says Rittichier. "Our other products have continued to grow pretty much in line with expectation. We have begun to make production shipments of 10G parts, albeit at low volumes," he adds. "We have a lot of development work going on in the fab this year and expect to fill devices in the wireless and data-center markets toward the end of 2017."

On a non-GAAP basis, full-year gross margin has fallen from 35.1% for 2015 to 33.6% for 2016. However, although still down on 41.1% a year ago, quarterly gross margin has rebounded further, from 33.1% last quarter to 35.6%, driven by improved operating efficiencies (following the lower 2.5G GPON chip pricing and lower material overhead absorption of fiscal Q3).

"Emcore is working to become a broad supplier of chip-level products to the entire telecom industry, thereby optimizing our product mix between captive and merchant use, which will drive higher blended margins both for the chip business and for the company overall," says Rittichier.

**A key part of our strategy is to transform fixed expense to variable cost at every opportunity and ultimately reduce our breakeven point. By the end of [fiscal] Q1, we will have outsourced our entire SatCom manufacturing process to the TAA-compliant EMS operation**

Operating expenses were $7.4m, up $1.5m on fiscal Q3's $5.9m (which had been positively impacted by the $2.6m reimbursement of legal expenses related to the arbitration agreement with Sumitomo Electric Industries, offset by higher severance charges) but cut from $8.2m a year ago. Full-year operating expenses have been cut by $5.2m from fiscal 2015's $33.2m to $28m for fiscal 2016, as Emcore continues to streamline operations and remove excess expenses from the business.

"A combination of strength in customer orders and improved manufacturing efficiency drove significant income generation in the fourth quarter and allowed us to finish the year strongly," says Rittichier.

Although still down slightly from $2.7m ($0.10 per diluted share) a year ago, pre-tax income from continuing operations was $2.6m ($0.10 per diluted share), up from $0.6m ($0.02 per diluted share) last quarter. Full year pre-tax income from continuing operations has risen from $4.2m ($0.14 per diluted share) for fiscal 2015 to $5.1m ($0.19 per diluted share) for fiscal 2016.

Capital expenditure (CapEx) was $1.3m in fiscal Q4, making $5.7m for the full year. Depreciation and amortization was about $750,000.

Also, on 29 July Emcore paid a special dividend of $1.50 per share ($39.2m) to shareholders of record as of 18 July.

Cash and cash equivalents have hence fallen further, by $41.1m from $105m a quarter ago to $63.9m.

"We have good visibility into demand at this time and see continued growth in DOCSIS 3.1 product deployments as well as growing momentum with our fiber-optic gyro and inertial measurement unit products," notes Rittichier. ►

Given the continued strength being seen in cable TV business, for fiscal first-quarter 2017 (ending 31 December 2016) Emcore expects revenue to rise to $28–30m, with gross margin of 34–36%.

"Although gross margin seems likely to remain range bound in the mid-30s over the next year, because of the impacts of the product mix, we believe that our continued focus on operational excellence will drive operating margins to roughly 12.5% on a non-GAAP basis in the next year or so and, with the benefit of additional volume, will get closer to 15% by the end of fiscal year 2018," says Rittichier. "This equates to 12.5–15% net operating margin target, nearly double the level achieved in our strong fourth quarter and at the higher end of the range in the broader optical component landscape," he adds.

"We are nearly complete with our 18 months effort to transform our manufacturing operations to hybrid EMS [electronics manufacturing services] model," says Rittichier. "This means the Emcore will only manufacture products which demonstrably add value over competing merchant EMS service," he adds.

"A key part of our strategy is to transform fixed expense to variable cost at every opportunity and ultimately reduce our breakeven point. This strategy has important implications for both our US and Chinese operations," continues Rittichier. "By the end of [fiscal] Q1, we will have outsourced our entire SatCom manufacturing process to the TAA-compliant EMS [electronics manufacturing services] operation. By the end of Q2, we expect to have completely moved out our assembly operations in Langfang, China to Emcore Asia, our new smaller automated facility inside the 5th Ring in Beijing," he adds.

"In China, we will reduce our total headcount by over 60% and our direct headcount by 75% even as manufacturing volumes continue to grow," says Rittichier. When complete this means that our assembly personnel will be 180% more efficient on a COGS per employee basis than we were when I joined in January 2015," he adds. These actions should lower Emcore's breakeven revenue point by $1–1.5m per quarter.

"Emcore is making substantial investments in the manufacturing technology for our Fiber Gyro and Inertial Measurement Unit product lines and will be retrofitting a building in Alhambra to optimize it for the needs of these products," says Rittichier. "The automation technology, which we develop at Emcore Asia located near Central Beijing, is going to be brought back to the US and upgraded to meet the needs of our navigation products. This will allow us to manufacture these militarily sensitive products cost effectively in the USA," he adds. "We will exit the year with navigation products running at 10% of revenue and higher thereafter."

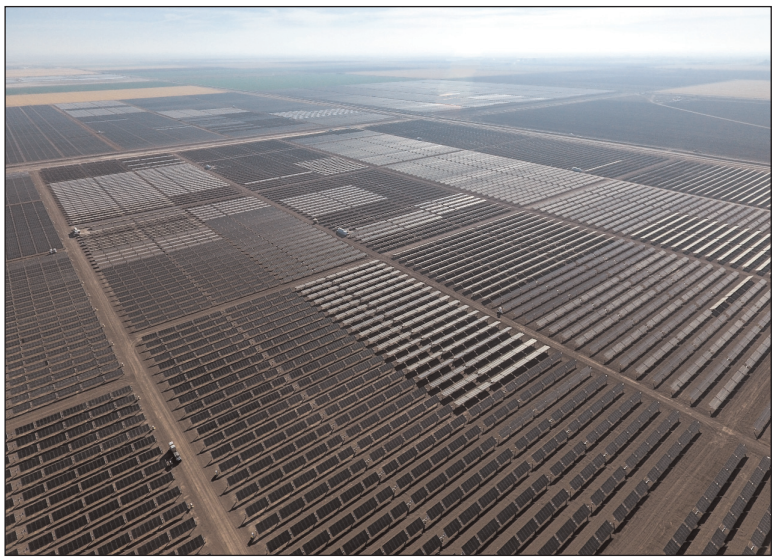
www.emcore.com

# Solar Frontier Americas nears completion of 106MW of utility-scale projects in Southern California

On 12 December, San Jose-based Solar Frontier Americas, the US subsidiary of Tokyo-based Solar Frontier — the largest manufacturer of CIS (copper indium selenium) thin-film photovoltaic (PV) solar modules — held a ribbon cutting event — presented by California State Assembly Member Eduardo Garcia — to celebrate nearing completion of two solar power plants totaling 106MW$_{dc}$ in the Imperial Valley of Southern California. Also in attendance were representatives from the Imperial Irrigation District, Imperial County and local city officials.

The projects Midway I & II are located a few miles northwest of Calipatria in the great Mojave Desert. Blattner Energy (recognized for building some of the largest and most complex energy projects in North America) handled the engineering, procurement and construction (EPC) services for the projects.

Developed and constructed for high performance, both solar plants are installed with NEXTracker single-axis trackers (valued for their ability to increase the system's energy yield) and autonomous row technology that enables easier access for operations and maintenance. The solar plants are constructed with Power Electronics' rugged HEC PLUS, which is reckoned to be one of the most powerful and reliable inverters on the market.



**Solar Frontier Americas' Midway I & II solar plants in the Imperial Valley of Southern California.**

"Solar Frontier Americas Development team encountered several project challenges and — through collaboration with the Imperial Irrigation District, local authorities and land owners — was able to effectively navigate solutions maintaining our high standard of quality and completing the projects on schedule," says Solar Frontier Americas Development's CEO Charles Pimentel.

Solar Frontier Americas are local experts on development in the Southern California region with almost 166MW of solar projects in operation or development. The company has a pipeline of over 400MW currently in various stages of development. The company also partners with small and medium size developers to support the completion of viable solar projects.

www.solar-frontier.com

# Solar Frontier unveils panels for Japanese residential market

Tokyo-based Solar Frontier — the largest manufacturer of CIS (copper indium selenium) thin-film photovoltaic (PV) solar modules — has unveiled SmaCIS, a solar power system specifically designed for homes and positioned as a strategic product to serve a Japanese domestic residential market that is forecast for increased solar power demand. The system combines specially developed and uniquely constructed mounts with CIS thin-film solar panels of a size that easily fits onto the hipped roofing of Japanese homes.

Solar Frontier plans to begin production of the solar panels at its manufacturing plant in Miyazaki from April 2017, with the system to be launched in July.

The smart form factor of the solar panels allows for more modules to be fitted on roofs of complex design, such as on the hipped roofing of Japanese homes; the visual appearance of the system makes it aesthetically compatible with the roofs, and a newly developed method of construction reduces the time needed to put the system together by about 20%, it is reckoned.

Solar Frontier says that, with rising consumer interest in energy self-sufficiency and the net zero energy houses (ZEH) standardization policy adopted and promoted by Japan's government for 2020, the domestic market for residential solar energy systems is expected to see robust demand moving forward.

Solar Frontier says that its CIS thin-film solar panels are found used in projects by housing companies, including industry giants, nationwide. Identifying a vital target in Japan's residential market, including already-constructed homes, Solar Frontier has now made the decision to launch a new product that maintains the size of its predecessors while improving on power output.

# Prairie Gold completes 1MW solar installation in Puerto Rico using Stion's frameless solar modules

Electricity can be costly and unreliable in the Caribbean, where resources for energy are limited. In Puerto Rico 80% of the island's electricity is generated by burning oil. The sun is prolific in the Caribbean, which receives more sunlight than the CA desert, and that is why businesses including Puerto Rican mining company Ecologica Carmelo are turning to solar.

Prairie Gold Inc, which partners with early-stage developers, engineering, procurement & construction (EPC) firms and equipment manufacturers to build, operate and own distributed-scale solar (from 250kW to 10MW), has completed installation of its first solar project on the island, a 1MW project for the mining company, which was completed in October.

The 1MW project consists of 6908 Stion 145W frameless CIGS (copper indium gallium selenium) solar modules (STL-145) made by Stion Corp of San Jose, CA, USA, installed on a ground mount. The project is expected to generate 1738MW-hr per year (6% more than a similarly sized traditional crystalline silicon array, it is reckoned). Stion's modules are certified for installation in the Commonwealth of Puerto Rico, with the CEC Puerto Rico Certification, and they also maintain the Salt Mist — Severity 6 IEC certification. Stion says that its modules were selected for their increased energy generation, and for their proven performance and durability in marine environments.

The project was constructed for Ecologica Carmelo, which mines sand and aggregates. The mining facility will save about $300,000 per year in energy costs. Moreover, with Puerto Rico experiencing an island-wide blackout in September that lasted nearly three days, solar can provide a more dependable source of energy for industrial and commercial companies in Puerto Rico.

The Georgia-based company Allied Energy Services (which provides energy consulting, electrical contracting and solar services throughout North America) developed the project and then sold it to Prairie Gold. The owners are now awaiting commissioning of the system. "With the warm climate in the Caribbean and Stion's industry-leading temperature coefficient, Prairie Gold, which owns the system, will realize a much better return on investment (ROI) than they would have with crystalline modules," the firm reckons.

**www.stion.com**
**www.prairiegoldsolar.com**

# Solar Frontier's CIS solar systems installed at Delta Electronics in Thailand

Tokyo-based Solar Frontier K.K., the world's largest provider of CIS (copper indium selenium) solar energy solutions, and power supply and electronic component producer Delta Electronics (Thailand) PCL have announced the completion of four projects totaling 510kWp at the Delta Electronics factory site in the Bangpoo Industrial Estate near Bangkok. The projects were constructed by Thai solar power engineering, procurement & construction (EPC) specialist Energy Pro Corporation Ltd from July to the beginning of October.

Solar Frontier's CIS (copper indium selenium) thin-film solar panels have been installed on rooftops and carparks of two Delta factories. The four projects are expected to provide about 793MWh annually, and all power generation will be for self-consumption by Delta Electronics. The transformerless Delta grid photovoltaic (PV) inverters installed are the PRI M50A and RPI-M20A series of products. Delta's designs have incorporated features to ensure optimum cost and space savings in addition to ease of installation and internationally certified safety standards. The entire solar power solution is linked with Delta's in-house developed software, which allows monitoring and controlling of the power consumption.

"Delta Electronics is planning to get the LEED (Leadership in Energy and Environmental Design) Certificate for all our factories in Thailand, and as Solar Frontier's premium CIS solar panels are able to achieve excellent power output under strong sunlight and even during the rainy season, it makes them a reliable solution all-year round," comments Hsieh Shen-yen, president of Delta Electronics (Thailand) PCL. "We have been providing inverters for Solar Frontier in Japan since 2015, and we are confident that the success of the four projects will further develop our business partnership with Solar Frontier in Thailand," he adds.

"Thailand aims to increase its installed solar power capacity to 6GW by 2036, and has great potential for solar power," notes Solar Frontier's executive officer Yuichi Kuroda. "Solar Frontier's CIS solar panels generate more electricity (kilowatt-hours per kilowatt-peak) compared to crystalline silicon modules in real-world environments, and the panels' high shadow tolerance means that they are efficient even during Bangkok's 6-month rainy season," he adds.

**www.solar-frontier.com**

# UNSW achieves record efficiency for perovskite cells

## 12.1% for 16cm² cell, over 10 times bigger than existing record cell

At the Asia-Pacific Solar Research Conference at the Australian National University, Canberra (29 November – 1 December), Anita Ho-Baillie, a senior research fellow at the Australian Centre for Advanced Photovoltaics (ACAP), announced that her team at the University of New South Wales (UNSW) has achieved the record efficiency with the largest perovskite solar cells to date.

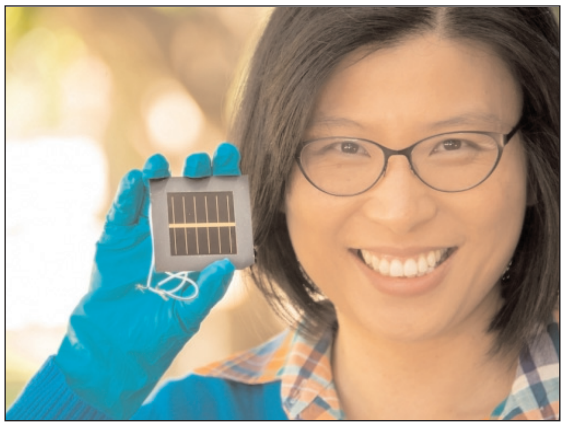
The 12.1% efficiency was for a 16cm$^2$ perovskite solar cell, the largest single perovskite photovoltaic cell certified with the highest energy conversion efficiency, and was independently confirmed by the international testing centre Newport Corp in Bozeman, Montana. The new cell is at least 10 times bigger than the existing certified record-efficiency perovskite solar cells, it is reckoned.

Ho-Baillie's team has also achieved 18% efficiency on a 1.2cm$^2$ single perovskite cell, and 11.5% for a 16cm$^2$ four-cell perovskite mini-module, both independently certified by Newport.

"This is a very hot area of research, with many teams competing to advance photovoltaic design," says Ho-Baillie. "Perovskites came out of nowhere in 2009, with an efficiency rating of 3.8%, and have since grown in leaps and bounds," she adds. "These results place UNSW among the best groups in the world producing high-performance perovskite solar cells. And I think we can get to 24% within a year or so."

Perovskite is a structured compound, where a hybrid organic–inorganic lead or tin halide-based material acts as the light-harvesting active layer. They represent the fastest-advancing solar technology to date, and are attractive because the compound is cheap to produce and simple to manufacture, and can even be sprayed onto surfaces.

"The versatility of solution deposition of perovskite makes it possible to spray-coat, print or paint on solar cells," notes Ho-Baillie. "The diversity of chemical compositions also allows cells to be transparent, or made of different colours. Imagine being able to cover every surface of buildings, devices and cars with solar cells."



**Dr Anita Ho-Baillie with perovskite cell.**

Most of the world's commercial solar cells are made from refined, highly purified silicon crystal and, like the most efficient commercial silicon cells (PERC cells, invented at UNSW), they need to be baked above 800ºC in multiple high-temperature nature steps. Perovskites, on the other hand, are made at low temperatures and are 200 times thinner than silicon cells.

But although perovskites hold much promise for cost-effective solar energy, they are currently prone to fluctuating temperatures and moisture, making them last only a few months without protection. Along with every other team in the world, Ho-Baillie's is trying to extend the durability. Due to what engineers learned from more than 40 years of work with layered silicon, they are confident that they can extend this.

Nevertheless, there are many existing applications where even disposable low-cost, high-efficiency solar cells could be attractive, such as use in disaster response, device charging and lighting in electricity-poor regions of the world. Perovskite solar cells also have the highest power-to-weight ratio among viable photovoltaic technologies, it is reckoned.

"We will capitalize on the advantages of perovskites and continue to tackle issues important for commercialization, like scaling to larger areas and improving cell durability," says Ho-Baillie's mentor, ACAP director Martin Green. The project's goal is to increase perovskite solar cell efficiency to 26%.

The research is part of a collaboration backed by $3.6m in funding through the Australian Renewable Energy Agency's (ARENA) 'solar excellence' initiative. ARENA's CEO Ivor Frischknecht says that the achievement demonstrated the importance of supporting early-stage renewable energy technologies: "In the future, this world-leading R&D could deliver efficiency wins for households and businesses through rooftop solar as well as for big solar projects like those being advanced through ARENA's investment in large-scale solar."

Ho-Baillie, who obtained her PhD at UNSW in 2004, is a former chief engineer for Solar Sailor, an Australian company that integrates solar cells into purpose-designed commercial marine ferries which currently ply waterways in Sydney, Shanghai and Hong Kong.

ACAP is a national research collaboration based at UNSW, whose partners are the University of Queensland, Monash University, the Australian National University, the University of Melbourne and the CSIRO Manufacturing Flagship. The collaboration is funded by an annual grant from ARENA, and partners include Arizona State University, Suntech Power and Trina Solar.

**www.apvi.org.au/solar-research-conference**
**www.arena.gov.au**
**www.acap.net.au**
**www.pv.unsw.edu.au**

# Oxford PV gains £8.1m funding and three strategic investors

## Second close of Series C round adds to £8.7m first close

UK-based Oxford Photovoltaics Ltd (which was founded in 2010 by professor Henry Snaith as a spin-off from the University of Oxford) has announced a further equity investment of £8.1m, adding to the £8.7m first-close investment announced on 18 October.

The bulk of this investment has come from three new large strategic investors: Statoil ASA, Legal & General Capital, and a technology-focused, innovative family fund investor.

On 10 November, Oxford PV announced the acquisition of a pilot line site in Germany (formerly operated by Bosch Solar CISTech GmbH) and on 1 December it announced a joint development agreement with a major solar panel manufacturer to scale its technology towards commercialization. The latest funding should help to accelerate these development activities as well as support the next-generation product research in the UK.

"The company has made tremendous progress over the last year, and this has been recognized by being able to attract investors of such high calibre and scale," says CEO Frank Averdung. "Together we will bring our perovskite technology to market as quickly as possible. In conjunction with our industry joint development partner, our perovskite technology now has a clear path and timetable to commercialization and the formidable support of global market leaders to enable that to happen," he adds.

"We are fully engaged with the global transition to a low-carbon energy system and we want to partner with the leading brain-power-backed British enterprises that will deliver the transformative change needed to provide reliable, low-cost clean energy on a global scale," comments John Bromley, head of clean energy strategy, Legal & General Capital. "We have taken the time to get to know Oxford PV, and are impressed by the technology, the scientists and engineers, and an experienced, disciplined management team," he adds.

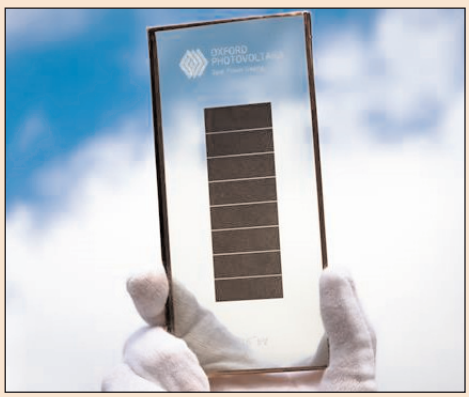
"Statoil has been an innovator in the energy sector for many decades, from deep sea oil recovery to offshore wind project development," says Gareth Burns, managing director of Statoil Energy Ventures (which was established as part of Statoil's new business area New Energy Solutions, and aims to invest up to $200m over a period of 4-7 years). "Statoil is supplementing its oil and gas portfolio with profitable renewable energy and, in addition to our significant portfolio within offshore wind, we are exploring opportunities within new growth areas, such as solar," he adds. "The investment in Oxford PV is our first investment within solar technology, and we see it as a great opportunity to be part of a technology development that has the potential to impact the next generation of solar cells."

# Oxford PV signs JDA with solar cell and module manufacturing industrial partner

## JDA to focus on commercialization, scaling up silicon/perovskite tandem PV technology, and developing manufacturing processes

UK-based Oxford Photovoltaics Ltd (which was founded in 2010 by professor Henry Snaith as a spin-off from the University of Oxford) has announced a joint development agreement (JDA) with a global manufacturer of solar cells and modules.

The two firms will work together to further develop Oxford PV's perovskite-based solar technology, taking it from lab scale to manufacturing-ready status. Oxford PV claims that it holds the world's largest patent portfolio for the use of perovskite material in photovoltaic (PV) applications, and that its technology already demonstrates the efficiency and long-term stability needed to move towards commercialization.



The JDA will focus on that path to commercialization, scaling up the silicon/perovskite tandem PV technology, and developing the necessary processes for manufacturing.

On 10 November Oxford PV announced the acquisition of a pilot line site in Brandenburg an der Havel, Germany. The bulk of the JDA-related development work will be conducted at that site.

"We have made tremendous progress over the last year and this JDA provides independent ratification of our perovskite solar technology and its prospects," says CEO Frank Averdung. "Whilst our research activities in Oxford focus on the future product roadmap, we are now ready to prepare our technology for commercialization and will work on this with our partner in the German pilot line."

**www.oxfordpv.com**

# Persistent photoconductivity in nitride semiconductor UV photodetectors

**Researchers reduce effect by three orders of magnitude from 39 hours to 24 seconds by localized Joule heating.**

Stanford University in the USA has used localized heating to reduce persistent photoconductivity (PPC) in aluminium gallium nitride on gallium nitride (AlGaN/GaN) ultraviolet (UV) photodetectors [Minmin Hou et al, IEEE Electron Device Letters, vol38 (2017), issue1, p56]. In particular, the PPC was reduced by more than three orders of magnitude from 39 hours to 24 seconds.

PPC is the time needed for the device to reset for its next detection sequence. The PPC of AlGaN/GaN photodetectors is typically between hours and days, making such devices unsuitable for most applications. The Stanford device suspended the AlGaN/GaN material of the photodetector, removing its thermal connection to the underlying silicon substrate. This allows the device to be locally heated to about 300°C, accelerating the capture of photo-generated carriers.

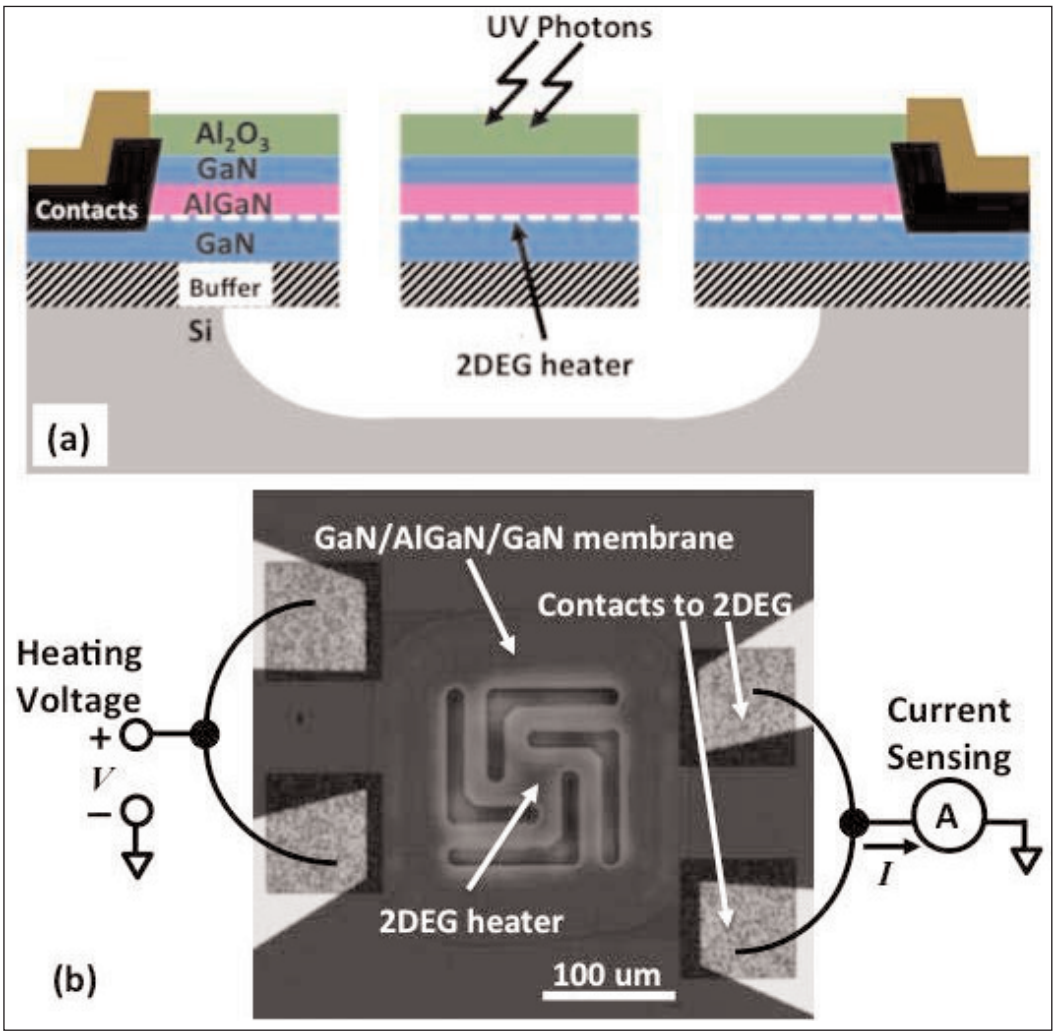



**Figure 1. (a) Schematic cross-section and (b) photograph with schematic for electrical connections of micro-fabricated and fully suspended AlGaN/GaN UV photodetector with integrated 2DEG heater.**

The researchers suggest that improved AlGaN/GaN photodetectors could find application in solar UV monitoring, satellite orientation, and combustion flame detection. Designers of military/defense systems use combustion flame detection for missile and anti-missile targeting.

The Stanford UV photodetectors were fabricated on AlGaN/GaN (30nm/1.5μm) on (111) silicon wafers with a GaN capping layer. The metal-organic chemical vapor deposition (MOCVD) material was supplied by Dowa Co. The electron mobility in the two-dimensional electron gas (2DEG) channel was 1400cm$^2$/V-s with 0.9x10$^{13}$/cm$^2$ carrier density.

Fabrication (Figure 1) consisted of mesa plasma etch, deposition of titanium/aluminium/platinum/gold ohmic contact electrodes, rapid thermal annealing, and further etching to suspend the photodiode structure above the silicon substrate. The suspension etch used an isotropic process involving xenon difluoride. The

arms of the suspended region were 100μm long and 20μm wide. The center plate was 50μmx50μm.

Suspending the photodetector somewhat reduced the photo-to-dark-current ratio (PDCR = (photo-dark current difference)/(dark current)). For 15V applied voltage, the reduction was from 1 to 0.09. This reduction was more severe at 30V, from 0.18 for a solid device without suspension to 0.04 with.

The low PDCRs are related to the relatively low intensity of the incident UV light with a power density of around 0.5mW/cm$^2$. The reductions for the suspended device are related to the temperature increase from Joule heating that reduces both carrier mobility (phonon scattering) and density (strain relaxation decreasing piezoelectric charge polarization) of the 2DEG.

Modeling of the solid device suggests that the temperature increase at 30V applied voltage was only about 1.5°C above room temperature due to the heat-sinking effect of the silicon substrate. Simulations of the suspended device indicated a temperature increase to the order of 270°C at 30V.

PPC was reduced by heating from 39 hours (1.4x10$^5$ seconds) with 1V applied to 24 seconds with 30V. The results give a capture barrier estimate of around 360meV. Previous researchers have suggested that the barrier is related to non-overlapping vibronic states of filled and unfilled defects. Thermal energy at high temperature (~50meV average at 300°C compared with 26meV at room temperature) increases the likelihood for electrons to be at high enough energy for capture, reducing the decay time.

The researchers comment: "The heating power and voltage can be reduced by optimization of the 2DEG heater size and layout. Since the AlGaN/GaN photodetector has a much shorter thermal time constant than its photocurrent decay time, pulsed heating can be utilized to further reduce power consumption. Future work can be conducted to study the effects of pulsed heating on PPC suppression." ■

http://dx.doi.org/10.1109/LED.2016.2626388

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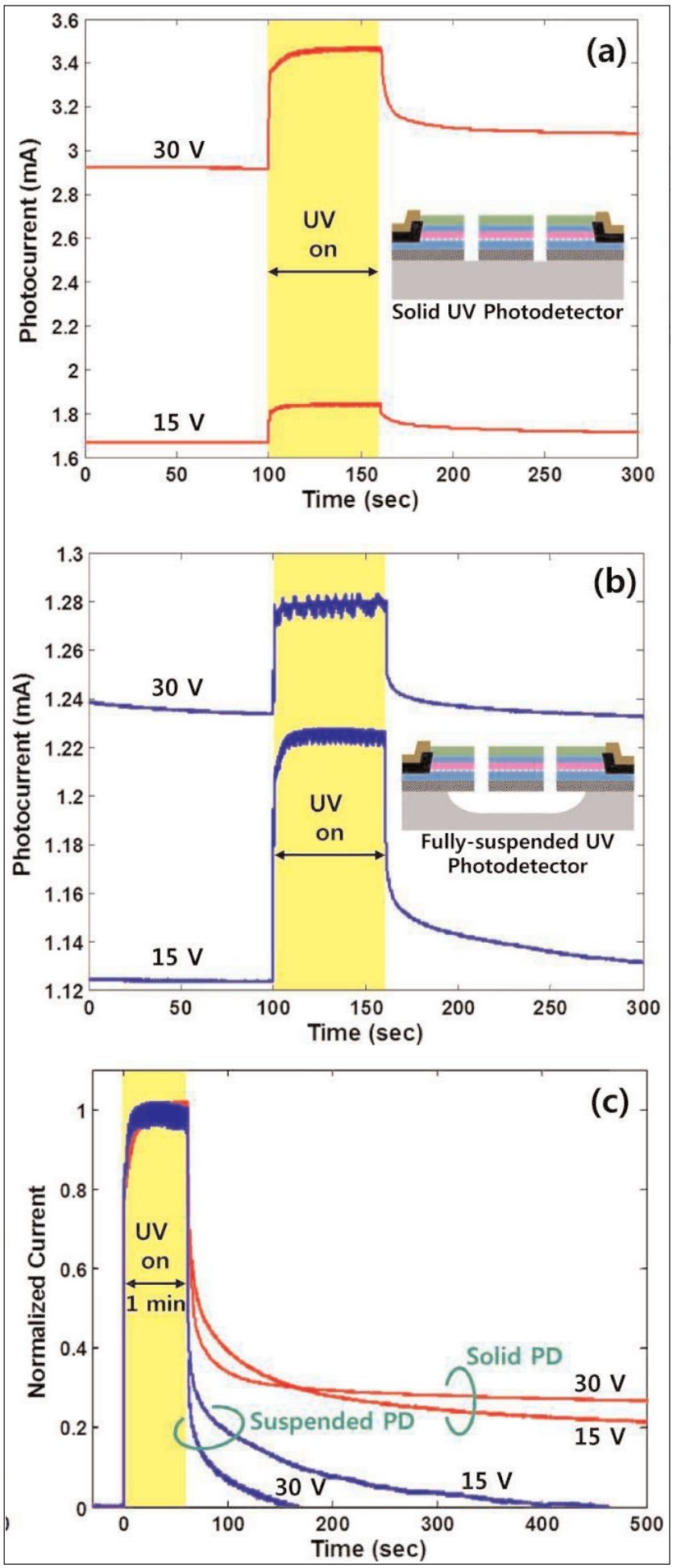


**Figure 2. The transient photocurrent response of (a) solid and (b) fully suspended AlGaN/GaN UV photodetectors under dark and 365nm illumination. (c) Normalized photocurrent values (0% dark, 100% maximum photocurrent under UV illumination).**

# Continuous-wave room-temperature broad-area quantum cascade lasers

**Researchers reduce the number of cascades to compensate for vertical-only heat dissipation.**

Two researchers at Humboldt University Berlin in Germany have developed broad-area quantum cascade lasers (QCLs) that can operate in continuous-wave mode beyond 100°C [M. P. Semtsiv and W. T. Masselink, Appl. Phys. Lett., vol109, p203502, 2016]. The emission wavelength was 4.6μm. One device achieved an output power of 1.3W at –27°C and 0.6W at +20°C.

QCLs are the leading semiconductor laser sources being developed for the mid- to far-infrared spectral regions. Although QCLs with wavelengths ranging from a couple of microns to hundreds of microns have been reported, the best performance comes in the mid-infrared (4–10μm). Pulsed operation is easier to achieve, since the active region does not accumulate heat that raises the effective temperature.

Continuous wave (cw) operation is needed for applications that require very narrow spectral width such as high-resolution spectroscopy. Further, cw operation allows for higher average power output, as is needed for infrared counter-measures against heat-seeking missiles.

In order to achieve cw performance with high power at room temperature, QCLs are produced with large numbers of cascades of between 30 and 40, along with a medium stripe width up to 16μm. Such devices depend on vertical and lateral heat flow to keep active-region temperatures down.

The approach of Semtsiv and Masselink was to reduce the number of cascades, allowing for wider stripes. Reducing the number of cascades in the active region reduced the heat generation, allowing for only the vertical dissipation that dominates in wide stripes.

The QCL material was grown on lightly sulfur-doped indium phosphide (n-InP) by molecular beam epitaxy (MBE). The substrate also served as bottom cladding for the laser cavity. The epitaxial layers consisted of a 360nm InGaAs bottom spacer, a 10-period InGaAs–InAlAs active region, a 360nm InGaAs top spacer, and a 4μm InP top cladding. The active region had a strain-compensated design.

Broad 30μm-wide ridges were formed with wet etching.

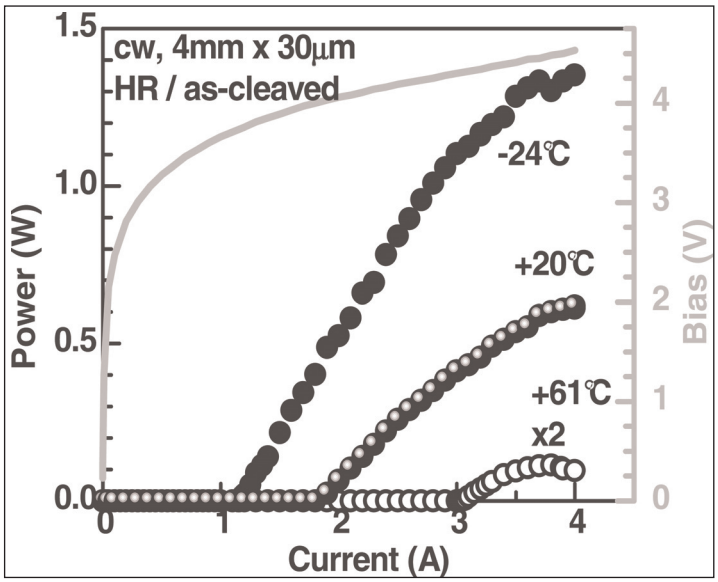


**Figure 1. (Grey line) Current-voltage characteristic at +20°C and (symbols) current-power characteristics at indicated temperatures for 4mm-long one-side HR-coated QCL stripe in cw mode.**

The sidewalls were covered with 600nm reactive magnetron sputtering silicon dioxide insulation. Contacts were made with chromium and gold. A heat spreader was formed with a 5μm-thick layer of galvanic gold over-coating.

The laser stripes were soldered epi-side down using semi-eutectic gold-tin on aluminium nitride submounts. A 1mm-wide and 30μm-thick copper foil was soldered to the back-side of the InP substrate as a contact.

Lasers with 4mm-long cavities and as-cleaved facets had a pulse-mode threshold current density of 2kA/cm$^2$ at room temperature. The power/wall-plug efficiency was 6% at 8kA/cm$^2$. Room-temperature QCLs have achieved power efficiency up to 28% in pulsed mode.

The threshold was reduced to 1.2kA/cm$^2$ by coating the back-facet with a high-reflectance (HR) coating of silicon dioxide, chromium and gold (Figure 1). The coating also allowed continuous-wave operation at room temperature with threshold power density of

6kW/cm$^2$ (1.5kA/cm$^2$x4V).

Further threshold reduction in continuous-wave operation to 3.4kW/cm$^2$ threshold power density (3.8Vx0.9kA/cm$^2$) was seen by coating both facets with the same silicon dioxide, chromium and gold layers with different thicknesses designed to give high- and semi-reflective properties. This two-sided coating device was 2mm long.

Using temperature-dependent measurements the researchers estimate the thermal conductance of the device at 240K to be 235W/K-cm$^2$ and at 375K to be 140W/K-cm$^2$. These values were consistent with a predicted value of 229W/K-cm$^2$, calculated using a model with one-sided heat flow in the region 9°C to 26°C. The researchers comment: "This strongly indicates asymmetric heat flow in our QCL, which is rather consistent with the manner in which our QCLs were mounted. This result promises, in turn, a significant improvement in performance by improving the heat removal at the top electrical contact."

The researchers operated the devices up to 102°C in continuous mode.

The team comments: "This demonstration opens an appealing route for almost unlimited cw power scaling by increasing the laser ridge width. For achieving high brightness in cw mode, this approach has to be combined in future with existing optical-mode-control solutions." ■

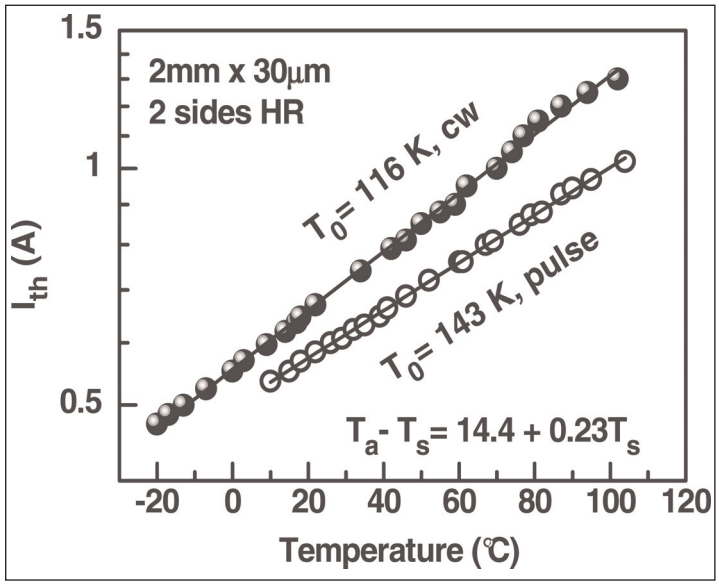


**Figure 2. Threshold current density, $J_{th}$, versus heat-sink temperature for two-side HR-coated 30μmx2mm laser driven with 100ns current pulses (open symbols) and with constant current (full symbols). Solid lines are the exponential fit used to determine characteristic temperature $T_0$.**

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*Author: Mike Cooke*

# Multi-functional metamorphic buffer for InAs QW laser diodes on indium phosphide

**Buffer layer structure combines lattice-mismatch bridging and bottom cladding for optical confinement.**

Yale University and University of Illinois at Urbana-Champaign in the USA have developed a multi-functional metamorphic buffer (MFMB) for indium phosphide (InP) substrates that acts both as a bridge between lattice constants and optical confinement for laser diodes (LDs) [Daehwan Jung et al, Appl. Phys. Lett., vol109, p211101, 2016]. The researchers have demonstrated the concept for 2.5μm short-wavelength infrared (SWIR, 1.4-3μm) devices with lasing up to room temperature (RT) in pulsed mode.

Usually the buffer layer that is used to bridge lattice mismatching is separate from the cladding layers that are used to provide optical confinement in laser diode structures. This increases the amount of material needed to be grown epitaxially, adding to processing times and costs. The MFMB was used to both bridge the substrate-laser lattice structures and provide graded-index cladding for optical confinement.

The team hopes that the technique could open up the range of semiconductor laser devices, allowing wavelength 'gaps' to be accessed efficiently. The 2–3μm range is one such gap. While other technologies — InP-based laser diodes or quantum cascade lasers (QCLs) from opposite ends – can be stretched into this gap, the result is usually suboptimal.

Gallium antimonide (GaSb) is often used as a substrate for SWIR LDs, but the material has lower thermal conductivity and immature commercial processing infrastructure compared with InP built up through extensive 1.55μm laser telecoms (i.e. fiber-optic) applications.

The researchers comment that the approach could be extended to devices on gallium arsenide (GaAs) or silicon (Si): "More generally, the MFMB concept may enable a new class of laser diodes for many applications such as GaAs-based mid-IR lasers or photonic integrated circuits (PICs) on Si," they write.

The Yale/Urbana-Champaign MFMB provided the bottom cladding for the laser diode, while the top cladding came from low-index p-AlGaAs (Figure 1). The asymmetric-index InAsP waveguide structure was designed to center the fundamental transverse-electric (TE) optical field on the device's active region. The confinement factor in the nine compressively strained QWs was estimated at 6.8%.

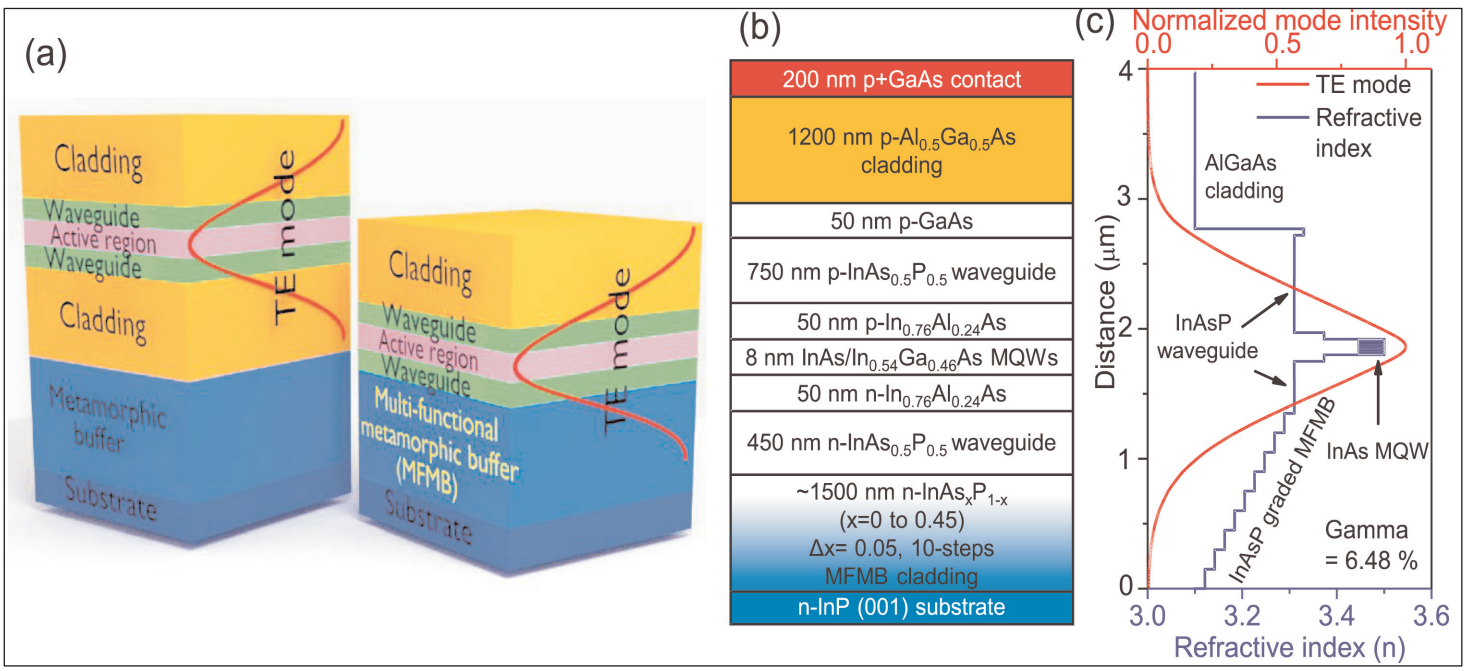



**Figure 1. (a) Comparison of conventional lasers grown on metamorphic buffers and MFMB. (b) MFMB laser structure. (c) Optical TE mode intensity profile (red) and refractive index (blue) in graded InAsP MFMB laser.**

Compressive strain leads to highly TE-polarized emission from the QWs. The strain-balancing of the QW region was achieved by performing photoluminescence studies with 8nm InAs QWs and 6.1nm $In_{0.54}Ga_{0.46}As$ barriers. The barriers were under tensile strain. The light-emission performance of this structure was much better than using 15nm $InAs_{0.5}P_{0.5}$ unstrained barriers. In fact, a single InAs QW outperformed 4 InAs QWs with unstrained barriers. Bright-field transmission electron microscopy showed the strain-balanced structure to be 'free' of misfit dislocations, unlike the unbalanced QWs.

The MFMB material was grown on InP by molecular beam epitaxy (MBE). The 10μm-wide laser ridge fabrication consisted of freon and inductively coupled plasma (ICP) etches. Electrical isolation was provided by 300nm silicon dioxide.

Contact pad regions were opened in the silicon dioxide layer and titanium/aluminium/gold p-contact metals applied. The back-side germanium/gold/nickel/gold n-contact was applied after lapping the laser material to the thickness range 150–200μm. Metal deposition was followed by annealing/alloying at 405°C for 5 minutes.

The material was cleaved into 1mm-long laser bars and mounted on a copper block with indium paste. The assembly was placed in a cryostat.

At 77K, the continuous-wave emission was at 2.50μm (0.5eV) with 108nm full-width at half maximum (FWHM) at a low current density of 120A/cm$^2$. The emission wavelength was consistent with the calculated energy of the QW ground-state electron-hole transition. By 250A/cm$^2$ current density, the FWHM fell dramatically to 2nm with much increased peak intensity, indicating laser behavior.

Light output power versus current curves indicate laser thresholds up to 300K for pulsed operation and 200K for continuous wave (Figure 2). "While the MFMB structure enables lasing by providing optical mode confinement and low threading dislocation density, the strain-balanced MQW active region improves the laser gain, enabling RT operation," the researchers comment.

The differential quantum efficiency was estimated at 4.6% and 0.13% for continuous-wave operation at 77K and 200K, respectively. Pulse-mode operation also saw a strong fall in differential quantum efficiency with temperature, except around 250K.

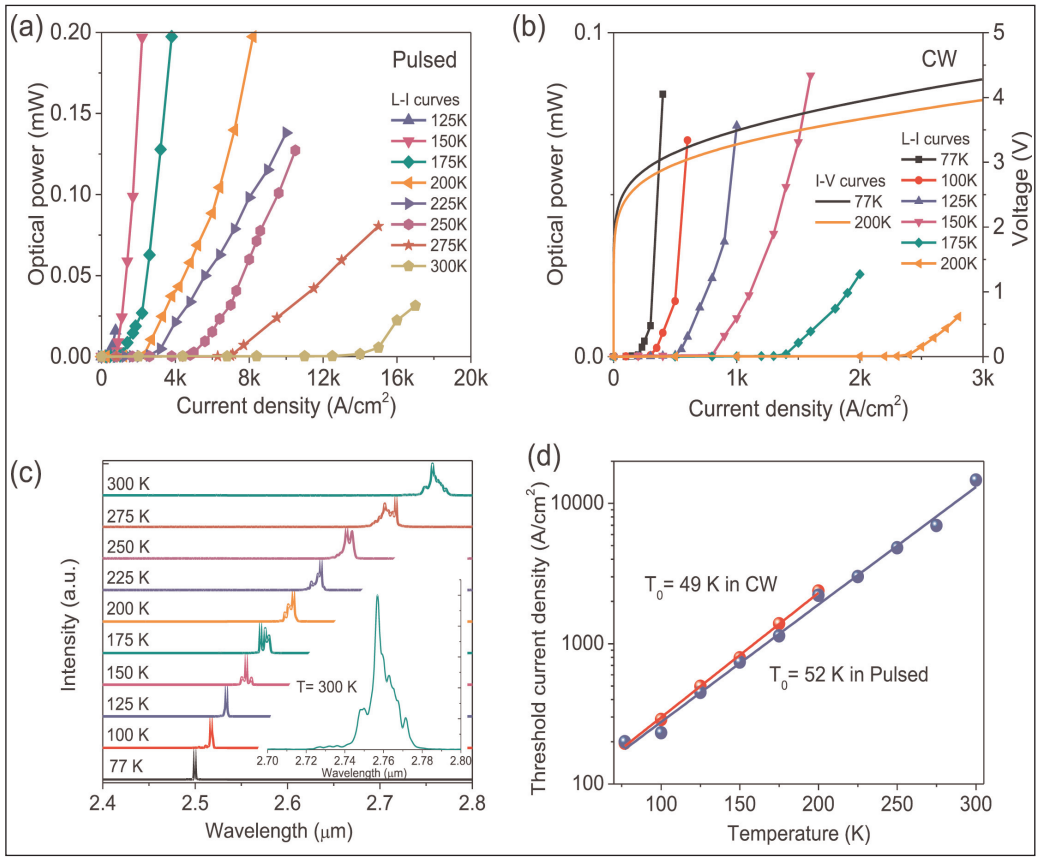



**Figure 2. (a) Temperature-dependent pulsed-mode output power vs current. (b) CW mode light output power and voltage versus current. (c) Pulsed-mode lasing spectra. Inset: 300K close-up. (d) Threshold current density versus temperature in CW (red) and pulsed mode (blue). Solid lines: semi-log fit.**

The emission wavelength red-shifted with increasing temperature, in line with an expected narrowing of the bandgap of the InAs QWs. At 300K/room temperature, the pulse-mode emission wavelength was 2.76μm.

The increase and relatively high threshold currents in both pulsed and continuous modes causes the researchers to comment: "Although the MFMB concept has enabled the longest-wavelength room-temperature emission for a type-I laser diode on InP, the threshold current density is still relatively high at this early stage. Improvements in laser performance can be obtained by optimizing the growth conditions and carrier confinement for the InAs MQW layers to increase the internal quantum efficiency. Optimization of the p-type doping profile will also be necessary to decrease the voltage drop across the device, diminish parasitic absorption, and improve the device temperature performance."

The team also suggests that further enhancements for lower thresholds could include graded-index top cladding based on AlGaAs and facet coating to adjust reflectivity at the ends of the cavity. ■

**http://dx.doi.org/10.1063/1.4968560**

*Author: Mike Cooke*

# Heterogeneous integration of 2.3µm DFB laser diodes on silicon photonics

**Device used for tunable diode laser absorption spectroscopy of carbon monoxide gas.**

Researchers in Belgium and Germany have produced ~2.3µm-wavelength distributed feedback (DFB) laser diodes on a silicon photonics integrated circuit (PIC) [Ruijun Wang et al, Appl. Phys. Lett., vol109, p221111, 2016]. The team from Ghent University–imec and Ghent University in Belgium and Technische Universität München in Germany see potential for compact integrated spectroscopic sensors. The researchers demonstrated the use of their device in a tunable diode laser absorption spectroscopy (TDLAS) experiment using carbon monoxide gas. Further, many important gases have narrow, dense absorption lines in the 2–3µm wavelength range.

The assembly consisted of a III-V gain section (Figure 1) over a silicon distributed feedback (DFB) grating and III-V/silicon spot-size converters (SSCs, Figure 2). The gain section was produced by molecular beam epitaxy (MBE) on n-type indium phosphide (n-InP). The active region consisted of six W-shaped wells separated by 9nm tensile-strained $GaAs_{0.58}Sb_{0.42}$ layers. The wells confined holes in a central 2.9nm $GaAs_{0.33}Sb_{0.67}$ layer, while the electrons were confined either side in two 2.6nm $In_{0.68}Ga_{0.32}As$ layers.

The III-V mesa was 1000µm long and 5µm wide. The mesa width was chosen to give low waveguide propagation loss and high optical confinement in the III-V active region.

The III-V material was bonded to the silicon with 60nm divinylsiloxane-bis-benzocyclobutene (DVS-BCB) adhesive, giving a calculated 10.1% confinement factor of the transverse electric (TE) fundamental mode in the quantum wells. The tail of the optical mode interacted with the underlying DFB grating, setting the emission wavelength. The DFB consisted of 180nm deep trenches dry etched in the 400nm silicon device layer. The structures were then filled with silicon dioxide and planarized by chemical mechanical polishing (CMP).

The SSCs were realized by tapering both the III-V structure (5µm to 1.2µm over 50µm, then down to 0.5µm) and underlying silicon (0.2µm to 3µm in 180µm) waveguides. Simulations suggested that such a structure would have more than 90% coupling efficiency.

| | | |
|---|---|---|
| Contact | $p^+$-InGaAs | 100nm |
| Cladding | p-InP | 1.5µm |
| Electron blocking | AlAsSb | 20nm |
| Confinement | AlGaAsSb | 250nm |
| Active region | 6x(W-shape well/barrier) | 6x(8.1nm/9nm) |
| Hole blocking | AlGaInAs | 10nm |
| Confinement | GaSb | 130nm |
| Contact | n-InP | 200nm |

**Figure 1. III-V gain section.**

The silicon PIC processing was performed on IMEC's CMOS pilot line on 200mm silicon-on-insulator (SOI) wafers with 400nm device layer on 2µm buried oxide insulator. The bonding of the III-V material was followed by removal of the InP growth substrate by hydrochloric acid wet etch. The DFB laser structure was then processed with ultraviolet lithography of a silicon nitride hard mask and anisotropic hydrochloric acid etch.

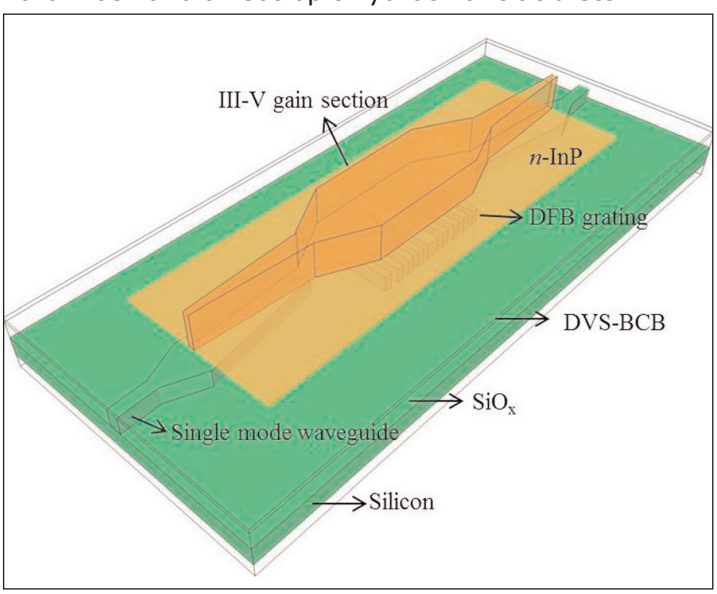



**Figure 2. Three-dimensional schematic view of heterogeneously integrated DFB laser.**

The structure was passivated with DVS-BCB, after which nickel/germanium/gold and titanium/gold were deposited as n- and p-contacts, respectively.

The DFB grating was produced with two periods — 348nm and 353nm, giving lasers '1' and '2', respectively. The devices had corresponding continuous wave (CW) threshold currents of 90mA and 102mA at 5°C, which translate into densities as 1.8kA/cm$^2$ and 2.04kA/cm$^2$. The researchers point out that these values are lower than the first demonstrated 'W'-shaped InGaAs/GaAsSb quantum well lasers grown on InP substrates that gave threshold current densities of 3.2kA/cm$^2$ at 0°C.

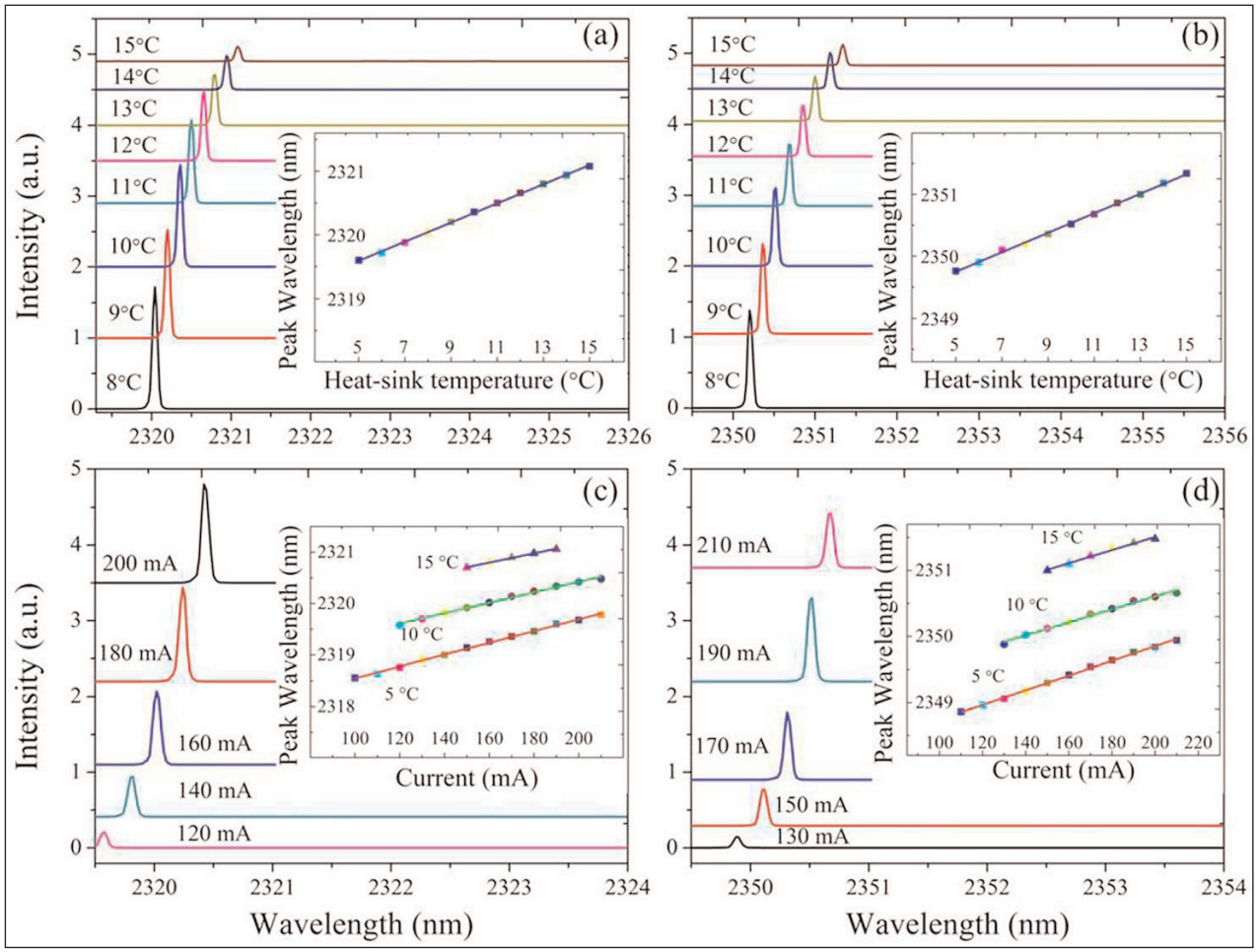



**Figure 3. Evolution of lasing spectra as function of heat-sink temperature for DFB grating periods of 348nm (a) and 353nm (b), with both devices biased at 190mA. Inset: dependence of lasing wavelength on temperature; (c) and (d): Emission wavelength versus injection current at heat-sink temperature of 10°C. Inset: wavelength versus injected current at 5°C, 10°C and 15°C.**

The 5°C output power was 1.3mW for Laser 1 and 0.8mW for Laser 2. The researchers comment: "The lower threshold current and higher output power of Laser1 can be attributed to the gain at the lasing wavelength of Laser 1 being higher than that of Laser 2 at 5°C."

At higher temperature, the gain spectrum shifts to longer wavelength, reversing the performance. At 15°C, the output power of Laser 2 was higher than that of Laser 1. The maximum for CW lasing performance was around 17°C for both devices.

The researchers suggest that threshold currents and operating temperatures could be improved by reducing thermal resistance by making the DVS-BCB layer thinner, along with connecting the top p-contact to the silicon substrate. Electrically, the series resistance (and resultant Joule heating) could be reduced by optimizing metallization processes.

At 10°C and 190mA current, the peak wavelength was 2320nm for Laser 1 and 2350nm for Laser 2. The lasing was single-mode with 40dB side-mode suppression ratio. The ratio was better than 35dB over the current range 120–210mA. At 5°C the suppression was more than 43dB. The researchers suggest that, by changing the DFB pitch to give different peak wavelengths, an array of lasers could be used for monitoring several gases using a single III–V epitaxial layer stack.

Varying the temperature shifts the wavelength at the rate ~0.15nm/°C due to changes in the effective refractive index of the DFB lasers. The current also changes the wavelength with a rate of 0.01nm/mA.

As a demonstration, the researchers performed spectroscopy on carbon monoxide gas at 740Torr using Laser 1 as the light source at 13°C. The absorption by CO in a gas cell was sensed and the spectrum derived from the current-wavelength relation. The experimental spectrum closely matched the reference form from the High Resolution Transmission (HITRAN) database [https://www.cfa.harvard.edu/hitran/]. ■

**http://dx.doi.org/10.1063/1.4971350**

*Author: Mike Cooke*

# High-quality AlN grown on nano-patterned sapphire substrates prepared by nano-imprint lithography

**Peking University researchers have recently greatly improved the quality of heteroepitaxial AlN films by using nano-patterned sapphire substrates prepared by nano-imprint lithography.**

Researchers from China's Peking University (PKU) have demonstrated high-quality aluminium nitride (AlN) grown on nano-patterned sapphire substrate (NPSS) prepared by nano-imprint lithography. Due to the application of NPSS and matched strategy for controlling threading dislocation density (TDD), the crystalline quality of AlN grown on sapphire has been greatly improved [L. S. Zhang, F. J. Xu, B. Shen, et al, Sci. Rep. 6, 35934 (2016)]. The best x-ray diffraction ω-scan full width at half maximum values for (0002) and (10$\bar{1}$2) reflections are 171 and 205 arcsec, respectively, and the calculated TDD is below $4x10^8 cm^{-2}$. Besides, by further balancing size of the pattern and lateral growth rate of AlN during epitaxy, an atomically flat surface with a root mean square (RMS) roughness of 0.096nm and straight and parallel steps were obtained, and the coalescence thickness was controlled to be less than 3μm (as shown in Figure 1).

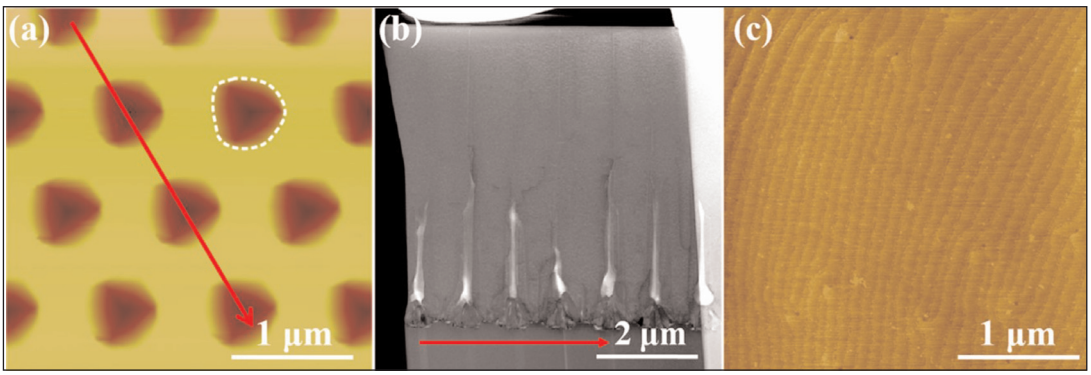



**Figure 1. (a) AFM image of a typical NPSS (3mm x 3mm). (b) Cross-sectional STEM image for this chosen sample, fabricated by focused ion beam. (c) Typical AFM image of the surface morphology of the AlN sample on NPSS with 650nm hole patterns (3mm x 3 mm).**

The PKU team believes this technique is promising. Although many techniques have been proposed to reduce the TDD of AlN grown on sapphire, a reliable method for obtaining AlN with TDD of the order of $10^8 cm^{-2}$ is still scarce. The need for qualified AlN templates is urgent for research and volume production of deep ultraviolet (DUV) optoelectronic devices. The PKU team therefore developed this convenient technique for high-quality AlN epitaxy, including the NPSS fabrication process and matched

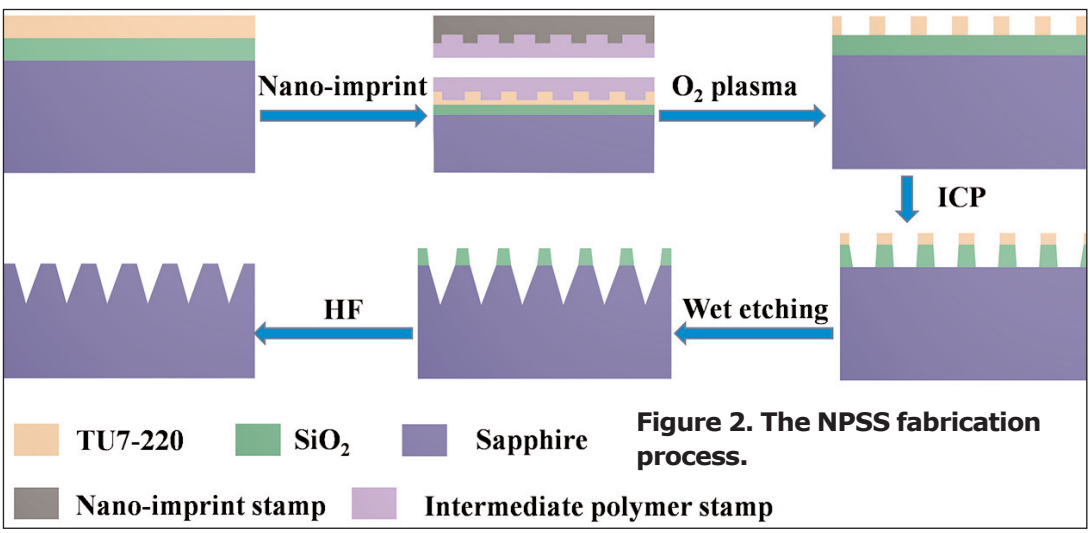



**Figure 2. The NPSS fabrication process.**

strategy for defect control on NPSS.

The NPSS fabrication process is illustrated in Figure 2. Stabilization and modification of the process can be ensured by benefiting from the mutual technologies of nano-imprint lithography, plasma-enhanced chemical vapor deposition (PECVD) and inductively coupled plasma (ICP).

During AlN epitaxy on the NPSS, the researchers found that there were three main competing processes influencing the TDD (shown schematically in Figure 3). The first is process A, where a large number of TDs are generated at the AlN/sapphire interface due to the large lattice mismatch. The second is process B, where TDs near the voids tend to bend towards the void sidewalls driven by the image force, which can effectively decrease the TDs on the mesa regions. The third is process C, where some TDs are generated around the boundaries during coalescence caused by misorientations between the adjacent regions. When width of the growth mesa is decreased, process B will gradually become the dominant one and nearly all of the TDs originating from process A can be eliminated. In this case, the TDD in the AlN epilayers is mainly determined by the dislocation generation in process C. As such, a strategy for decreasing the TDD of AlN grown on NPSS is proposed, which means suppressing TDs from process A via process B with the optimized pattern size, and then decreasing TDs in process C. These suggest that, to gain a deeper insight into the role of NPSS in AlN epitaxy, both the effect of image force and impact of misorientations should be taken into account. In particular, process C had better be accomplished adopting a low lateral growth rate to avoid large misorientation and dislocation generation.

Ideally, almost all of the TDs in AlN grown on this NPSS locate above the hole patterns on the substrate, as shown schematically in Figure 4(a). The white discs represent regions with high TDD and the black dots represent dislocation outcrops. In order to verify how reasonable the schematic model is, the AlN grown on NPSS is characterized by wet etching in molten KOH/NaOH. The AFM images in Figure 4(b) and (c) show the post-etch surface morphologies of AlN. The relationship in relative position between Figure 4(c) and the simplified outlines of holes on the NPSS is determined according to the reference edge of the sapphire, as shown in Figure 4(d). As illustrated in Figure 4(d), most of the TDs are distributed in the outlines, which is only 38% of the total area of the substrate. This distribution feature of TDs roughly corresponds to the schematic model.

The great advantage of this technology is that not only can it improve the crystalline quality of the AlN drastically but it also will benefit the light extraction efficiency of DUV light-emitting diodes (LEDs) in the long term. ■

**www.nature.com/articles/srep35934**

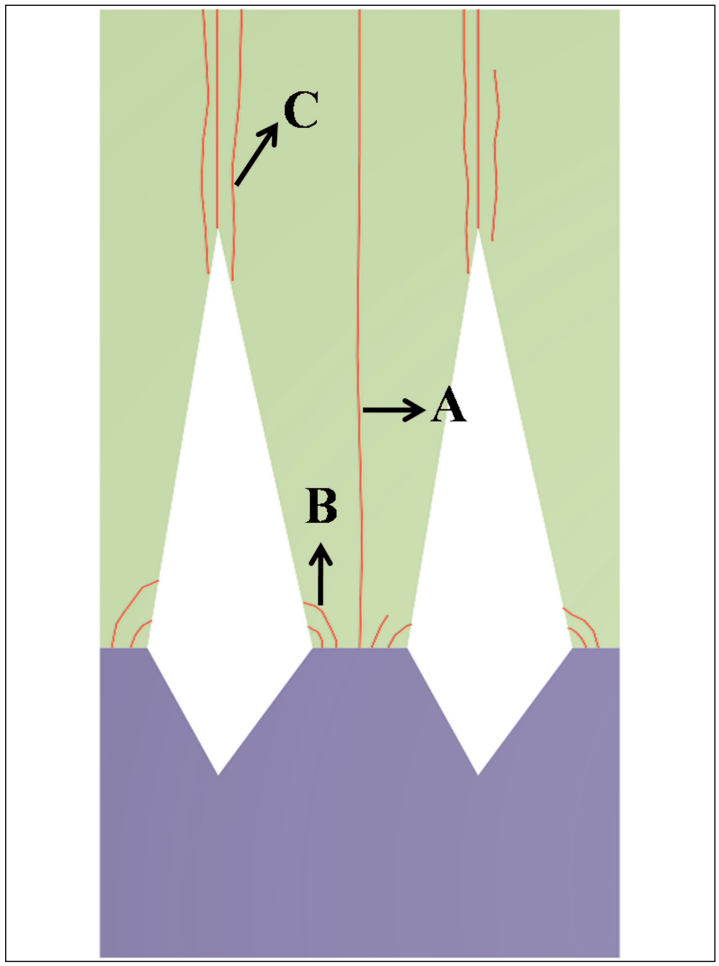



**Figure 3. The three main competing processes influencing the TDD in AlN epilayers on NPSS.**

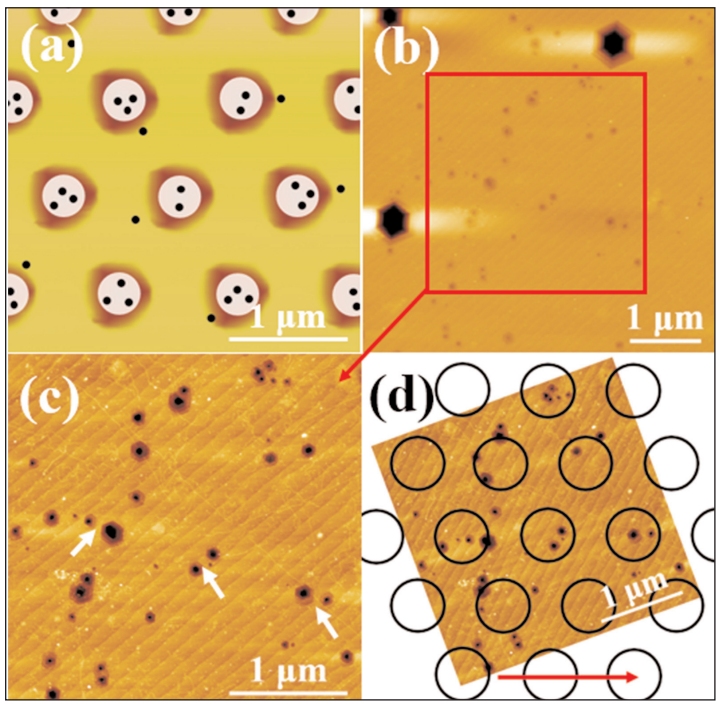



**Figure 4. (a) Schematic of dislocation distribution above the NPSS. AFM images of the post-wet-etch AlN (b) in 5μm x 5μm, (c) in 3μm x 3μm. (d) Relationship between the positions of etching pits with the hole type patterns on the NPSS.**

# Technical innovations in LEDs and power electronics converging to handle module-level thermal management

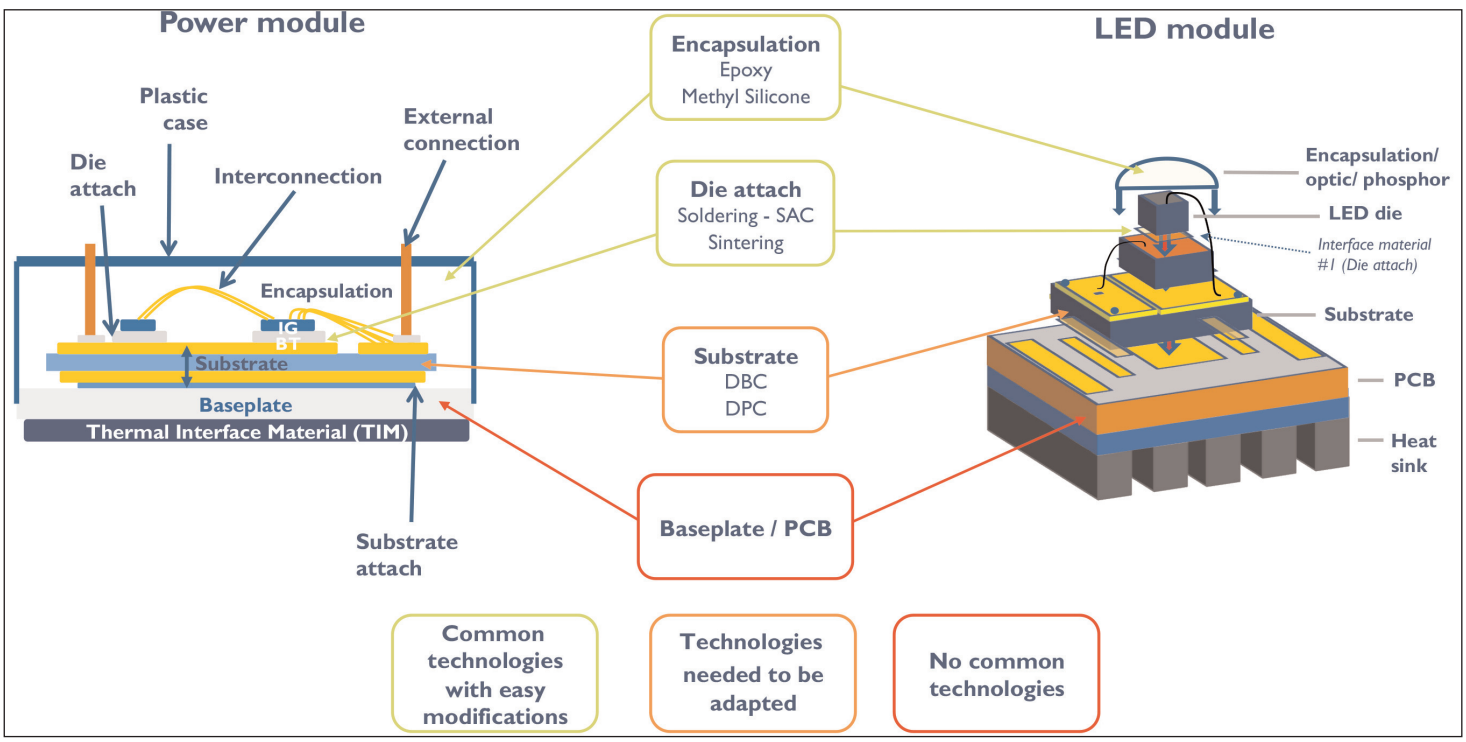
In 2015, all economic indicators pointed to continued market growth for both the power electronics and LED industries, especially due to (1) insulated-gate bipolar transistor (IGBT) modules — boosted by the EV/HEV (electric vehicle/hybrid electric vehicle) industry — and (2) general lighting applications (a killer application for LEDs since 2012).

To support this growth and answer the thermal management needs in power electronics and LEDs, a lot of innovative technologies are emerging. According to the report 'Thermal Management Technology and Market Perspectives in Power Electronics and LEDs 2017' from market analyst firm Yole Développement's Power Electronics & LED teams, one of the most impressive technical developments is the convergence of thermal management for both the LED and power electronics sectors, particularly the materials used for thermal management.

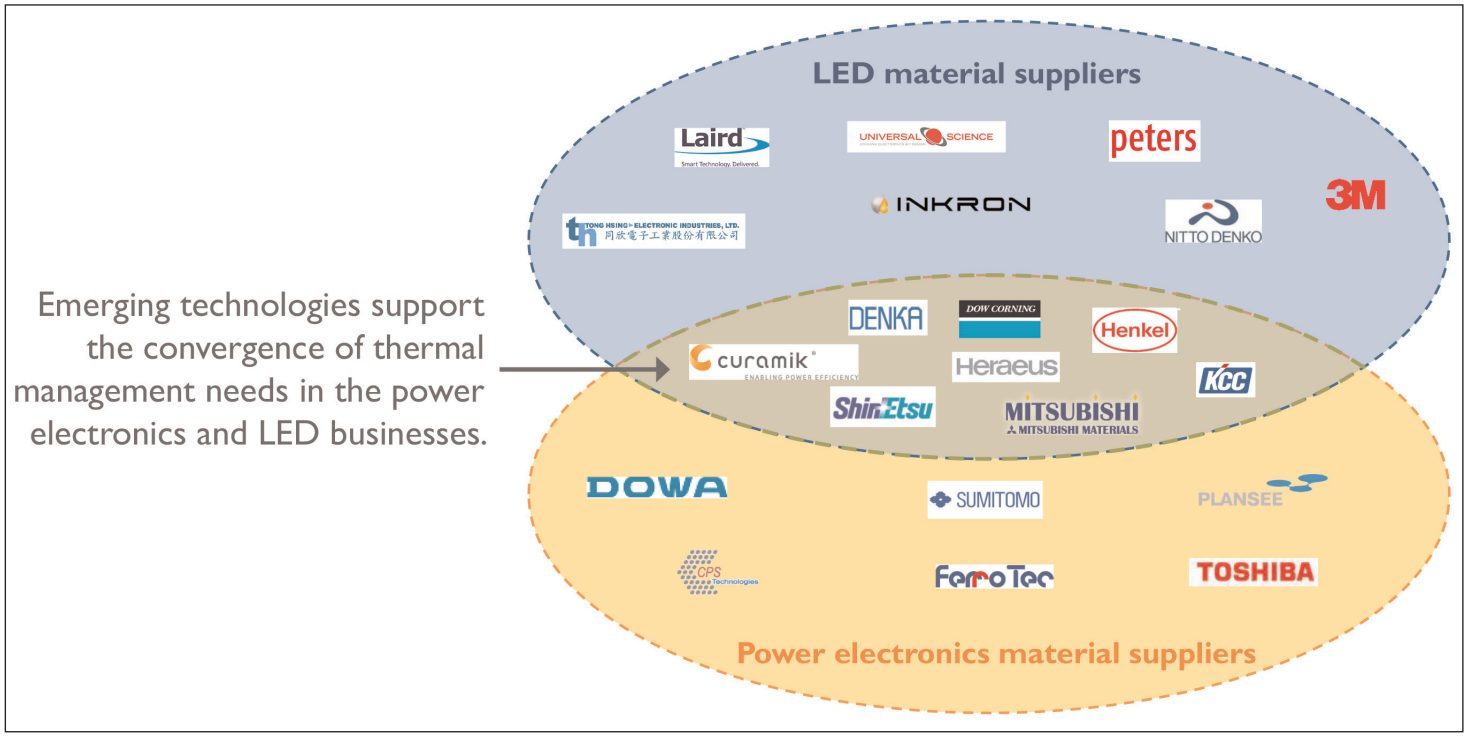
**Power density targets in both power electronics and LEDs bring a convergence of thermal management requirements, supporting the development of new materials**

"Power electronics and LEDs are different industries that today face similar challenges," remarks Dr Pierric Gueguen, business unit manager at Yole. "Needs for green energy with lower $CO_2$ emissions have led these industries to develop more efficient and smaller solutions," he adds. At the device level, cost pressure and the need for better performance is pushing designers towards smaller and thinner chips, leading also to increased power density. Such power density targets in both power electronics and LEDs bring a convergence of thermal management requirements, supporting the development of new materials.

Among materials used for thermal management, Yole specifically investigated the market and technology evolution of die attach, substrates, base-plates/PCBs and encapsulants. Overall, this market will rise at a




**Synergies and differences between power modules and LED modules.**



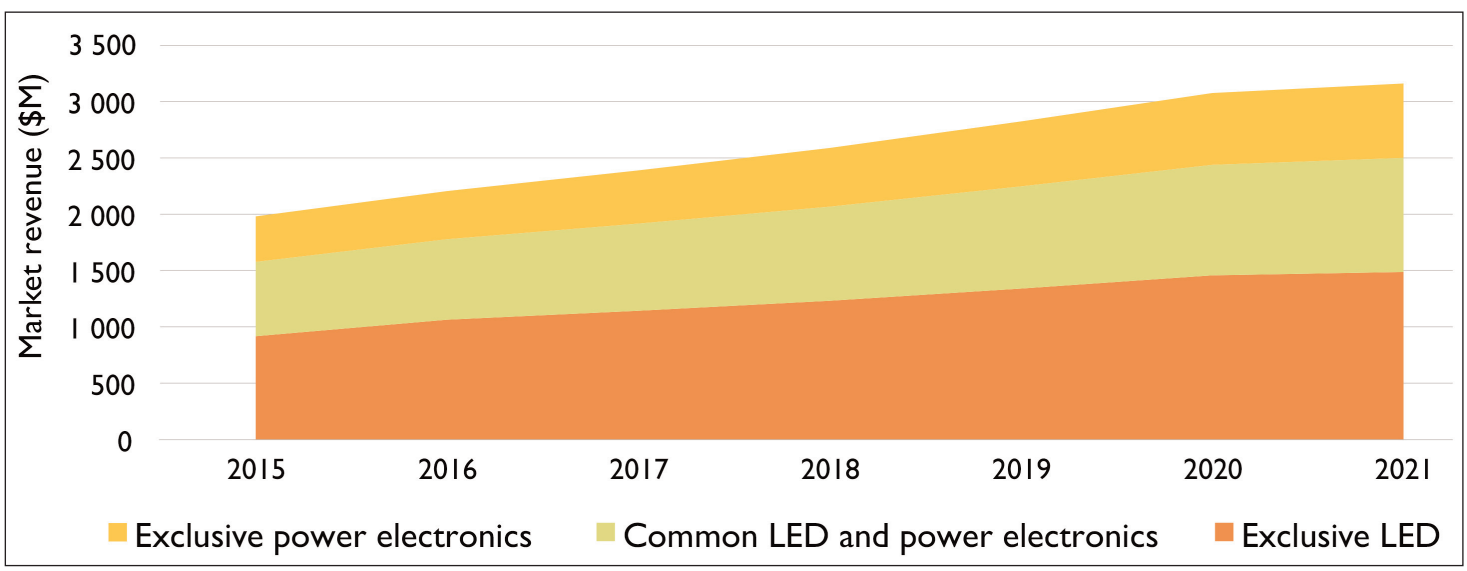

**Material supplier synergies.**

compound annual growth rate (CAGR) of 6% from $1.98bn in 2015 to $3.16bn by 2021, forecasts Yole. "Their value proposition has the potential to bring business to their suppliers and key differentiating factors to device manufacturers," comments Pierrick Boulay, technology & market analyst at Yole.

Power electronic modules represent a healthy market, growing at a 9% CAGR from $2.9bn in 2015 to $4.5bn in 2021. In parallel, the LED packaging market reached $15bn in 2015, after years of strong growth led by LED TV and general lighting. However, price pressure will moderate growth in coming years, with a 3.4% CAGR leading to a market worth $18.5bn in 2021.

Power electronics and LEDs need the right materials to handle thermal management challenges, notes Yole. As these applications are driven by similar technical requirements, one technical solution can be adopted and developed for one industry before being used by another industry. "The 30% of the overall thermal management material market that is common to both LED and power electronics represents $660m in 2015," notes Boulay. "According to our estimations, such market segment will reach $1014m in 2021," he adds. Moreover, another 30% can be reached by adapting existing technologies used in LED or power for the other application, it is reckoned.

**www.i-micronews.com/category-listing/product/thermal-management-technology-and-market-perspectives-in-power-electronics-and-leds-2017.html**




**Thermal management market for power electronics and LEDs, 2015-2021.**

# Driving deployment of wide-bandgap power devices on 200mm

**Hans Auer and scientist Dr Dominik Jaeger of Evatec introduce the advantages of wide-bandgap (WBG) power devices and some of the development challenges ahead.**

Today's silicon power device technology has evolved to a very mature state. However, with limited options for major future innovation steps, that is where wide-bandgap (WBG) semiconductors now have the opportunity to step in. Their capabilities to operate at higher voltages and temperatures — along with significantly lower switching losses — enable power circuits to run at much higher frequencies, resulting in reduced size. For example, the heat-sink size for variable-speed drives of industrial electric motors could be reduced by more than 50%. Battery-operated vehicles, mobile computing or wearable electronics could all benefit from longer battery lives. Electric drives like fans, pumps, compressors, conveyer systems etc could all use less power, achieving overall energy savings of more than 20% once wide adoption is achieved.

The two most interesting materials for fabricating WBG power devices are silicon carbide (SiC) and gallium nitride (GaN).

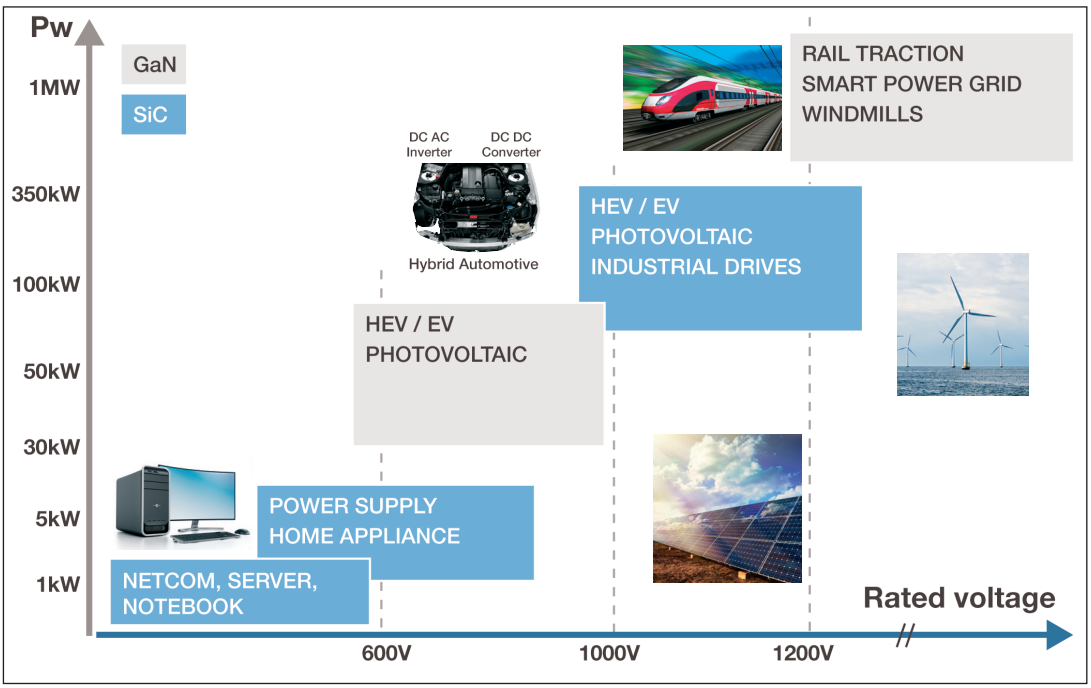



**Figure 1: Application fields for SiC and GaN power devices.**

**Hans Auer, Senior Manager Product Marketing.**

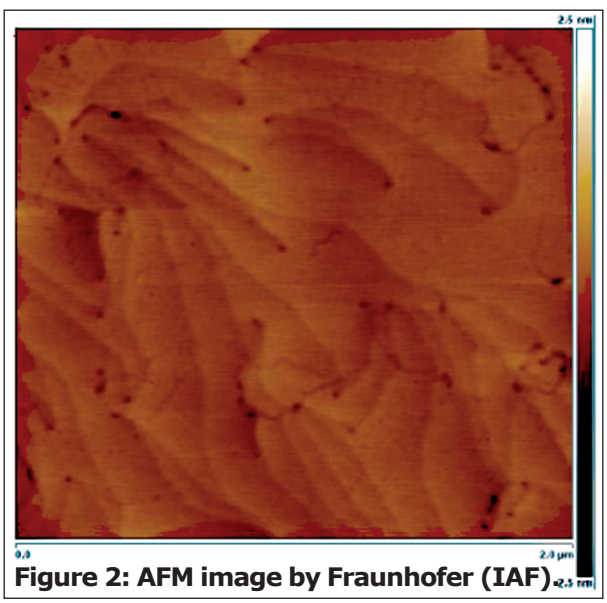


**Figure 2: AFM image by Fraunhofer (IAF).**


**Figure 3: HEMT structure, as overgrown by Fraunhofer Institute for Applied Solid State Physics (IAF).**

Although their use is still small today, the projected sales growth for these devices is between 50% and 80% for the next 5–10 years. SiC is the preferred material for device ratings in excess of 600V with applications in hybrid/electric vehicles (HEV), solar inverters and industrial power supplies while, due to its low switching loss, GaN is expected to dominate low-voltage applications, with a focus on DC/DC converters/commodity power supplies and motor drives.

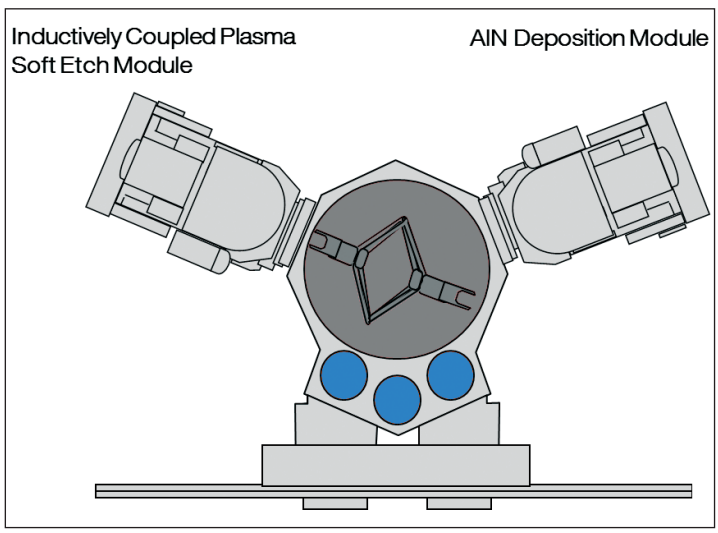



**Figure 4: CLUSTERLINE 200 II.**

**Film data of sputtered AlN overgrown with AlGaN**

XRD FWHM 00.2 (tilt) of 0.127º
Surface roughness comparable to reference (RMS<0.2nm)
2DEG depth 35.0nm
$N_{min} \approx 10^{13}/cm^3$
$V_{th} \approx -3.3V$
$N_s \approx 5x10^{12}/cm^2$

**Data of sputtered AlN buffer layer: film properties (100nm AlN on Si)**

| | |
|---|---|
| Deposition rate (nm/s) | 0.2 |
| Thickness uniformity | ±3.5% |
| Film stress (GPa) | 0.6 (tensile) |
| XRD rocking curve AlN (002) | < 2500arcsec |
| XRD rocking curve GaN (102) | Comparable to MOCVD AlN buffer |
| Roughness (AFM, RMS) | <1nm |

## An alternative production approach

While the SiC power devices are manufactured from bulk SiC wafers, GaN devices are made on silicon wafers with epitaxially grown GaN, a lower-cost method than building the devices from bulk GaN. The main challenge in manufacturing GaN-on-silicon substrates is the high lattice strain at the GaN/Si interface, which necessitates an aluminium nitride (AlN) buffer layer for subsequent GaN crystal growth. While this layer is traditionally formed by metal-organic chemical vapor deposition (MOCVD), sputtered AlN has recently made inroads due to the significantly lower cost over MOCVD. Compared to MOCVD deposition, sputtering of AlN enables higher deposition rates, and the amount of cleaning cycles in the MOCVD reactor can be reduced dramatically. Furthermore, the pit density in the GaN MOCVD is reduced by the AlN PVD buffer layer and hence results in a higher yield.

## The PVD solution is ready to implement

A manufacturing solution already used in the LED market for GaN-on-Si is also now ready to be deployed for the power device market. Process integration work, with a focus on 8" silicon wafers, is ongoing with multiple partners. The sputtered AlN buffer layers represent savings in MOCVD capacity of >20%. ■

**www.evatecnet.com/technology/technology-overview/layers-magazine**

| Hardware information |
|---|
| Standard soft etch-module |
| Heated chuck in the process module at T>800ºC with good uniformity (<40ºC) |
| Standard AlN deposition hardware (cathode) for full face deposition |
| Temperature-characterization in Transfer-Module |

# GaN – A truly revolutionary semiconductor technology matures

**Chief marketing officer Dr Markus Behet and chief technology officer Dr Joff Derluyn of epiwafer supplier EpiGaN discuss the benefits of GaN-on-silicon technology for RF power and power switching applications.**

The power management and RF market will experience a major technology transformation in the coming years that will impact the semiconductor industry in a profound way. The benefits of gallium nitride (GaN) as a wide-bandgap semiconductor in power switching, RF power, and sensor applications are evident, and mainstream commercial applications will increasingly start to adopt this revolutionary technology.

## A retrospective view

For the past few decades, silicon- and gallium arsenide (GaAs)-based technologies, devices and integrated circuits have paved the way for many power electronic innovations such as 3G, 4G-LTE wireless systems or power switching topologies in converter and inverter systems. Products enabled by these semiconductor technologies such as smartphones, computer power supplies, photovoltaic inverters, variable-speed motor drives — to name just a few — became commercial reality and are taken for granted in our daily lives.

These commercial applications were fuelled by generations of GaAs HEMTs, HBTs and silicon MOSFETs and IGBTs with ever increasing performance characteristics. However, improvements are nowadays only happening in incremental steps, as these incumbent semiconductor technologies are approaching their theoretical limits. Squeezing out an additional dB or Ohm of performance for power devices and systems requires a huge effort by design engineers at continuously increasing development cost.

Technology stagnation is not an option for a modern society. In that sense, Moore's Law of increasing the computing power at an exponential pace has set the pace of innovation and provided guidance for the semiconductor industry for several decades. However, Moore's Law seems to be running out of steam because shrinking traditional silicon transistors below the 10nm node is hitting physical and economical limits. Also, in other application fields (such as power switching) silicon technology has hit the hard wall of its fundamental limitations. Here, III–V semiconductors and especially wide-bandgap GaN-on-Si technology come to the rescue. For the first time a new semiconductor technology combines the capability to significantly outperform the incumbent silicon and GaAs technologies in power switching, RF power and sensors applications while leveraging Si-based economies of scale manufacturing to exploit economic gains. The good news is that next-generation III–V technologies like GaN combined with higher functional integration and new transistor design concepts will help Moore's Law to survive through functional diversification.

## GaN promises a bright future

Even if a disruptive technology like GaN offers a very appealing value proposition, it is unfortunately not adopted overnight. Past market studies have proven to be much too optimistic regarding the rate of adoption of GaN technology. The existing market value chains are very complex and many stakeholders at different steps in the value chain need to be convinced before a switch to a new technology is initiated. In addition, unmet needs of end users differ significantly per market application with regard to performance, cost, ease of use or reliability for new technologies.

Nevertheless, the number of applications demonstrating superior performance enabled by GaN technology has increased exponentially in the past years. The initial development focus was on transistors for 600V power-switching applications and lower-voltage, low-loss DC–DC converters. Recently, high-resolution LiDAR, wireless charging, ET (envelope tracking) for 4G-LT, medical or high-radiation applications have appeared and demonstrated the added value from the ultra-fast switching capabilities of GaN HEMTs.

Another big development focus is RF systems for the future 5G wireless communication standard. GaN RF power amplifiers have already demonstrated their capability to boost RF performance significantly compared with incumbent GaAs or LDMOS technologies while also reducing size, weight and power consumption

of the overall system. The high breakdown voltage, gain and efficiency at millimetre-wave (mmW) frequencies — combined with a 8–10x higher power density — makes GaN an ideal choice for RF systems. Of all RF power semiconductor technologies, GaN offers the highest output power up to 100GHz. Moreover, GaN RF transistors have a high output impedance, resulting in very good linearity performance and the widest bandwidth, enabling RF amplifiers to support multiple protocols. Additionally, GaN can operate at higher device operating temperatures, which in turn decreases cooling requirements and maintenance costs as well as improving reliability.

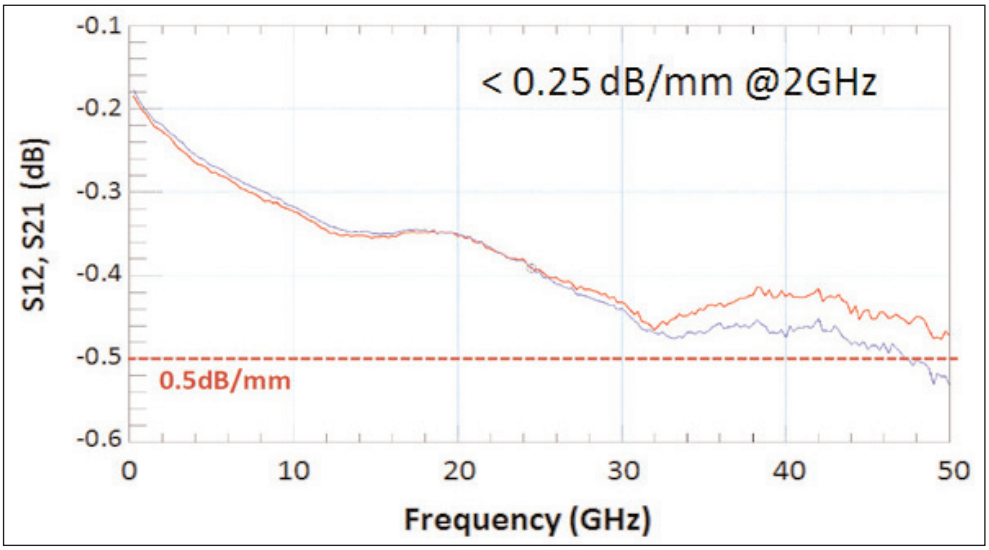



**Figure 1: RF losses in dB/mm measured on transmission line structures of an optimized RF GaN-on-Si HEMT structure (courtesy of F Medjdoub, IEMN, Lille, France).**

Two flavours of RF GaN power technologies exist today: GaN-on-SiC for specialized highest-performance applications and GaN-on-Si for cost-sensitive volume applications. With the latest technology improvements for GaN-on-Si, the performance gap for these two technologies for RF power seems to disappear.

Last but not least, GaN-on-Si technology has begun to attract significant attention for gas- and bio-sensing applications such as air quality, medical (glucose monitoring or cancer diagnosis), and automotive anti-pollution systems for $NO_x$. The added value that GaN can provide here over Si-based sensors is its unique capability to operate in harsh environments and high temperatures while performing at orders-of-magnitude better sensitivity.

## The GaN value chain matures

Typically, new industries are fragmented and consolidate as they mature. We do see this happening today for the wide-bandgap technologies like SiC and GaN. Large silicon integrated device manufacturers (IDMs) that have a mature silicon power and RF product portfolio start adding GaN and SiC technologies. This will give them a big advantage as they now can address any requirement, from the most cost-sensitive to the highest-performance application over the full range of voltage breakdowns. The scale of these formerly silicon IDMs will allow them to also become dominant players in compound semiconductor technology. Furthermore, silicon foundries start adding GaN-on-Si process offerings to diversify their technology portfolio with high-value and high-performance processes. Altogether, these are very encouraging indicators that GaN is at the onset of facing mainstream availability and adoption in many different applications and markets.

These next paragraphs will highlight the latest technical advances in both GaN epiwafer and device technology for power switching and RF power applications. EpiGaN is at the forefront of this research area and has achieved significant technological milestones that will help drive GaN technology into the next stage of commercialization.

## Advances of GaN technology for RF power

For GaN-on-Si to compete directly with GaN-on-SiC in high-end RF applications, there are a few technical hurdles to overcome. Some are intrinsic, such as the lower thermal conductivity of silicon compared to SiC, which can be overcome by an aggressive reduction of the substrate thickness during device processing. Another major hurdle is the creation of a conductive interface between the silicon substrate and the III–nitride layer stack during the epitaxial deposition. This parasitic conduction path causes the dissipation of RF signals. Transistors manufactured on such lossy substrates will never be able to attain high efficiencies.

At EpiGaN we have developed a robust interface technology to mitigate this conductive path, reducing RF signal loss on GaN-on-Si at 2GHz from 1.5dB/mm or more to below 0.25dB/mm, which is very close to the performance that can be obtained on the much more expensive GaN-on-SiC material. Even around 50GHz, the RF signal loss stays below 0.5 dB/mm (Figure 1). In the near future EpiGaN will validate the feasibility of high-resistivity 200mm Czochralski (CZ) silicon substrates for RF power applications. This should ultimately drive cost down further for RF power GaN-on-Si technology and will ease its entry in today's mainstream 200mm lines, both at silicon integrated device manufacturers and at silicon foundries.

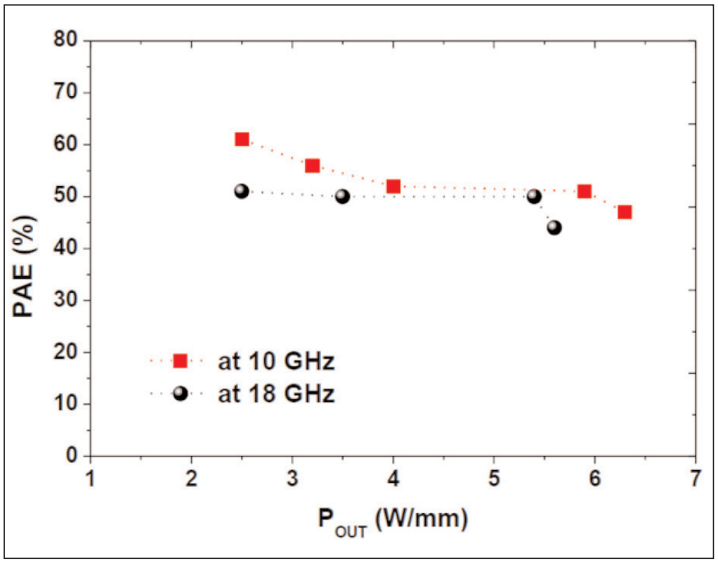



**Figure 2: 0.15µm gate-length AlN/GaN-on-SiC power measurements at 10GHz and 18GHz (courtesy of F Medjdoub, IEMN, Lille, France).**

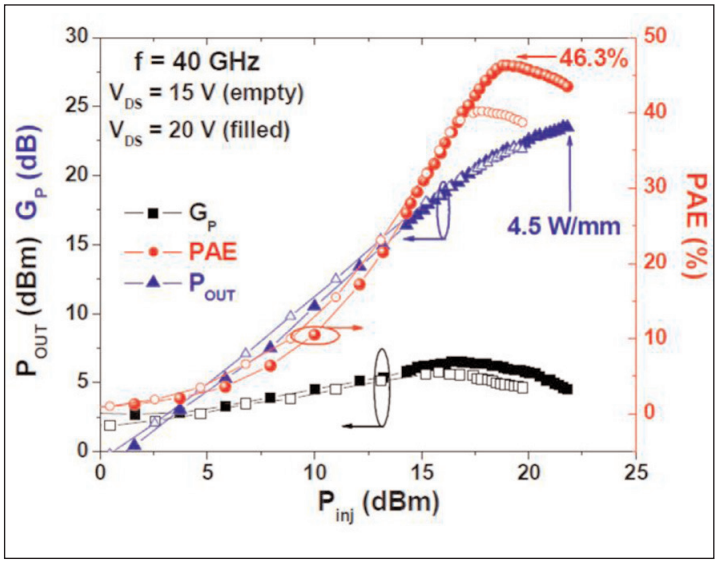



**Figure 3: CW power performance of a 2x25µm AlN/GaN HEMT at f = 40GHz with $V_{DS}$ = 15V and 20V (courtesy of F Medjdoub, IEMN, Lille, France).**

## The beauty of binary AlN barriers

In parallel, EpiGaN has been developing HEMT heterostructures featuring pure AlN barrier layers in combination with an in-situ SiN cap layer to complement and eventually replace their typical AlGaN counterparts. With this configuration, it is possible to reduce the thickness of the barrier from typical values of around 20nm down to only 4nm. This allows bringing the transistor's gate very close to the densely populated channel, thus maximizing the electrostatic coupling between the two (i.e. improved gate control) and resulting in far superior RF transistor characteristics. The so-called 'short-channel parasitic effects' — i.e. reduction of the transconductance due to a poor gate length/gate-to-channel distance aspect ratio (ideally >=15) when scaling transistor gates below 0.15µm — are supressed drastically. In addition, the AlN barrier maximizes the inherent piezoelectric effect in this material system, which leads to carrier densities >$2x10^{13}cm^{-2}$ in the transistor's 2DEG (two-dimensional electron gas) channel. This boosts power densities and, with an appropriate thermal chip layout, significant chip size reductions are achievable.

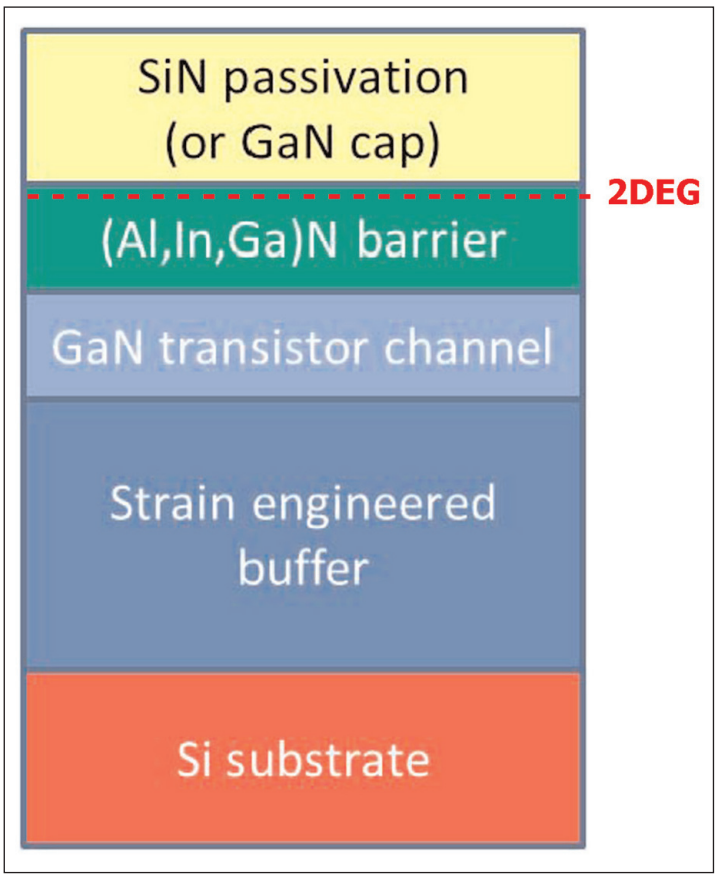



**Figure 4: Typical GaN-on-Si HEMT structure.**

Collaborators at IEMN–CNRS have manufactured prototype transistors on EpiGaN's GaN-on-SiC RF wafers that show a power density above 5W/mm together with a power-added efficiency (PAE) above 50%, at an operating frequency of 18GHz (Figure 2). This level of performance is even maintained at much higher frequencies: at 40GHz, transistors with 120nm gate length exhibited power gain cut-off frequencies above 230GHz at $V_{DS}$ = 20V. A 2x25µm AlN/GaN HEMT still produced a peak output power density of 4.5W/mm with an associated peak PAE of 46.3% at 40GHz.

## GaN-on-Si technology for 600V power switching

In power switching applications, GaN is usually introduced to address the 600V node of the market, because there silicon technology has reached fundamental physical limits that can no longer be overcome. A typical layer stack for these applications consists of a buffer stack grown on the silicon substrates, typically several microns thick, covered by an active part consisting of a classical GaN/AlGaN HEMT heterostructure (Figure 3).

Even though it is the active HEMT part that will be processed into switching transistors, the buffer stack fulfils a number of important functions: first it serves as a mechanical absorber to take care of naturally induced stress between the substrate and the GaN material, second it needs to block leakage currents between the grounded substrate and the high-voltage nodes of active switching devices, and last it needs to be free of undesirable charge trapping sites to which the active HEMT devices are very sensitive (and cause an increase in the transistor's resistance while in operation). The latter issue becomes even more severe at higher operating temperatures.

EpiGaN's latest generation of high-voltage buffer technology fulfils all three requirements. The 650V epiwafers are flat, with a bow of less than 50µm. They have negligible vertical leakage currents below 1µA/mm$^2$ up to 650V, and in both polarities, the latter aspect enabling new on-wafer topologies such as integrated half-bridges (Figure 5). Finally, EpiGaN has recently demonstrated that, even at 150ºC and when operated at 600V, there is no change in transistor resistivity compared to the steady state — thus the dynamic $R_{ds,on}$ effect is completely eliminated (see Figure 6).

## New device features enabled with EpiGaN's in-situ SiN technology

In the past few years EpiGaN has developed and optimized a solution for sealing the top of the GaN-on-Si wafers directly after growth by means of an in-situ-grown silicon nitride (SiN) passivation layer. As a consequence, there is no exposure of (Al,Ga)N layers to the fab environment, which will facilitate the entrance of GaN-on-Si technology into silicon CMOS fabs. EpiGaN pioneered this in-situ SiN surface passivation and now applies it to much broader purposes, among them a unique gate dielectric with a smooth and contamination-free surface.

This in-situ SiN capping layer also controls the filling of the surface states during device operation. SiN can provide enough charge to neutralize the surface charge of the AlGaN barrier layer in a GaN-on-Si device so that its surface potential no longer contributes to 2DEG depletion. Another beneficial effect is that the SiN layer adds device stability at elevated temperatures.

In combination with the in-situ SiN deposition it is possible to replace the AlGaN layer with a pure AlN layer without material degradation, as described in the previous paragraphs. For such a SiN/AlN/GaN layer design, sheet resistance falls well below 300Ω/sq. This low resistance enables the fabrication of transistor devices with higher current densities — and hence a smaller device at lower costs for the same current rating.

**Figure 6: Dynamic $R_{ds,on}$ suppression at 150ºC in latest generation of EpiGaN's HV650 GaN-on-Si products.**

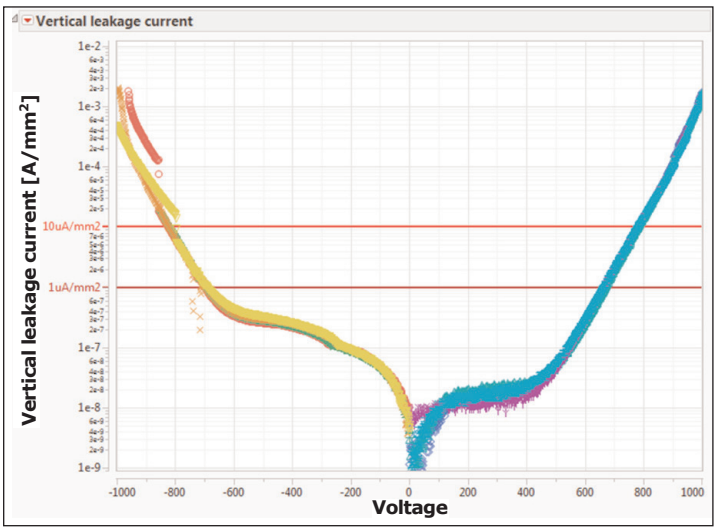



**Figure 5: Vertical leakage current of 650V GaN-on-Si HEMT with <µA/mm$^2$@650V in forward & reverse bias.**

## Conclusion and outlook

GaN technology will come to the masses — no doubt about that. The value proposition that GaN brings to the table is simply too attractive and it has already started to spur innovations in many existing applications and markets such as RF power and power switching. In parallel, emerging applications will appear for which GaN technology is an enabler, for example in markets such as unique medical and chemical sensors.

Reaching true mass-market adoption of GaN technology will require a mature supply chain and ecosystem that is not in place today. However, the big industry players are positioning themselves to build a solid supply chain for GaN device manufacturing as it becomes more and more evident that GaN owns the future, and incumbent silicon and GaAs will be displaced to a large extent. ■

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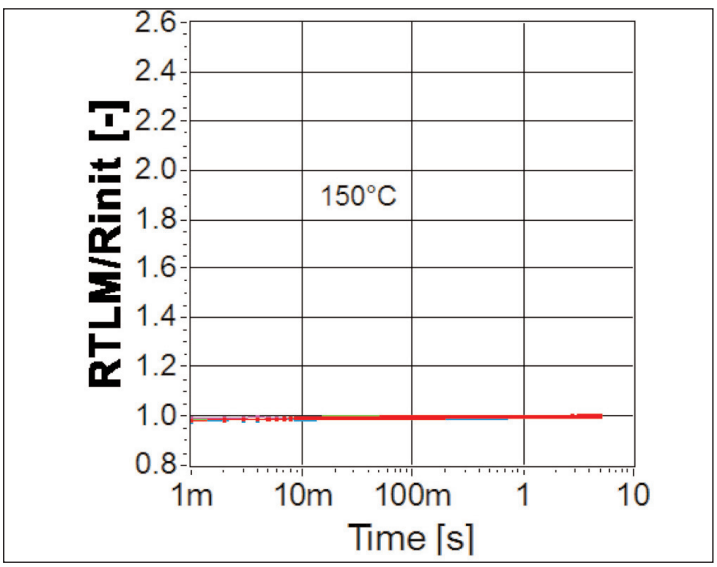
## Acknowledgment

The authors thank professor F. Medjdoub and his team at IEMN–CNRS, Villeneuve d'Ascq, for the device data.



# Normally-off gallium nitride power transistor on (110) silicon

**Researchers see high potential for monolithic wafer-level integration of GaN power and CMOS electronics in first demonstration of technology.**

Researchers in Korea have reported a normally-off metal-oxide-semiconductor heterostructure field-effect transistor (MOS-HFET) fabricated from aluminium gallium nitride/gallium nitride (AlGaN/GaN) material grown by ammonia ($NH_3$) molecular beam epitaxy (MBE) on (110) oriented silicon (Si) substrate [Sang-Woo Han et al, IEEE Electron Device Letters, published online 25 October 2016].

The team from Hongik University, Hanyang University and Seoul National University comments: "Demonstration of normally-off device or breakdown voltage characteristics has not been reported yet on GaN-on-Si(110) wafers to the best of our knowledge."

The researchers believe the devices have a "high potential" for power device applications and monolithic wafer-level integration of GaN power and Si (110) complementary MOS (CMOS) electronics.

Normally, epitaxial layers for GaN power transistors are grown on (111) Si. By contrast, high-performance CMOS is fabricated on

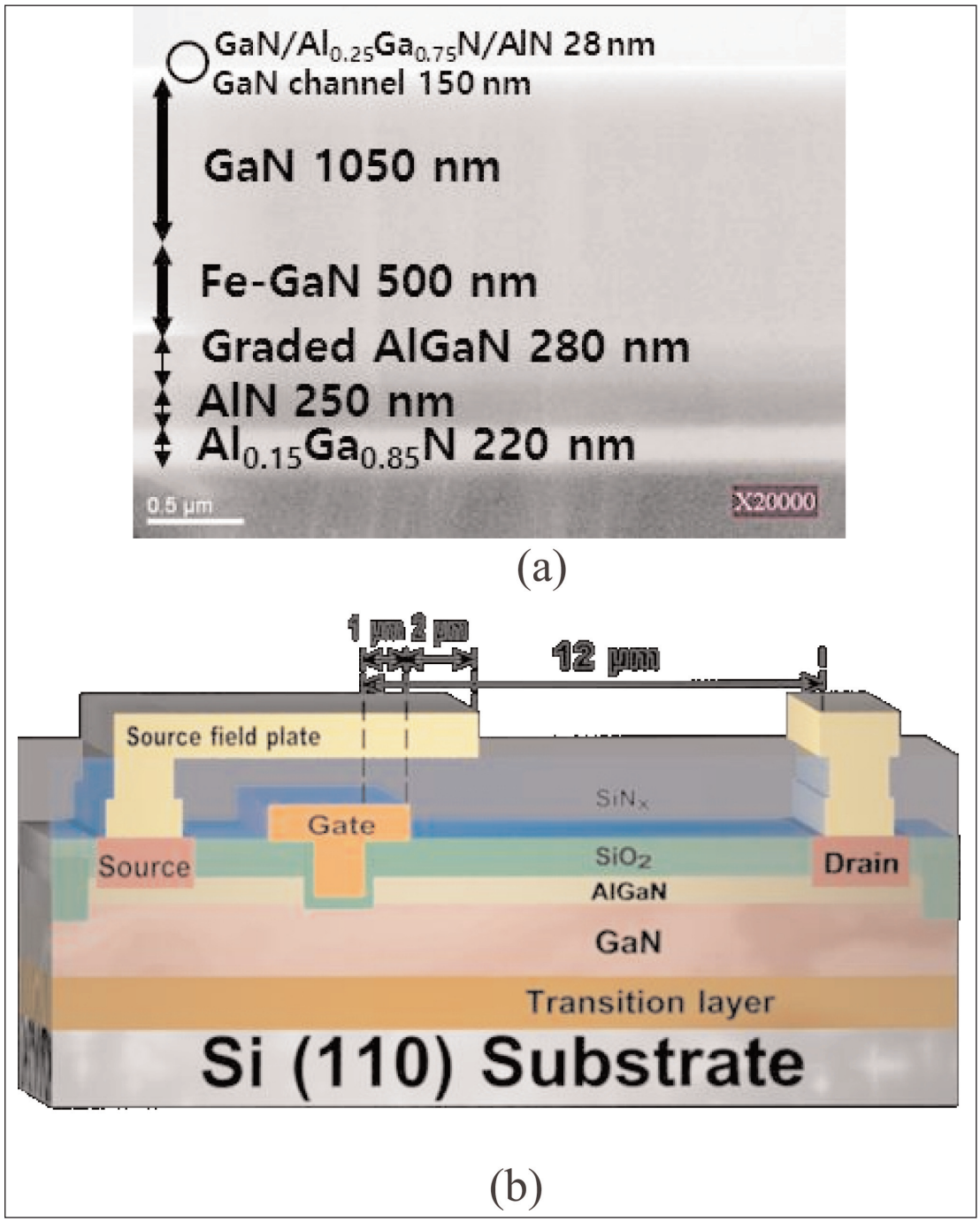



**Figure 1. (a) Epitaxial structure and (b) schematic cross-section of fabricated AlGaN/GaN-on-Si(110) MOS-HFET.**

(001) Si. The (111) crystal orientation of silicon has very poor electrical performance, blocking integration of GaN power with Si CMOS. The (110) Si orientation has a good structure for AlN seed layer growth and a hole mobility that is even better than the standard (001) Si orientation that is conventionally used for CMOS.

GaN power devices benefit from high breakdown fields and high electron mobility. Normally-off transistors are preferred for reduced power consumption and fail-safety. Growth on silicon should reduce material costs. Also, most commercial power devices are presently produced using silicon technology.

CMOS electronics tends to have a tighter thermal budget, compared with GaN-based devices. Ion implants, for example, suffer from dopant diffusion when subjected to raised temperature. MBE GaN growth processes generally run at lower temperature compared with the more popular metal-organic chemical vapor deposition (MOCVD).

The epitaxial structure (Figure 1) was grown on p-type Si (110) substrate in nitrogen-rich conditions supplied by ammonia MBE. The AlN growth was carried out at 900°C and the GaN growth at 780°C.

The device isolation mesa was defined by inductively coupled plasma reactive-ion etch (ICP-RIE). Source and drain electrodes were titanium/aluminium/nickel/gold annealed at 820°C for 30 seconds in nitrogen. The gate region was defined by ICP-RIE down to the GaN channel. Plasma-enhanced chemical vapor deposition (PECVD) of 30nm silicon dioxide followed surface cleaning.

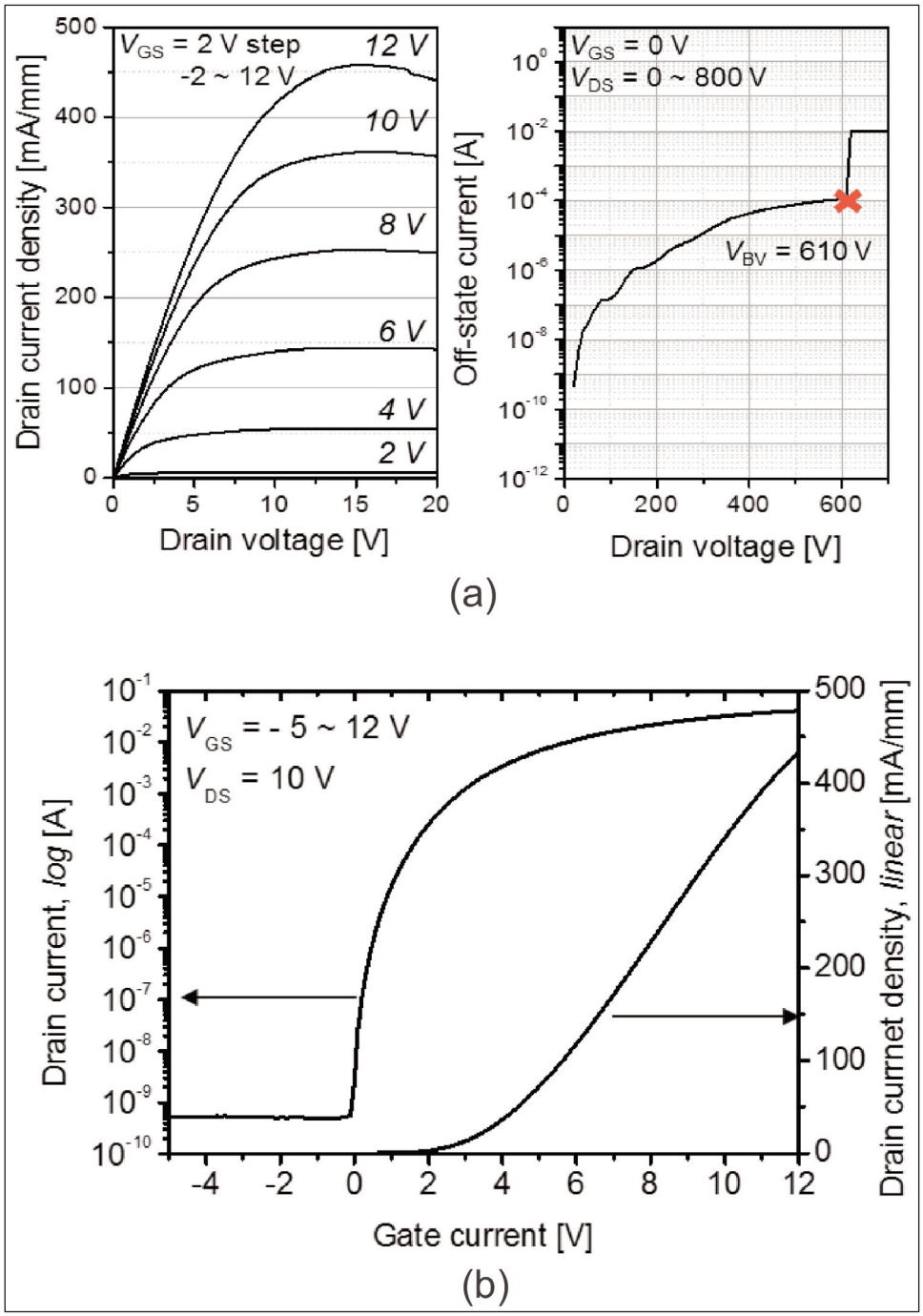



**Figure 2. (a) Output and (b) transfer characteristics of fabricated AlGaN/GaN-on-Si(110) MOS-HFET.**

The 2μm-long T-gate was nickel/gold with 1μm overhangs in each direction. The source–gate and gate–drain distances were 3μm and 12μm, respectively.

The device was then annealed in oxygen at 400°C for 10 minutes to improve oxide and interface quality. Passivation was provided by 200nm of silicon nitride on which source-connected field plates were deposited.

Hall measurements gave 1640cm$^2$/V-s electron mobility and 1.04x10$^{13}$/cm$^2$ carrier sheet density for the GaN channel.

The researchers describe their device as exhibiting "promising characteristics" with 460mA/mm maximum current density at 12V gate potential and 2.84Ω-cm$^2$ specific on-resistance at 1V drain-bias (Figure 2). Off-state breakdown (0V gate) occurred at 610V. The on/off ratio was 10$^8$. The threshold voltage was +1.5V with a 1mA/mm threshold. Often GaN devices are normally-on (current at 0V gate potential) or only weakly normally-off (small positive threshold) with the 'off' state referring to a negative gate potential.

These performance parameters are comparable with those obtained for conventional GaN-on-(111) Si, according to the researchers. ■

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# Crystal orientation and gallium nitride trench MOSFET performance

**Non-polar m-plane interface doubles drain current over a-plane devices.**

University of California, Santa Barbara (UCSB) in the USA and Mitsubishi Chemical Corp in Japan have developed gallium nitride (GaN) trench metal-oxide-semiconductor field-effect transistors (MOSFETs) with different orientations with respect to the crystal structure [Chirag Gupta et al, Appl. Phys. Express, vol9, p121001, 2016]. The devices were oriented nominally in the nonpolar m-plane ($1\bar{1}00$) and a-plane ($11\bar{2}0$) directions, although the fabrication process was such that the real surfaces of the channel/oxide interface were at an angle to the true GaN crystal planes.

The m-plane devices had better performance compared with the a-plane MOSFETs. In particular, the drain on-current was doubled by orienting the devices with m-planes without increasing the off-current.

Gallium nitride has high critical electric fields for high breakdown voltages along with high mobilities and saturation carrier velocities. Trench MOSFETs are a favorable architecture for reduced on-resistance. High cell density is possible when these transistors are fabricated in hexagonal grids. The crystal structure of gallium nitride is also hexagonal, opening the possibility of performance enhancements through placing the devices in a particular geometric orientation.

The researchers comment: "Understanding the impact of the planes on the channel characteristics is crucial to improving trench-gate device design and performance. However, little is understood since the orientation of hexagonal packed GaN trench-gate MOSFETs has not been disclosed nor discussed in the literature. To the best of our knowledge, these investigations have not yet been pursued."

The epitaxial material with a p-type layer sandwiched between source–drain n-type layers was grown by metal-organic chemical vapor deposition (MOCVD) on sapphire (Figure 1). The 300nm thickness of the p-type layer constituted the gate length of the devices. Cleaning before the final n-type cap source-contact layer deposition aimed to strip magnesium from the surface, avoiding surface riding of magnesium atoms from the p-type region into the n-type regions. Surface riding refers to a layer of magnesium-rich material on the growth surface of the p-GaN, which can then reduce the effectiveness of subsequent n-type growth with silicon doping.

Fabrication began with trench reactive-ion etching of hexagonal structures aligned variously along the m-plane and a-plane directions. The taper angle of the trench sidewalls was 81°. The researchers point out that the MOS channel planes were not crystallographically accurate crystal planes.

The samples were cleaned with ultraviolet-ozone and hydrofluoric-acid treatments to remove residual silicon from interfaces. After annealing at 930°C to heal etch damage, the 50nm aluminium oxide ($Al_2O_3$) gate dielectric was applied using 700°C MOCVD. Further etching of the source, drain, and body regions was

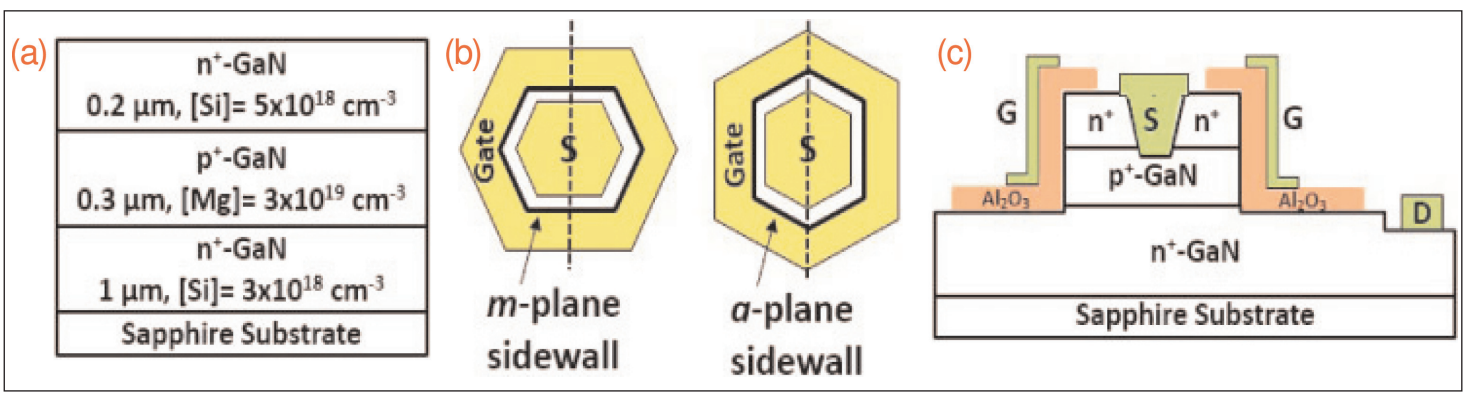


**Figure 1. (a) Trench-gate MOSFET epitaxial structure. (b) Hexagonal a-plane and m-plane-sidewall-oriented devices (top view). (c) Cross-sectional device schematic drawn at dashed lines shown in (b).**

performed to prepare for the titanium/gold source, drain and gate electrodes.

Normal trench MOSFETs have thick lightly doped drift regions to allow higher breakdown voltages to be reached. There was no drift region in the present device structure since its purpose was studying the effect of trench orientation.

The hexagonal structure gave a 180μm gate width. The thresholds of the devices were found to be +9.3V and +9.1V for a- and m-plane orientations, respectively. Positive thresholds imply normally-off behavior, as desired for power applications. However, thresholds are lower than the +26V predicted by one-dimensional simulations.

"Lowered experimental threshold values compared with estimated values have been observed by other researchers as well and were attributed to sidewall etch damage, which can cause nitrogen vacancies to form and act as donors," the team comments.

There was also some clockwise hysteresis in the threshold voltage value: 0.4V for a-plane and 0.2V for m-plane MOSFETs.

The on/off current ratios were around $10^7$ for both devices. The subthreshold swing was 480mV/decade for m-plane orientation and 630mV/decade for a-plane orientation. Low values are usually desired for sharp turn-on. Planar device structures can approach the lower theoretical limit of 60mV/decade at room temperature. Devices based on tunneling can go even lower.

The drain current response was higher in the m-plane devices by a factor of about 2 (Figure 2). The researchers estimate the peak channel mobility at 5cm$^2$/V-s for the a-plane MOSFETs and 10cm$^2$/V-s for m-plane devices.

The team comments: "Further investigations are needed to fully understand the reasons behind the low channel mobility, which could be a result of the fabrication process or fundamental interfacial quality (depending on the gate dielectric used) or both."

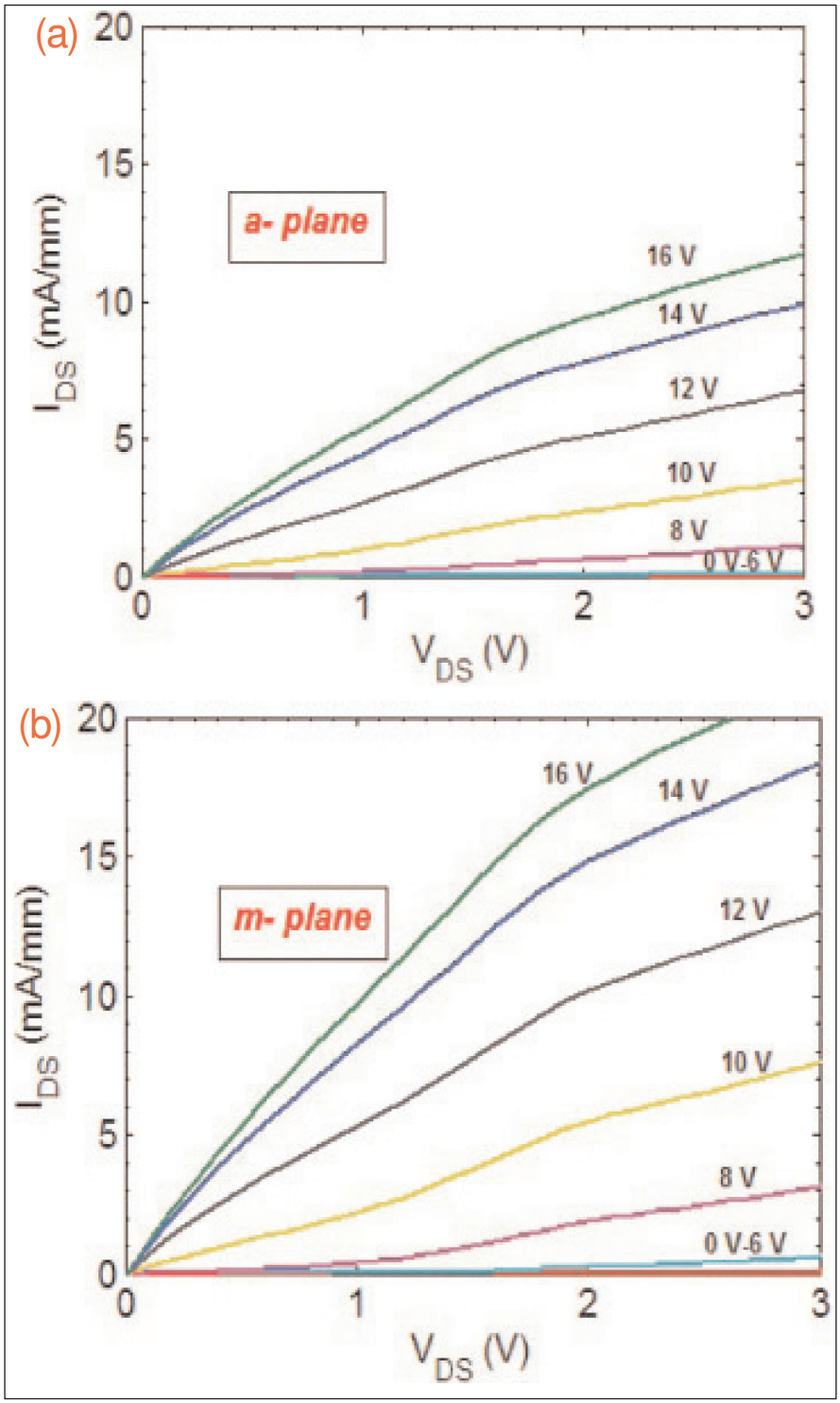


**Figure 2. Output drain current-voltage ($I_{DS}$–$V_{DS}$) characteristics for (a) a-plane and (b) m-plane-sidewall-oriented trench-gate MOSFETs at applied gate voltage range of 0–16V in steps of 2V.**

Low channel mobility has been an issue for aluminium oxide gate dielectric with planar MOSFETs. Higher channel mobilities have been obtained with silicon nitride or silicon dioxide gate dielectrics.

The team reports "marginal" variations of 10–15% for all performance parameters of the devices.

Other processing factors being equal, the researchers believe the differences in performance between the m-plane and a-plane MOSFETs could be due to different atom/bond configurations at the sidewall aluminium oxide/non-polar GaN interface. They add: "Higher hysteresis, higher sub-threshold slope, and lower channel mobility together indicate higher trap density and lower interfacial quality in a-plane-oriented devices compared to m-plane-oriented devices. ■

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# Advancing high-frequency and high-power electron device technology

**Mike Cooke reports on work presented at the IEEE International Electron Devices Meeting (IEDM) in December.**

The microelectronics industry is always looking forward to new technologies. The IEEE International Electron Devices Meeting (IEDM) forms an end-of-year report on progress towards many potential futures. Here we look at some of the achievements centered on III–V materials presented at the 62nd IEDM in San Francisco, USA (3–7 December 2016).

## InGaAs transistors

Lund University reported on indium gallium arsenide (InGaAs) tri-gate metal-oxide-semiconductor field-effect transistors (MOSFETs) [session 3.2] and vertical tunneling field-effect transistors (TFETs) on silicon [session 19.1]. The research team for the two pieces of work were different but did overlap in senior personnel.

The tri-gate MOSFET team claimed a record on-current ($I_{on}$) of 650μA/μm for its devices at 0.5V operation, compared with state-of-the-art III–V planar and non-planar MOSFETs (Figure 1). The off current ($I_{off}$) was 100nA/μm.

The devices were based on nanowires of $In_{0.85}Ga_{0.15}As$ formed by selective-area metal-organic chemical vapor deposition (MOCVD) growth on indium phosphide (InP) using a hydrogen silsesquioxane (HSQ) mask. A device with 75nm-long gate and 25nm nanowire width achieved subthreshold swings (SSs) as low as 66mV/decade and 61mV/decade at drain biases of 0.5V and 0.05V, respectively. The drain-induced barrier lowering (DIBL) was 65mV/V with drain current density of 1μA/μm, with the gate width being the three sides of the trigate.

A quality factor given by the ratio of the maximum transconductance (3mS/μm) over the subthreshold swing (66mV/decade) of 45 (units = (S-decade)/(V-mm)?) is also claimed as a record.

Moving on to Lund's vertical nanowire TFETs, as non-planar devices, dependent on band-to-band tunneling, they were able to access SS values below the 60mV/decade room-temperature limit for planar devices, dependent on thermionic emission effects.

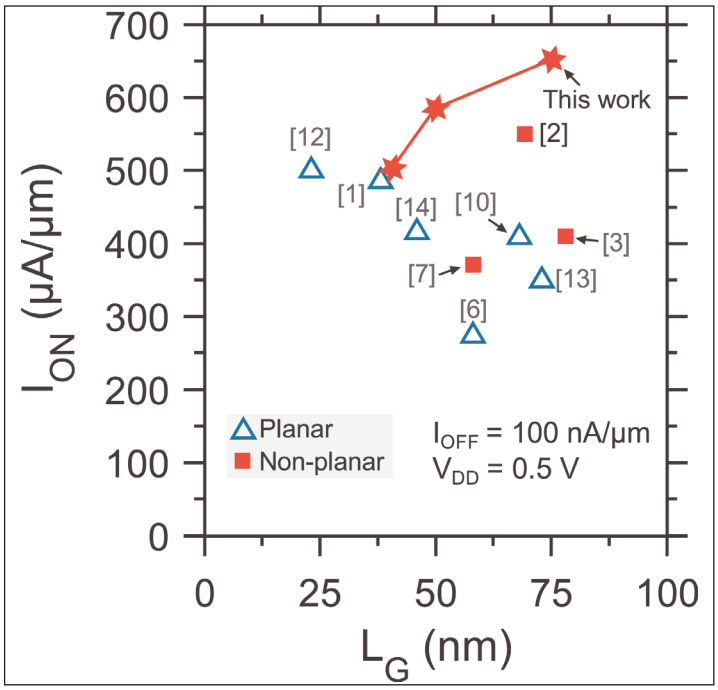


**Figure 1. Benchmark at 0.5V and $I_{off}$ = 100nA/μm.**

The 0.31μA/μm current level where SS was 60mV/decade was claimed by the researchers as a record high. The minimum value achieved was 48mV/decade. With a drain bias of 0.3V, the on-current was 10μA/μm and the off-current 1nA/μm.

The nanowire positions were defined by 40nm-diameter gold disks of 15nm thickness in arrays with 1.5μm spacing. The disks were patterned using electron-beam lithography. The substrate was a 260nm layer of highly doped InAs on high-resistivity (111) silicon. The nanowires included III–antimonide (III–Sb) compound semiconductor sections.

The gold disks constituted seeds for the metal-organic vapor phase epitaxy (MOVPE) growth of 200nm/100nm/300nm InAs/p-GaAsSb/p-GaSb nanowires. The bottom 100nm of the InAs part of the nanowire was doped n-type. The top, undoped section of InAs formed the channel of the fabricated TFETs.

The InAs section of the nanowire was selectively thinned from 40nm to 20nm diameter using digital etching cycles of ozone oxidation and citric acid. The etching had no noticeable effect on the p-GaSb section, but the p-GaAsSb was thinned from 35nm to 22nm.

TFETs (Figure 2) were fabricated with atomic layer deposition (ALD) of 1nm aluminium oxide ($Al_2O_3$) and 4nm hafnium dioxide ($HfO_2$) gate insulator, evaporation deposition of 15nm silicon dioxide ($SiO_2$) gate–drain spacer, sputtering of 60nm tungsten (W) that was etched into 260nm long gates, spin coating of organic material as gate–source spacer, and the formation of nickel/gold (Ni/Au) contact pads.

By reducing drain bias to 0.05V, the subthreshold swing could be reduced to 44mV/decade. The minimum SS with 1V drain bias was weakly temperature dependent, increasing from 38mV/decade to 54mV/decade between 223K and 323K. "This change is smaller than the one expected from thermionic emission, which further confirms that direct band-to-band tunneling is the dominant transport mechanism in these devices," the researchers comment.

University of Tokyo and JST–CREST reported on the use of lanthanum oxide ($La_2O_3$) as a gate insulator for InGaAs MOSFETs [session 12.5]. The team found that $La_2O_3$ gate insulation resulted in lower SS with 93mV/decade minimum and lower carrier trapping at interfaces than with $Al_2O_3$ or $HfO_2$. However, a 3x higher fixed oxide charge density in the $La_2O_3$/InGaAs interfaces gave lower channel mobility.

The epitaxial InGaAs material was grown on InP by MOVPE. The MOSFETs were fabricated through a gate-last process and source–drain Si ion implantation. The $La_2O_3$ was deposited by an ALD process with (tris(isopropylcyclopentadienyl)lanthanum ($La(iPrCp)_3$) and water ($H_2O$) precursors. The gate was W. The post-metal anneal temperature was 300ºC.

The researchers also claimed to have found for the first time ferroelectric behavior of the W/$La_2O_3$/InGaAs MOS structure. The ferroelectricity was revealed as counterclockwise hysteresis in capacitance–voltage (C–V) and polarization-electric field curves when the $La_2O_3$ thickness exceeded 10nm. Similar behavior was seen in W/$La_2O_3$/W metal–insulator–metal structures.

With 15nm $La_2O_3$ gate insulator, negative capacitance (NC) FETs were realized. A reduction in SS to 82mV/decade is attributed to the ferroelectricity. The researchers comment: "The steep slope characteristics due to the NC effect have been demonstrated, for the first time, in W/$La_2O_3$/InGaAs MOSFETs, which is very promising for realizing high-$I_{on}$ and small-SS logic applications."

Korea Institute of Science and Technology (KIST), Kookmin University, and Korea Advanced Nanofab Center (KANC) reported on a cost-effective epitaxial lift-off (ELO) process for creating monolithic $In_{0.53}Ga_{0.47}As$ layers on silicon [session 25.4]. The team hopes that its method could contribute to incorporation of III–V devices in monolithic three-dimensional electronic structures on silicon, reducing signal delays and increasing transistor density.

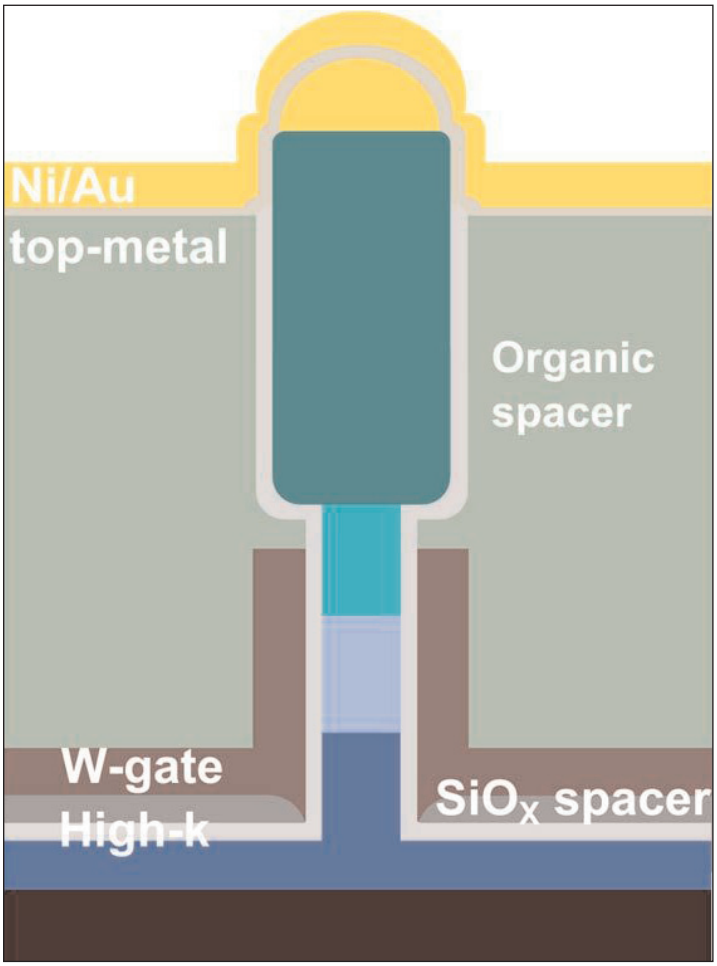


**Figure 2. Schematic of InAs/GaAsSb/GaSb TFET.**

The 20nm InGaAs layers were grown on AlAs sacrificial layers on InP (100). Direct wafer bonding (DWB) between the InGaAs and Si was made through 20nm yttrium oxide ($Y_2O_3$) layers on both surfaces. This gives an InGaAs on insulator (InGaAs-OI) structure.

The surface of the donor wafer containing the InGaAs layer was patterned to enable faster epitaxial lift-off through enlargement of the exposed area for undercutting and efficient release of gas bubbles from the AlAs hydrofluoric acid etch process. The typical area of the patterned sections was 100μmx100μm. While the InGaAs surface left by the release process was quite rough, this could be smoothed to 0.22nm root-mean-square roughness by cleaning with hydrochloric acid. A 40% reduced ELO time was enabled by a 1V electrical bias between the etch solution and target bonded wafer.

The researchers used the material to fabricate MOSFETs with 120mV/decade SS and an on/off current ratio of more than $10^6$. The researchers believe these values

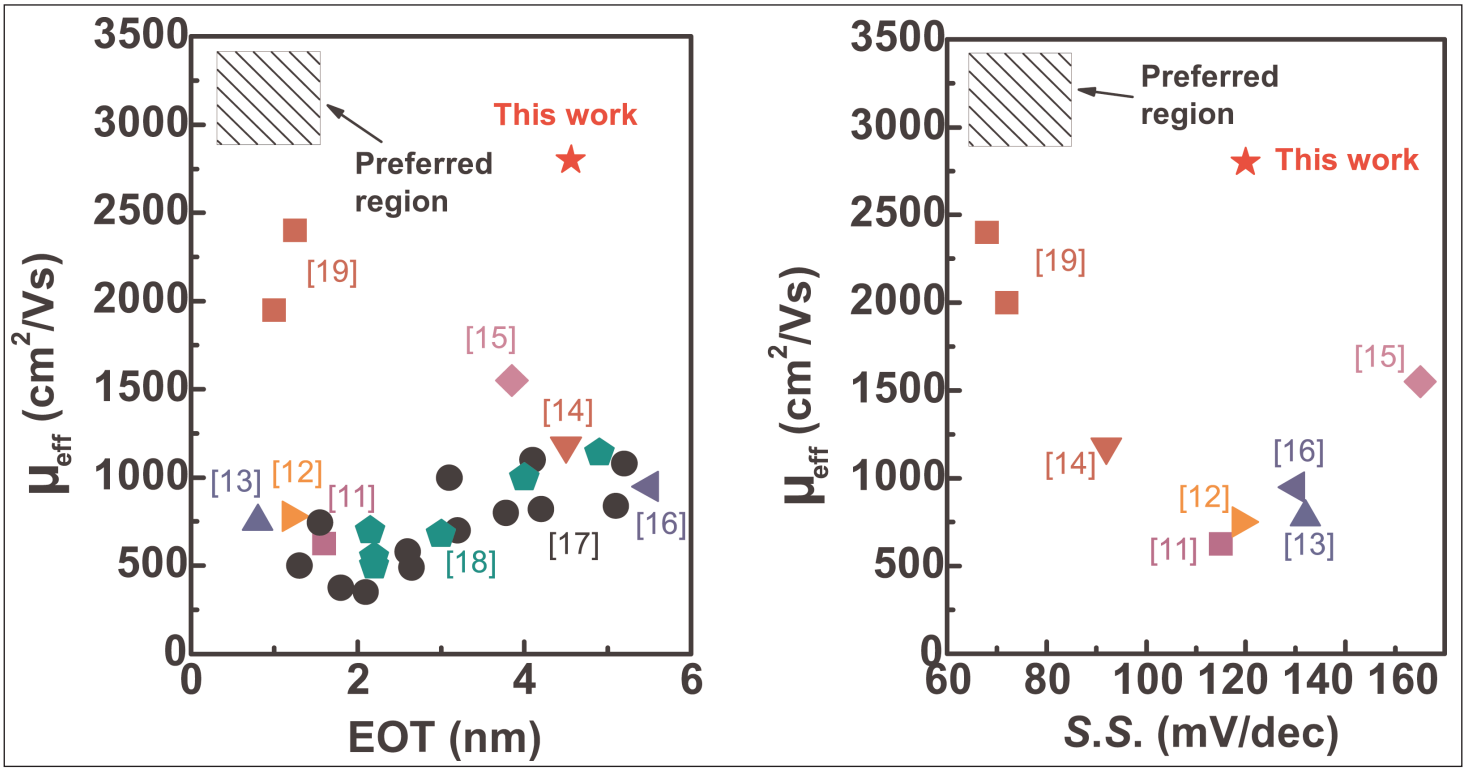


**Figure 3. Benchmarks of effective mobility as function of EOT/CET (left) and SS (right) for surface channel InGaAs MOSFETs at 3x10$^{12}$/cm$^2$ sheet carrier density.**

can be improved from the present thick 10nm/5nm $Y_2O_3/Al_2O_3$ gate insulator and unoptimized processes. The team comments: "These results highlight the first successful operation of InGaAs-OI MOSFETs fabricated by DWB and ELO." The peak effective channel mobility was 2800cm$^2$/V-s, claimed as a record high for given equivalent oxide thickness and SS (Figure 3).

The team also demonstrated re-usability of the InP donor wafer, creating transistors with similar performance as those produced from InGaAs layers grown on virgin wafers.

Massachusetts Institute of Technology claimed record self-aligned InGaAs MOSFET performance through mitigation of an anomalous instability mechanism [session 3.4]. According to the team, the anomalous instability arises from electric-field-induced fluorine (F) ion migration and passivation/depassivation of silicon dopants in n-InAlAs cap layers.

The researchers studied devices grown by MBE on InP. Finding that F reactive ion etch of n-InAlAs caused the anomalous instability, the researchers eliminated this material from the part of the structure subjected

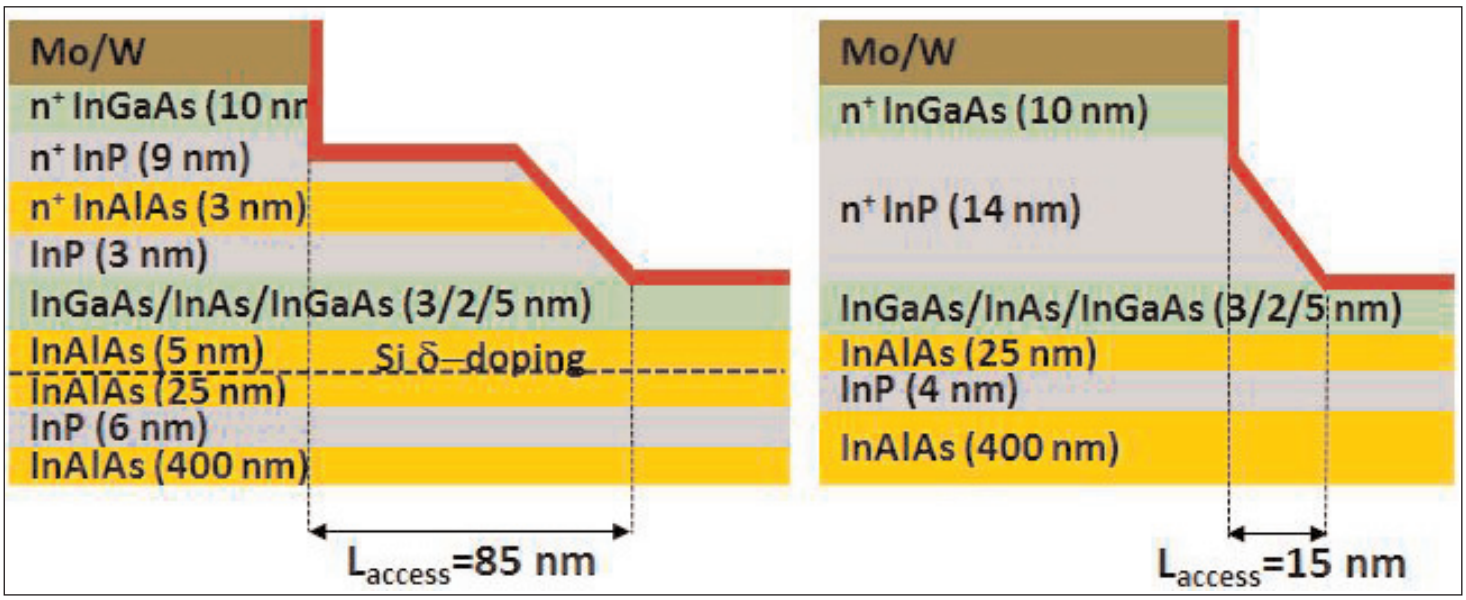


**Figure 4. Conventional (left) and alternative (right) device structure with n-InAlAs layer removed to avoid anomalous instability.**

to etching, using n-InP instead (Figure 4). The higher electron concentration in the access region of a 70nm-gate-length transistor enabled record low on-resistance of 190Ω-μm and transconductance of 3.45mS/μm, "the highest among InGaAs FETs of any kind," according to the team. The researchers add: "More significantly, the new device structure is far more stable."

**Table 1. HRL's mm-wave T-Gate GaN MMIC nodes**

| Quantities | T2 | T3 | T4A |
|---|---|---|---|
| Gate length | 150nm | 40nm | 20nm |
| $f_T$ | 90GHz | 200GHz | 329GHz |
| $f_{max}$ | 220GHz | 400GHz | 558GHz |
| Breakdown | > 40V | > 40V | 17V |
| Minimum noise figure at 50GHz | 2dB | 1.2dB | 0.8dB |
| | SOA prior to NEXT | Advances under NEXT | |

The new structure gives a classic positive-bias temperature instability (PBTI) that can be explained as being due to electron trapping in the gate oxide.

A multi-national team reported on record minimum switching slope p-type TFETs using III–V and compound semiconductor heterostructures [session 19.6]. The team was variously associated with Pennsylvania State University, University of Notre Dame, Massachusetts Institute of Technology, Peter Grünberg Institute (PGI-9) and JARA-FIT, Forschungszentrum Jülich GmbH, IMEC, Kurt J. Lesker Company, and Taiwan Semiconductor Manufacturing Company (TSMC).

The III–V structure used p-type $In_{0.65}Ga_{0.35}As/GaAs_{0.4}Sb_{0.6}$ tunnel junctions. The group IV devices used a germanium tin ($Ge/Ge_{0.93}Sn_{0.07}$) structure. The gate oxide was applied to the $GaAs_{0.4}Sb_{0.6}$ and $Ge_{0.93}Sn_{0.07}$ parts of the TFETs. The researchers claim that the thinnest gate insulators demonstrate equivalent oxide thickness of ~0.8nm.

The group IV devices exhibited 10x lower interface trap density ($D_{it}$) compared with the group III–V PTFETs, This enabled the group IV PTFETs to achieve high $I_{on}$ and SS below the planar limit of 60mV/decade at 0.5V drain bias.

## GaN/SiC transistors

HRL Laboratories LLC reported on its work developing highly scaled GaN HEMTs and their incorporation into process flows for monolithic microwave integrated circuits (MMICs) [session 3,3]. HRL GaN HEMTs have reached state-of-the-art (SOA) cut-off ($f_T$) and maximum oscillation ($f_{max}$) frequencies exceeding 400GHz and 500GHz, respectively. HRL claims that its highly scaled GaN devices have five times higher breakdown voltage than transistors with similar high-frequency RF power gain in other semiconductor systems (Si, SiGe, InP, GaAs).

First-generation MMIC power amplifiers (PAs) achieved power-added efficiency (PAE) of 59% measured at 32GHz frequency with 3V bias and 24.3dBm output power. The researchers claim 15% higher PAE than the best reported for Ka-band (26.5–40GHz) MMICs, along with output power comparable to similarly sized GaAs pseudomorphic and metamorphic HEMT MMICs operating in the 2–3V range.

The researchers believe that their highly scaled GaN transistors could be "excellent candidates for MMIC PAs for next-generation 28GHz, 39GHz, and higher-frequency 5G mobile bands, because they would greatly extend battery lifetime in mobile handsets, due to their superior PAE compared to competing semiconductor technologies."

HRL Laboratories has been working in part under the Nitride Electronic NeXt-Generation Technology (NEXT) Defense Advanced Research Projects Agency (DARPA) program. The MMICs were developed based on HRL's latest T4A HEMT (Table 1) with reduced gate length of 20nm, boosting $f_T$ and $f_{max}$.

The MMIC process features microstrip and grounded coplanar waveguide (GCPW) interconnects, backside vias, 50Ω/square epi resistors, two metal layers with benzocyclobutene (BCB) interlayer interconnect dielectric with air-box shielding around active devices and $SiN_x$ capacitors.

The Ka-band PA reported at IEDM builds on work reported earlier in the year with low-noise amplifiers (LNAs).

University of California Santa Barbara (UCSB) claimed a record PAE of 27.8% for W-band (75–110GHz) N-polar GaN MISHEMTs [session 3.5]. The device was designed to mitigate dispersion. The associated output power density was 3.0W/mm and the peak gain was 7.4dB at 94GHz.

Panasonic Corp used GaN to create normally-off vertical transistors on GaN substrates with low specific on-state resistance of 1.0mΩ-cm$^2$ and high breakdown voltage of 1.7kV [session 10.1]. "The vertical GaN transistor with p-GaN/AlGaN/GaN semi-polar gate structure exhibits high threshold voltage of +2.5V and stable switching operation of 400V/15A," the team reports.

The devices (Figure 5) featured a V-groove between the two source electrodes with re-grown undoped GaN and AlGaN layers and p-GaN gate. The initial epitaxial structure included a p-GaN well and a carbon-doped semi-insulating GaN layer. The carbon-doped layer formed a hybrid blocking layer with the p-GaN gate structure, reducing punch-through/off-current leakage. The use of the groove avoided the creation of large electric fields from charge polarization effects that

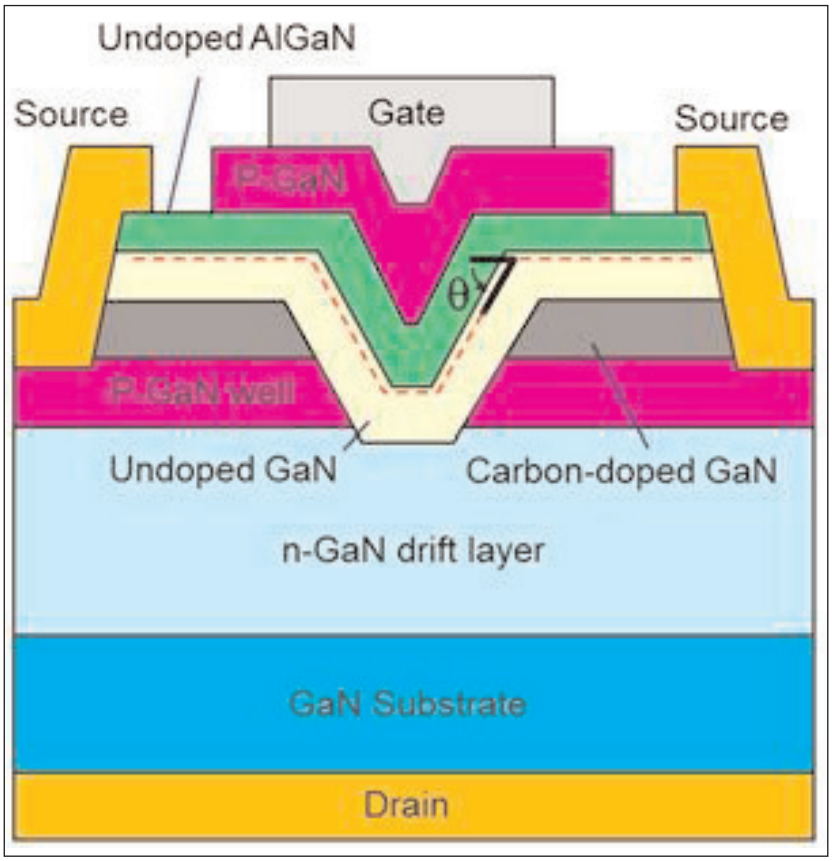


**Figure 5. Schematic of vertical GaN transistor with p-GaN/AlGaN/GaN semipolar gate structure.**

occur in normal c-plane material. This reduced the sheet carrier concentration of the 2DEG at the AlGaN/GaN interface, increasing the threshold voltage in a positive direction, giving true normally-off behavior.

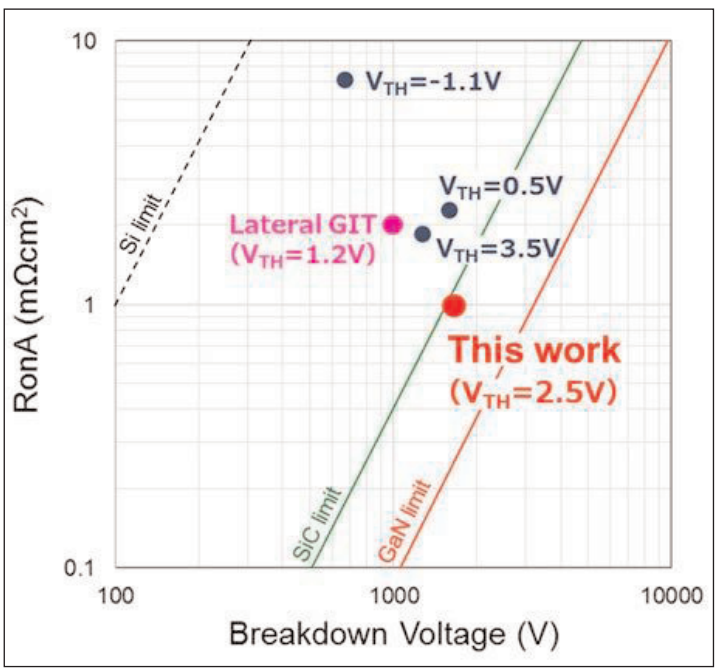


**Figure 6. Specific on-resistance ($R_{on}$ x Area) and breakdown voltage of vertical GaN transistor, compared with lateral p-type gate and state-of-the-art GaN-based vertical transistors.**

The epitaxial growth and re-growth were achieved by MOCVD. The metalization consisted of titanium/aluminium (Ti/Al) source, palladium/gold (Pd/Au) gate, and Ti/Al/Ti/Au drain. The drain electrode was deposited on the back of the GaN substrate to give a vertical conduction structure.

The device beat the theoretical limit for silicon carbide transistors in terms of on-resistance and breakdown voltage trade-offs (Figure 6). The Panasonic transistor also showed good stability during off-state bias stress tests at 400V drain and 125ºC temperature. The researchers report: "The off-state leakage current and threshold voltage is stable over 300 hours at present indicating further no-change after extension of the testing period. To the best of authors' knowledge, this is the first demonstration of the stable gate performance in vertical GaN transistors."

Massachusetts Institute of Technology, Singapore–MIT Alliance for Research Technology and IQE RF LLC reported on vertical GaN Schottky rectifiers, claiming "greatly enhanced reverse characteristics ($10^4$-fold lower leakage and 700V breakdown voltage) while maintaining a good forward conduction, with high-temperature (250ºC) operation and fast switching capability" [session 10.2].

The devices (Figure 7) consisted of trenches with corners rounded by a special tetramethylammonium hydroxide (TMAH) treatment to reduce electric field crowding, avoiding premature breakdown. Field rings were formed below the trench bottom with argon ion implantation. The field rings were designed to further

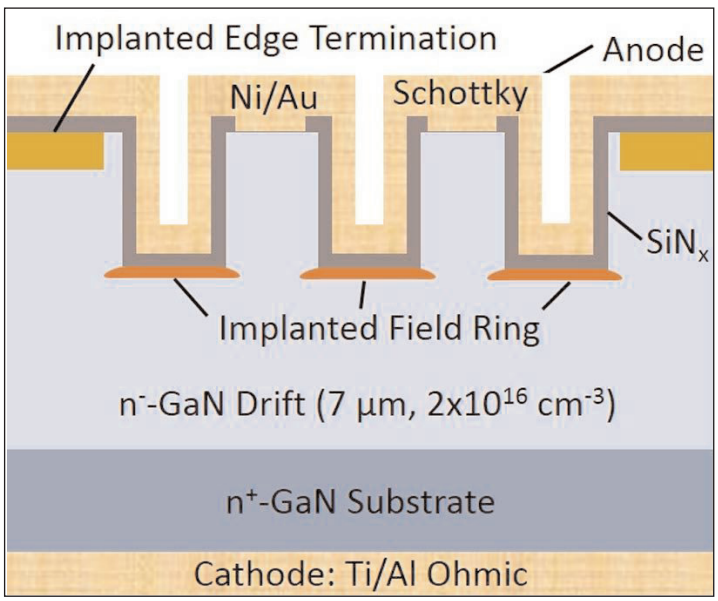


**Figure 7. Schematic of developed GaN vertical trench MIS barrier Schottky rectifier with implanted trench rings. Trench depth is 2µm.**

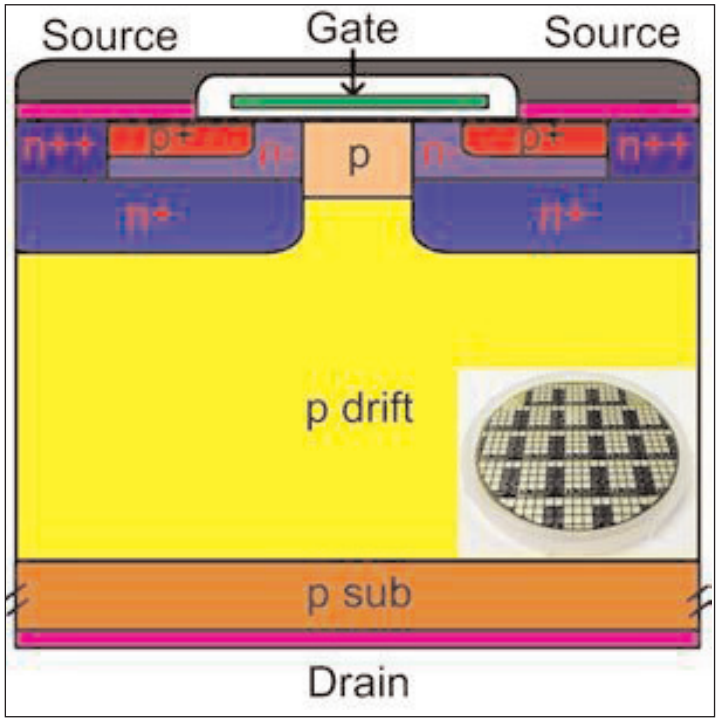


**Figure 8. Schematic cross-section and wafer of fabricated SiC p-MOSFET.**

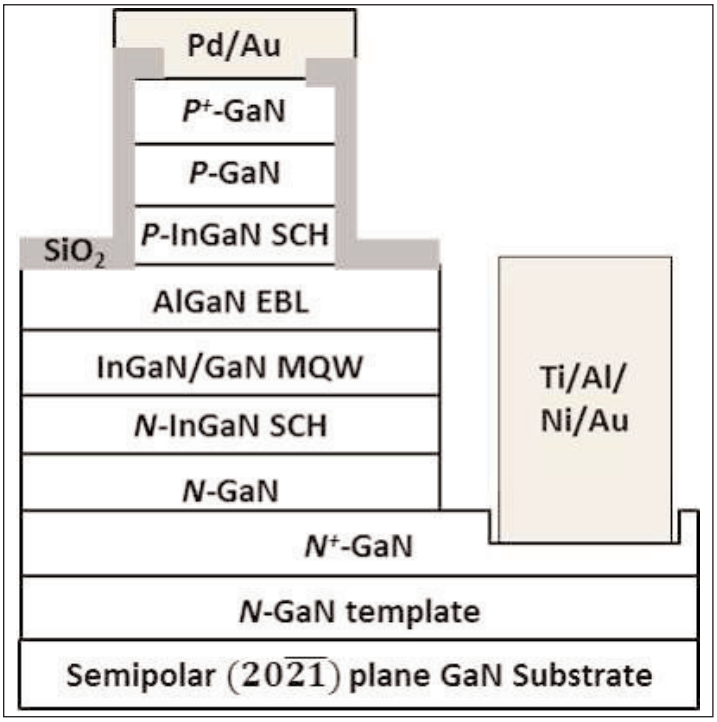


**Figure 9. Cross-section of the semiconductor optical amplifier laser diode (SOA-LD) structure.**

smooth the electric field stress. The next process step was plasma enhanced chemical vapor deposition of $SiN_x$. The $SiN_x$ at the top of the trench structure was removed and Ni/Au/Ni was deposited as Schottky contact. The other ohmic diode contact was formed on the back-side of the GaN substrate by annealed Ti/Al.

The researchers claim the devices exhibit the second best on-resistance versus breakdown trade-off, with a high on/off ratio of $10^6$ at 600V. The team also reports operation above 200ºC for the first time in a high-voltage GaN vertical Schottky barrier diode.

University of Tsukuba claims the first p-channel vertical 4H-SiC MOSFET fabrication. The breakdown voltage was more than 730V [session 10.7]. At the same time, short-circuit handling was 15% better than that of 4H-SiC n-channel MOSFETs. The researchers suggest applications could include high-frequency complementary inverters.

The MOSFET had a vertical structure based on the n-channel implantation and epitaxial devices (IEMOSFETs) developed by Japan's National Institute of Advanced Industrial Science and Technology (Figure 8). The substrate was Si-face p-type 4H SiC.

The highly doped ($4x10^{18}/cm^2$) $n^+$-type regions of the bottom part of the channel were formed with nitrogen ion implantation. The lightly doped ($5x10^{15}/cm^3$) n-type material was achieved using epitaxial growth of a 0.5μm layer. The p-type region of the junction FET was provided with aluminium ion implantation.

The gate oxide was a 50nm layer, followed by an annealed polysilicon gate electrode. The 3mmx3mm die was completed with metal deposition of source and drain contacts.

Although the on-resistance of the device is ten times higher than equivalent n-channel devices, the researchers suggest that "this could be greatly improved by adopting advanced cell design, such as super-junction, the trench gate structure and state-of-the-art fabrication technologies."

## Optoelectronics

King Abdullah University of Science and Technology, University of California Santa Barbara, and the King Abdulaziz City for Science and Technology have claimed the first experimental demonstration of a two-section semi-polar InGaN-based laser diode with monolithically integrated semiconductor optical amplifier (SOA-LD) [session 22.4].

The SOA-LD material (Figure 9) was grown on semi-polar (20$\bar{2}\bar{1}$) GaN using MOCVD. The device fabrication resulted in 300μm-long SOA and 1190μm-long laser diode sections (Figure 10). The quantum well active region was shared between the sections. The ridge waveguide was 2μm wide. Electrical isolation between the sections was achieved by trench etching and was aided by the high lateral resistance of the InGaN waveguide layer.

With the SOA unbiased (0V), the current threshold for lasing was 229mA. At 250mA the output power was 8.2mW. Biasing the SOA reduced the threshold current and increased output power. At 6V SOA bias, the threshold was 138mA and the output power 28.0mW at 250mA. The 6V SOA bias gives a gain of 5.32dB in output power. The wavelength of the emissions was

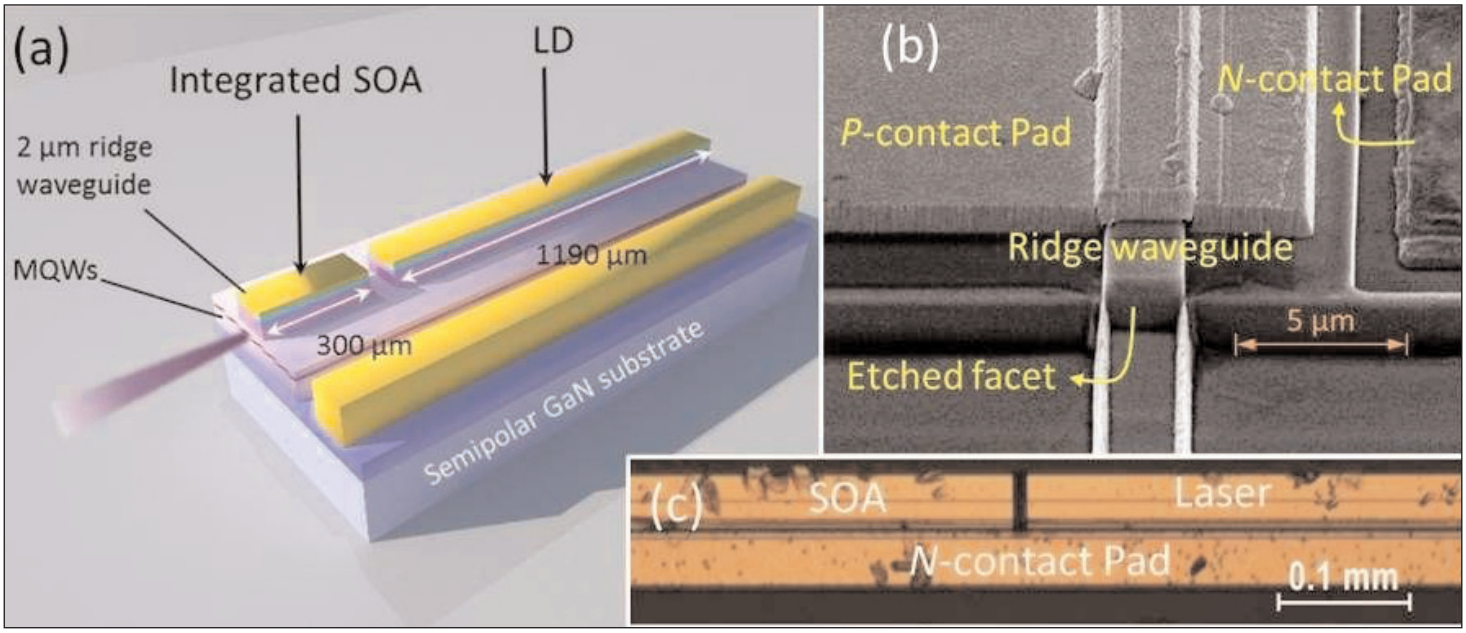


**Figure 10. (a) 3D illustration of integrated SOA-LD, (b) elevation-view scanning electron microscope (SEM) image showing the facet and (c) top-view optical microscope image.**

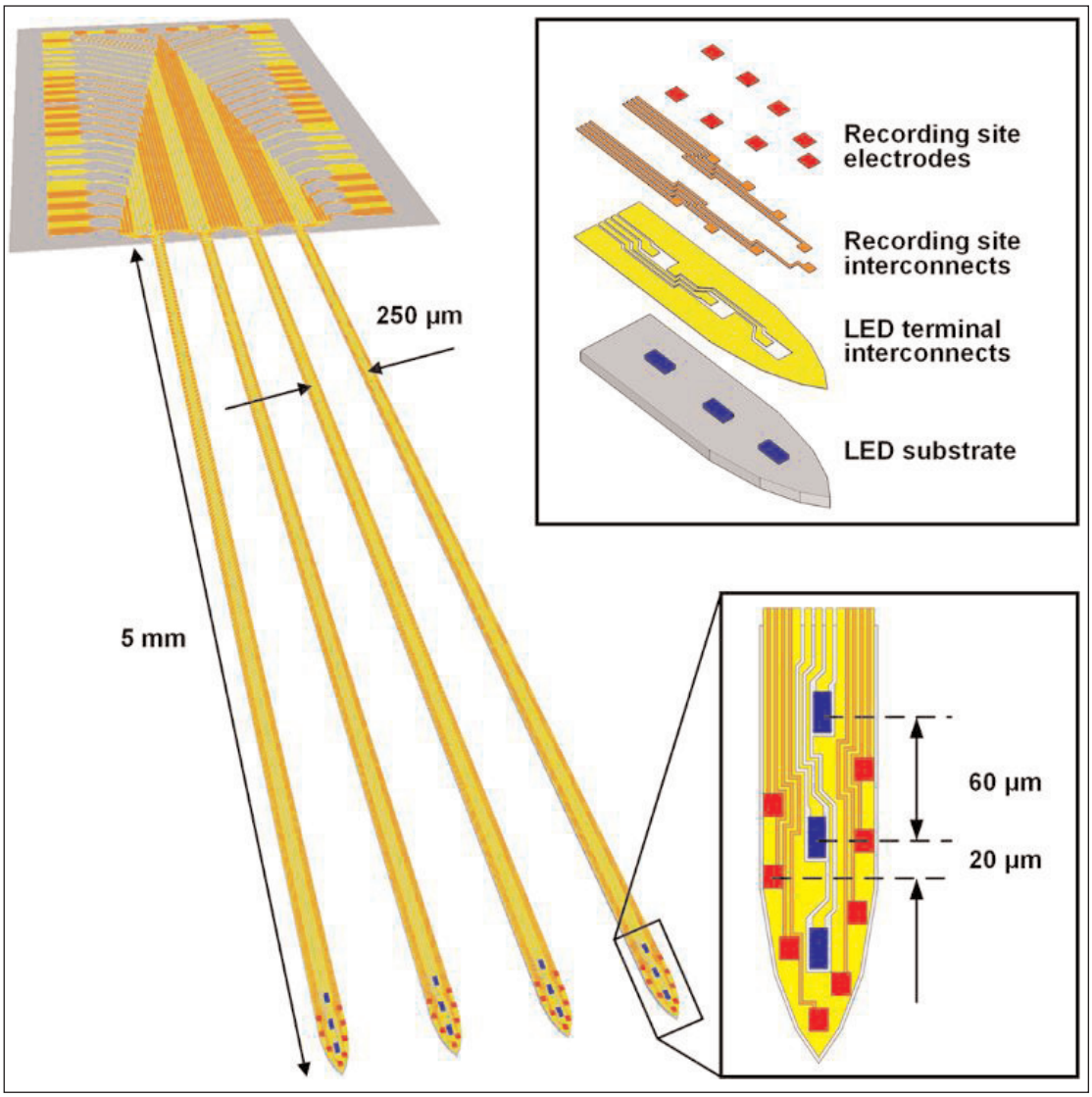


**Figure 11. Schematic of GaN-on-Si µLED optoelectrode for high-spatiotemporal-resolution optogenetics. Insets (top right) exploded schematic of optoelectrode tip and (bottom right) top view of optoelectrode tip.**

around 404nm.

The researchers also confirmed that the SOA was not acting as an independent laser. No laser emissions were seen up to 71mA — a density of 11.8kA/cm$^3$. The 138mA threshold of the laser diode section with 6V SOA bias corresponded to a density of 5.8kA/cm$^2$.

The researchers comment: "The SOA-LD, in the violet–blue–green spectrum range, enables high-power operation of the laser by extending the thermal roll-over to a significantly higher output power, and is promising for applications in visible-light communications, optical interconnects and photonics integrated circuits."

The team foresees solid-state lighting, optical storage, display, optical clocking, and sensing applications. Although these aspects are already covered to some extent by existing laser diodes, an integrated SOA would

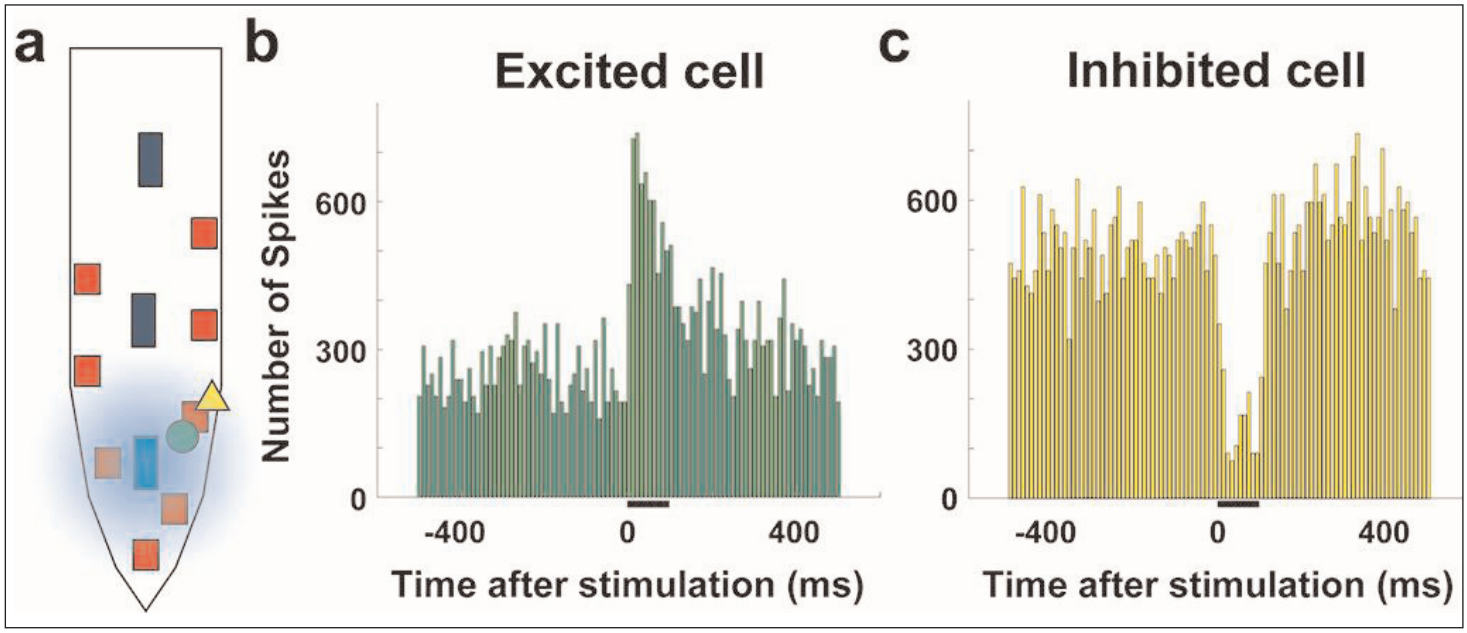


**Figure 12. In-vivo validation of light-induced neuronal modulation. (a) Locations of the interneuron (green circle) and the pyramidal neuron (yellow triangle) are identified for monitoring while optically stimulated by the bottommost μLED. (b) Peristimulus time histogram (PSTH) of optically activated interneuron (green circle). (c) PSTH of inhibited non-opsin expressing neuron (yellow triangle) which indirectly responds to optically activated interneuron.**

provide space- and power-efficient volume-manufactured components for high-capacity optical communications and high-power pulse generation.

University of Michigan and New York University reported on micro-machined GaN-on-Si μLED optoelectrodes designed for optical stimulation and electrical recording in the brains of genetically modified animals [session 26.5].

The optoelectrode consisted of four 5mmx70μmx30μm shanks (Figure 11). The shanks contained three 15μmx10μm GaN/InGaN μLEDs with 60μm pitch. The shanks also featured eight platinum/iridium site recording electrodes on their tips with 20μm pitch. The conducting interconnections consisted of two metal layers designed to suppress stimulation artifacts that arise from the n-GaN not giving a stable ground potential and thus affecting neighboring devices.

**The team foresees solid-state lighting, optical storage, display, optical clocking, and sensing applications. Although these aspects are already covered to some extent by existing laser diodes, an integrated semiconductor optical amplifier would provide space- and power-efficient volume-manufactured components for high-capacity optical communications and high power pulse generation**

The epitaxial material for the probes was MOCVD GaN/InGaN multi-quantum well structures on silicon supplied by NovaGaN. Following μLED and electrode fabrication, the optoelectrodes were sculpted by deep reactive ion etch bulk micro-machining. The optoelectrodes were then mounted on four-layer printed circuit boards.

The researchers report: "The measured optical output power suggests that, with as little as 13.8μA of injected current at 3.2V, the μLED is capable of providing 1mW/mm$^2$, which is the threshold irradiance for activation of channelrhodopsin-2 (ChR2) in neurons at the surface of μLEDs. At 4V, 1.9μW of optical power can be generated, which is equivalent to 12.7mW/mm$^2$ of radiant flux density at the surface of the μLED and is sufficient to stimulate neurons in more than the adequate volume around the μLED. The peak plug efficiency of the μLED was measured as 0.59±0.07%."

The in-vivo performance of the optoelectrode was tested by implantation in the hippocampal CA1 layer of a freely moving PV-ChR2 transgenic mouse (Figure 12).

STMicroelectronics, CEA-LETI, Vistec Electron Beam GmbH, and University of Grenoble Alpes claimed the first integration of a III–V/Si hybrid laser on the backside of a SOI wafer [session 22.2]. The aim was to preserve compatibility with Si-waveguide integration and with CMOS front-side metal interconnects, allowing passive and active photonic device integration. ■

*The author Mike Cooke is a freelance technology journalist who has worked in the semiconductor and advanced technology sectors since 1997.*

# Single III-V channel structure for complementary MOS transistors

**One indium arsenide/gallium antimonide compound semiconductor structure has been developed that can provide both n- and p-channel mobility.**

Researchers based in Japan have developed a single ultrathin body (UTB) structure of indium arsenide and gallium antimonide on insulator (InAs/GaSb-OI) on silicon (Si) that can function as a complementary metal-oxide-semiconductor (CMOS) field-effect transistor (FET) [Masafumi Yokoyama et al, Appl. Phys. Lett., vol109, p213505, 2016].

The team from University of Tokyo, NTT Photonics Laboratories and JST-CREST achieved high channel mobilities in their devices.

Present proposals for CMOS electronics involving high-mobility III-V compound semiconductors such as InAs and GaSb use separate 'co-integrated' transistor structures for the n- and p-channel transistors. Alternatively, the co-integration involves InAs (or InGaAs) for the n-channel and germanium (Ge) for the p-channel devices. Co-integration is complex and would increase production costs.

The Tokyo/NTT/JST-CREST group proposes combining InAs and GaSb layers in a single structure on silicon. The type of conduction was controlled by a back-gate potential. The n-channel forms at gate-insulator/

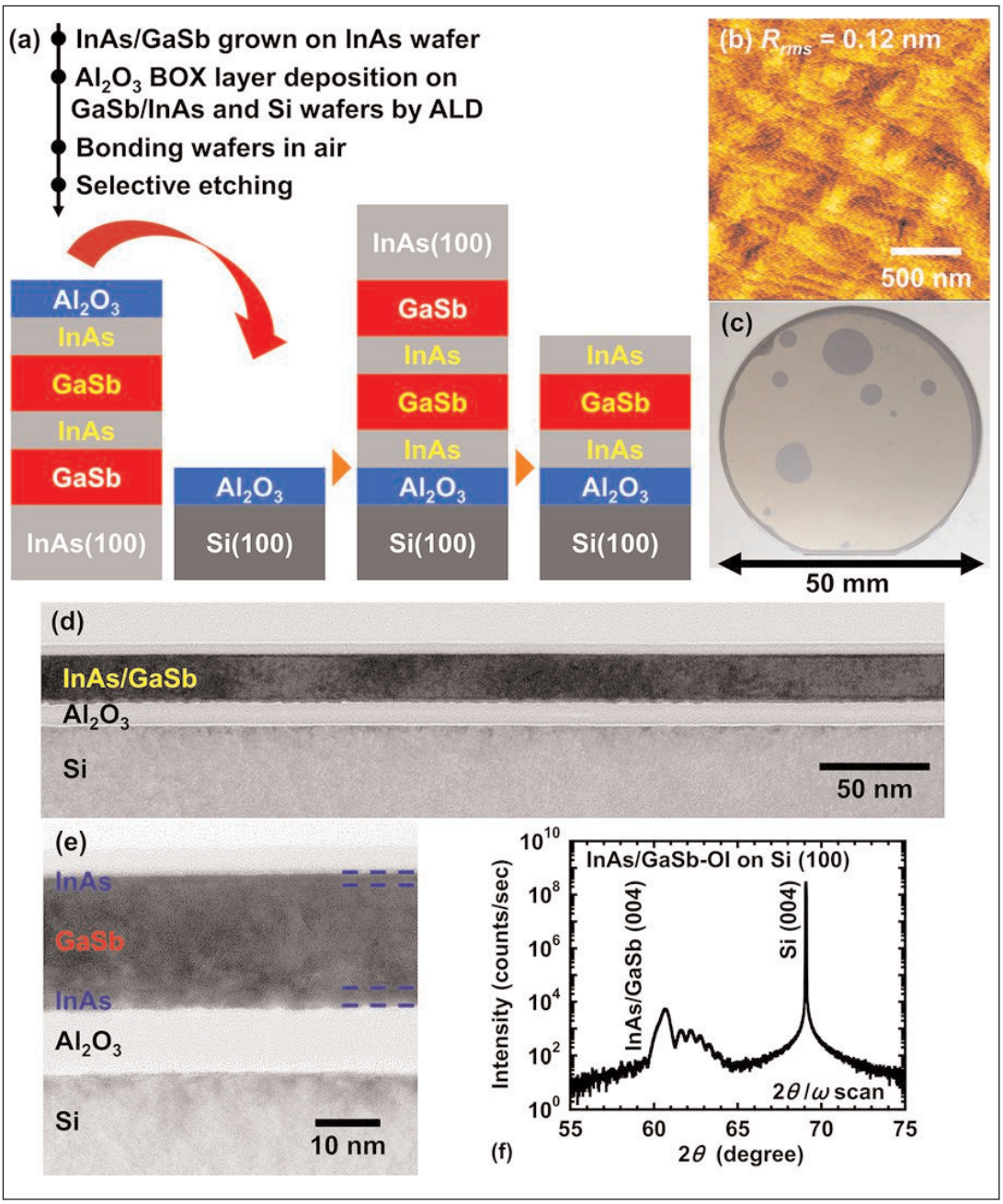


**Figure 1. (a) Fabrication of InAs/GaSb-OI on Si wafers. (b) Atomic force microscope (AFM) image of InAs/GaSb-OI on Si wafer surface with root-mean-roughness (rms) of 0.12nm. (c) Photograph of 50mm-diameter InAs/GaSb-OI on Si wafer. (d and e) Transmission electron microscope (TEM) cross-sections. (f) X-ray diffraction spectra.**

InAs interfaces, while the p-channel forms at GaSb/InAs interfaces. If the InAs layer is ultrathin, the hole mobility in the p-channel is enhanced due to size quantization, increasing the InAs energy gap to give insulating properties.

InAs/GaSb-OI layers were direct wafer bonded to (100) Si (Figure 1). The III-V layers were grown on InAs substrates. The bonding was made at room temperature in air between atomic layer deposition (ALD) aluminium oxide ($Al_2O_3$) layers on the III-V source and silicon wafers. Etching removed the InAs wafer and GaSb buffer layer, leaving the InAs/GaSb channel layers on the $Al_2O_3$ buried oxide insulator. X-ray analysis confirmed that the high crystal quality of the InAs/GaSb layers was maintained after the wafer bonding process.

Back-gate operation of an InAs/GaSb/InAs transistor with respective 2.5nm/20nm/2.5nm thicknesses gave a GaSb p-channel hole mobility of 159cm$^2$/V-s. The researchers say this value exceeds that for silicon p-MOSFETs in the high-carrier-density region. An InAs n-channel of 5nm thickness gave an electron mobility of 1200cm$^2$/V-s. Even with 2.5nm thickness the electron mobility, while lower, was still higher than UTB silicon-on-insulator devices with similar physical thickness, according to the team.

By using the back gate to set the p-/n-channel type of transistor, front-gate operation was also studied (Figure 2). A back-gate voltage of –2V was used for a GaSb-OI p-MOSFET and a voltage of –0.5V for an InAs-OI n-MOSFET. The InAs/GaSb/InAs structure was 2.5nm/20nm/2.5nm in both cases. Increasing the InAs layer thicknesses to 5nm created devices dominated by electron conduction: "Sufficient p-MOSFET operation cannot be achieved even under the strong hole accumulation condition with the negative back bias," the researchers report.

The team suggests that further optimization of InAs/GaSb thicknesses and transistor fabrication such as in the metal source-drain contact formation, along with improvement of InAs/GaSb channel material quality, could reduce off leakage current between source and drain. These factors could lead to CMOS operation with constant back-gate potential.

Also, device off-current was too high for applications. Even if further refinement such as thinning the GaSb and InAs layers were not sufficient, the team suggests that use of InGaAs and GaAsSb alloys could reduce off-current by suitable adjustments of band offsets. ■

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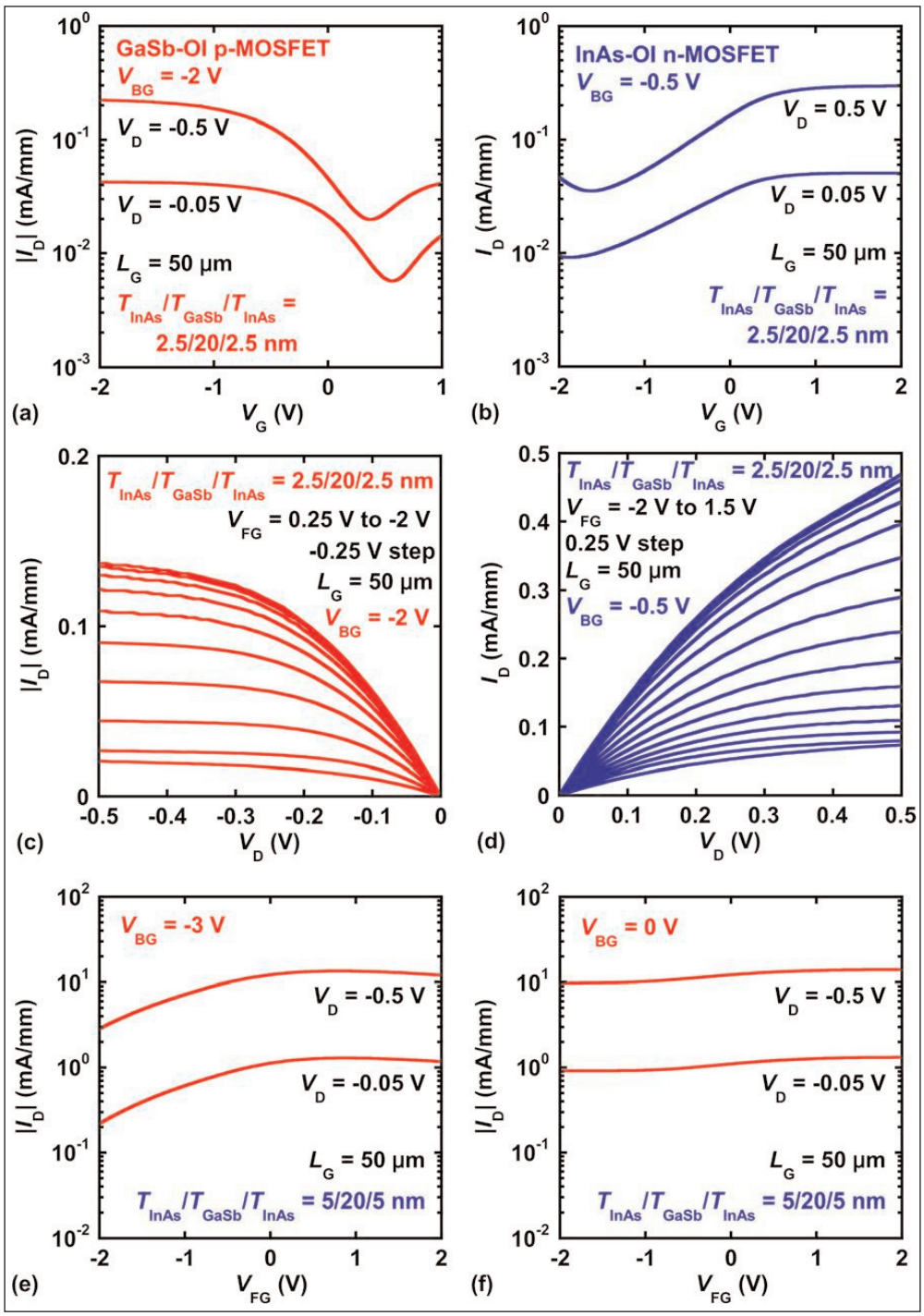


**Figure 2. Front-gate operation of III–V CMOS InAs/GaSb-OI device with 2.5nm/20nm/2.5nm (a–d) or 5nm/20nm/5nm (e–f) InAs/GaSb/InAs layers with various back-gate potentials ($V_{BG}$) to give p- or n-MOSFET behavior. Drain current ($I_D$) vs (front) gate ($V_G$/$V_{FG}$) potential or drain bias ($V_D$).**

# Black polycrystalline diamond transistors with high breakdown

**Despite material imperfections such as cracks and grain boundaries, devices also achieve high maximum drain currents.**

Waseda University and Yokogawa Electric Corp in Japan have used black polycrystalline diamond (BPD) to fabricate field-effect transistors (FETs) with breakdown voltages up to 1.8kV, comparable with the performance of silicon carbide (SiC) and gallium nitride (GaN) devices [M. Syamsul et al, Appl. Phys. Lett., vol109, 203504, 2016]. Despite imperfections of the polycrystalline material such as cracks and grain boundaries, the resulting devices also achieved high maximum drain currents.

The researchers comment: "We showed that BPD-FETs may be worthy candidates for high-power FET devices, and demonstrated comparable electrical characteristics to single-crystalline diamond and clear polycrystalline diamond FETs."

Most research on diamond-based devices is based on white polycrystalline or single-crystal material. Polycrystalline silicon is widely used for thin-film transistors in displays.

Undaunted by the "unappealing large grain boundaries and cracks" of BPD, the researchers believe the material is worth further research into its full potential. "Breakdown and stress voltages of BPD in an FET have not been previously studied," they add.

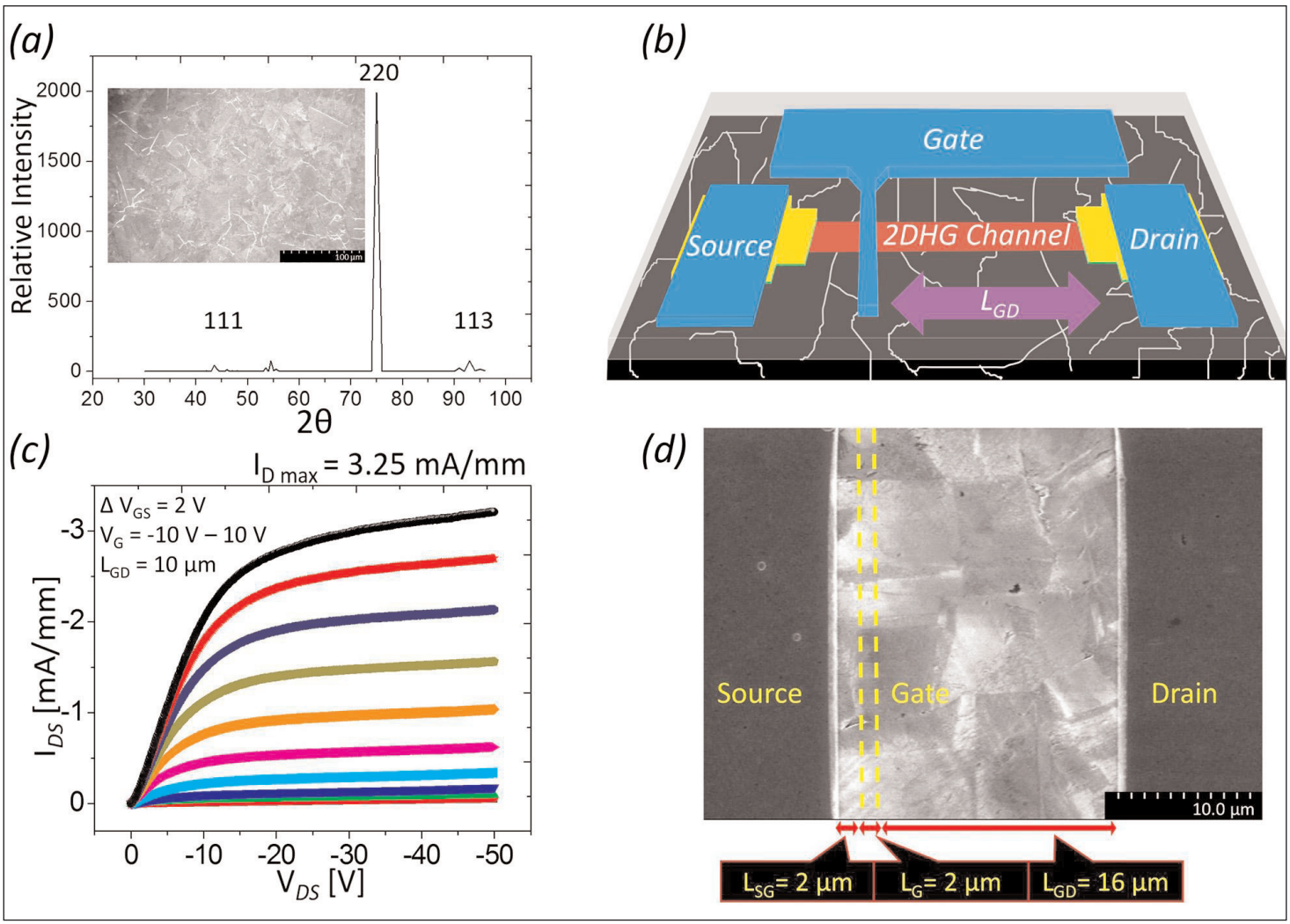


**Figure 1. (a) X-ray diffraction pattern of BPD. Inset: field-emission scanning electron microscope image of rough BPD surface. (b) Diagram of BPD-FET. (c) Drain current–voltage ($I_{DS}$–$V_{DS}$) characteristics in vacuum at room temperature with $L_{GD}$ of 10µm. (d) Field-emission scanning electron microscope image of region between the source and drain of the BPD-FET after stripping metallization and $Al_2O_3$ passivation.**

The devices (Figure 1b) were fabricated on 10mmx10mmx0.5mm commercial BPD substrates produced by chemical vapor deposition (CVD). According to atomic force microscopy (AFM), the roughness was 2.72nm and grains covered 98% of the surface.

Source–drain contacts consisted of gold/titanium layers. The electrodes were annealed at 450°C for 30 minutes in hydrogen. This formed a layer of titanium carbide (TiC) between the titanium contact and carbon material of the BPD. After annealing, the sample was heat treated with hydrogen plasma at 600°C for 6 minutes.

A narrow 25µm-wide horizontal two-dimensional hole gas (2DHG) channel was defined with photoresist. The 2DHG was created using treatment involving ultraviolet light and ozone, giving a partially carbon–oxygen (C–O) bond surface termination. This gave a potential barrier of 2eV between the carbon–hydrogen bonded 2DHG region and the surrounding C–O terminated areas, giving electrical isolation of the channel.

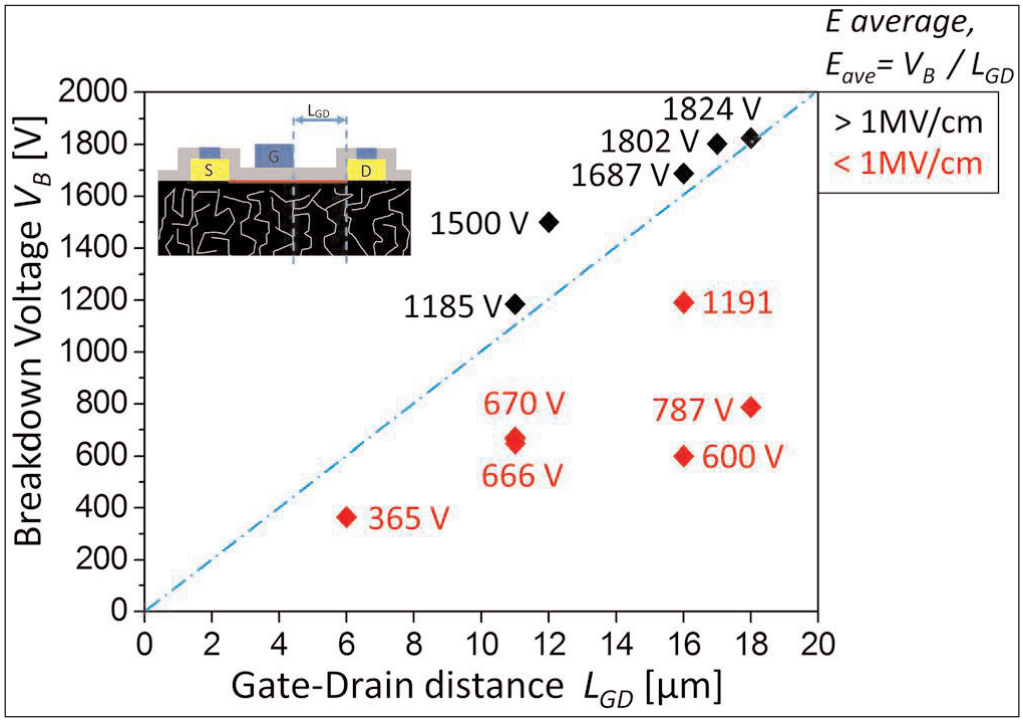


**Figure 2. Breakdown voltage versus $L_{GD}$ — those above the dashed line satisfy $V_B/L_{GD}$ greater than 1MV/cm.**

The photoresist was removed and then a 200nm aluminium oxide ($Al_2O_3$) gate dielectric layer built up using alternate exposures to trimethyl-aluminium and water ($H_2O$) at 450°C.

The device was completed with the removal of $Al_2O_3$ from the source–drain areas and deposition of the aluminium gate electrode.

Measurements (Figure 1c) were made on a device with 10µm gate-drain distance ($L_{GD}$), 2µm gate length ($L_G$) and 2µm source-gate distance ($L_{SG}$) in vacuum. "The characteristics of the saturation curves, including the pinch-off and saturation region, were similar to those of single-crystalline or clear-type polycrystalline diamond FETs, exhibiting nearly perfect modulation," the team comments.

The maximum drain current ($I_{Dmax}$) was 3.25mA/mm. The researchers point out: "The maximum drain current was unusually high for BPD considering the room-temperature operation and 25µm channel width. This value is also nearly three times higher than the boron-doped metal-semiconductor field-effect transistors (MESFETs) and junction field-effect transistors (JFETs)."

Increasing $L_{GD}$ to 18µm enabled a breakdown voltage ($V_B$) of 1824V with $I_{Dmax}$ of 1.1mA/mm. The team claims: "These findings indicate that our BPD-FET has the highest breakdown voltage of any diamond FET reported to date. The breakdown voltage was more than 300V higher than boron-doped diamond FETs and three times greater than JFETs."

Over a range of devices with varying $L_{GD}$ values, the average electric field at breakdown ($V_B/L_{GD}$) reached as high as 1.25MV/cm. Values greater than 1MV/cm are taken as indicative of high-voltage robustness in FETs, according to the researchers. Out of ten devices presented in the paper, five met this criterion (Figure 2).

Aluminium gallium nitride barrier/gallium nitride (AlGaN/GaN) channel FETs have achieved values of $V_B/L_{GD}$ up 1.7MV/cm. The researchers comment that their devices have demonstrated among the highest values for planar FETs, adding: "Performance of our BPD-FETs exceeded those of Ga2O3, SiC and AlGaN/GaN based devices, which have shown $V_B/L_{GD}$ values of 0.5, 0.8, and 1MV/cm, respectively."

The researchers also studied the degradation of the devices after subjecting them to harsh voltage stresses. The degradation in $I_{Dmax}$ after 500V stress was 6% for a 16µm $L_{GD}$ from 2.42mA/mm, before, to 2.28mA/mm, after. A 1000V stress reduced $I_{Dmax}$ further to 1.81mA/mm (25% down on the original value). Breakdown occurred at 1191V. Voltage stress of 2000V destroyed the device.

The team believes that better understanding of the effect of polycrystalline grain boundaries on high voltage breakdown could lead to further improvements in BPD-FET devices. ■

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*Author: Mike Cooke*

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www.temescal.net

Temescal, the expert in metallization systems for the processing of compound semiconductor-based substrates, provides the finest evaporation systems available. Multi-layer coatings of materials such as Ti, Pt, Au, Pd, Ag, NiCr, Al, Cr, Cu, Mo, Nb, $SiO_2$, with high uniformity are guaranteed. Today the world's most sophisticated handsets, optical, wireless and telecom systems rely on millions of devices that are made using Temescal deposition systems and components.

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North End, Yatton,
Bristol, Avon BS49 4AP, UK
Tel: +44 1934 837 000
Fax: +44 1934 837 001
www.oxford-instruments.co.uk

We provide flexible tools and processes for precise materials deposition, etching and controlled nanostructure growth. Core technologies include plasma and ion-beam deposition and etch and ALD.

**Plasma-Therm LLC**
10050 16th Street North,
St. Petersburg, FL 33716, USA
Tel: +1 727 577 4999
Fax: +1 727 577 7035
www.plasmatherm.com

Plasma-Therm, LLC is an established leading provider of advanced plasma processing equipment for the semiconductor industry and related specialty markets.

**Riber**
31 rue Casimir Périer, BP 70083,
95873 Bezons Cedex, France
Tel: +33 (0) 1 39 96 65 00
Fax: +33 (0) 1 39 47 45 62
www.riber.com

**SVT Associates Inc**
7620 Executive Drive,
Eden Prairie, MN 55344, USA
Tel: +1 952 934 2100
Fax: +1 952 934 2737
www.svta.com

**Veeco Instruments Inc**
100 Sunnyside Blvd.,
Woodbury, NY 11797,
USA
Tel: +1 516 677 0200
Fax: +1 516 714 1231
www.veeco.com

Veeco is a world-leading supplier of compound semiconductor equipment, and the only company offering both MOCVD and MBE solutions. With complementary AFM technology and the industry's most advanced Process Integration Center, Veeco tools help grow and measure nanoscale devices in worldwide LED/wireless, data storage, semiconductor and scientific research markets—offering important choices, delivering ideal solutions.

## 7 Wafer processing materials

**Air Products and Chemicals Inc**
7201 Hamilton Blvd.,
Allentown, PA 18195, USA
Tel: +1 610 481 4911
www.airproducts.com/compound

**MicroChem Corp**
1254 Chestnut St. Newton,
MA 02464, USA
Tel: +1 617 965 5511
Fax: +1 617 965 5818
www.microchem.com

**Praxair Electronics**
(see section 5 for full contact details)

## 8 Wafer processing equipment

**EV Group**
DI Erich Thallner Strasse 1,
St. Florian/Inn, 4782,
Austria
Tel: +43 7712 5311 0
Fax: +43 7712 5311 4600
www.EVGroup.com
Technology and market leader for wafer processing equipment.
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Erskine Ferry Road,
Old Kilpatrick,
near Glasgow G60 5EU,
Scotland, UK
Tel: +44 (0) 1389 875 444
Fax: +44 (0) 1389 879 042
www.logitech.uk.com

**Oxford Instruments Plasma Technology**
(see section 6 for full contact details)

**Plasma-Therm LLC**
(see section 6 for full contact details)

**SAMCO International Inc**
532 Weddell Drive,
Sunnyvale,
CA,
USA
Tel: +1 408 734 0459
Fax: +1 408 734 0961
www.samcointl.com

**SPTS Technology Ltd**
Ringland Way,
Newport NP18 2TA,
UK
Tel: +44 (0)1633 414000
Fax: +44 (0)1633 414141
www.spts.com

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85748 Garching,
Germany
Tel: +49 89 32007 0
Fax: +49 89 32007 162
www.suss.com

**Veeco Instruments Inc**
(see section 6 for full contact details)

## 9 Materials & metals

**Goodfellow Cambridge Ltd**
Ermine Business Park,
Huntingdon,
Cambridgeshire
PE29 6WR,
UK
Tel: +44 (0) 1480 424800
Fax: +44 (0) 1480 424900
www.goodfellow.com
Goodfellow supplies small quantities of metals and materials for research, development, prototyping and specialised manufacturing operations.

## 10 Gas and liquid handling equipment

**Air Products and Chemicals Inc**
(see section 7 for full contact details)

**Cambridge Fluid Systems**
12 Trafalgar Way, Bar Hill,
Cambridge CB3 8SQ,
UK
Tel: +44 (0)1954 786800
Fax: +44 (0)1954 786818
www.cambridge-fluid.com

**CS CLEAN SYSTEMS AG**
Fraunhoferstrasse 4,
Ismaning, 85737,
Germany
Tel: +49 89 96 24 00 0
Fax: +49 89 96 24 00 122
www.cscleansystems.com

**SAES Pure Gas Inc**
4175 Santa Fe Road,
San Luis Obispo,
CA 93401,
USA
Tel: +1 805 541 9299
Fax: +1 805 541 9399
www.saesgetters.com

## 11 Process monitoring and control

**k-Space Associates Inc**
2182 Bishop Circle
East, Dexter,
MI 48130,
USA
Tel: +1 734 426 7977
Fax: +1 734 426 7955
www.k-space.com
k-Space Associates Inc specializes in in-situ, real-time thin-film process monitoring tools for MBE, MOCVD, PVD, and thermal evaporation. Applications and materials include the research and production line monitoring of compound semiconductor-based electronic, optoelectronic, and photovoltaic devices.

**KLA-Tencor**
One Technology Dr,
1-2221I, Milpitas, CA 95035, USA
Tel: +1 408 875 3000
Fax: +1 408 875 4144
www.kla-tencor.com

**LayTec AG**
Seesener Str. 10–13,
10709 Berlin,
Germany
Tel: +49 30 89 00 55 0
Fax: +49 30 89 00 180
www.laytec.de
LayTec develops and manufactures optical in-situ and in-line metrology systems for thin-film processes with particular focus on compound semiconductor and photovoltaic applications. Its know-how is based on optical techniques: reflectometry, emissivity corrected pyrometry, curvature measurements and reflectance anisotropy spectroscopy.

**WEP (Ingenieurbüro Wolff für Elektronik- und Programmentwicklungen)**
Bregstrasse 90, D-78120
Furtwangen im Schwarzwald,
Germany
Tel: +49 7723 9197 0
Fax: +49 7723 9197 22
www.wepcontrol.com

## 12 Inspection equipment

**Bruker AXS GmbH**
Oestliche Rheinbrueckenstrasse 49,
Karlsruhe, 76187,
Germany
Tel: +49 (0)721 595 2888
Fax: +49 (0)721 595 4587
www.bruker-axs.de

## 13 Characterization equipment

**J.A. Woollam Co. Inc.**
645 M Street Suite 102,
Lincoln, NE 68508, USA
Tel: +1 402 477 7501
Fax: +1 402 477 8214
www.jawoollam.com

**Lake Shore Cryotronics Inc**
575 McCorkle Boulevard,
Westerville, OH 43082,
USA
Tel: +1 614 891 2244
Fax: +1 614 818 1600
www.lakeshore.com

## 14 Chip test equipment

**Keithley Instruments Inc**
28775 Aurora Road,
Cleveland, OH 44139,
USA
Tel: +1 440.248.0400
Fax: +1 440.248.6168
www.keithley.com

## 15 Assembly/packaging materials

**ePAK International Inc**
4926 Spicewood Springs Road,
Austin, TX 78759,
USA
Tel: +1 512 231 8083
Fax: +1 512 231 8183
www.epak.com

**Gel-Pak**
31398 Huntwood Avenue,
Hayward, CA 94544, USA
Tel: +1 510 576 2220
Fax: +1 510 576 2282
www.gelpak.com

**Wafer World Inc**
(see section 3 for full contact details)

**Materion Advanced Materials Group**
2978 Main Street,
Buffalo, NY 14214,
USA
Tel: +1 716 837 1000
Fax: +1 716 833 2926
www.williams-adv.com

## 16 Assembly/packaging equipment

**Ismeca Europe Semiconductor SA**
Helvetie 283, La Chaux-de-Fonds,
2301, Switzerland
Tel: +41 329257111
Fax: +41 329257115
www.ismeca.com

**Kulicke & Soffa Industries**
1005 Virginia Drive,
Fort Washington,
PA 19034,
USA
Tel: +1 215 784 6000
Fax: +1 215 784 6001
www.kns.com

**Palomar Technologies Inc**
2728 Loker Avenue West,
Carlsbad, CA 92010,
USA
Tel: +1 760 931 3600
Fax: +1 760 931 5191
www.PalomarTechnologies.com

**TECDIA Inc**
2700 Augustine Drive, Suite 110,
Santa Clara, CA 95054,
USA
Tel: +1 408 748 0100
Fax: +1 408 748 0111
www.tecdia.com

## 17 Assembly/packaging foundry

**Quik-Pak**
10987 Via Frontera,
San Diego, CA 92127, USA
Tel: +1 858 674 4676
Fax: +1 8586 74 4681
www.quikicpak.com

## 18 Chip foundry

**Compound Semiconductor Technologies Ltd**
Block 7, Kelvin Campus,
West of Scotland, Glasgow,
Scotland G20 0TH,
UK
Tel: +44 141 579 3000
Fax: +44 141 579 3040
www.compoundsemi.co.uk

**United Monolithic Semiconductors**
Route departementale 128,
BP46, Orsay, 91401,
France
Tel: +33 1 69 33 04 72
Fax: +33 169 33 02 92
www.ums-gaas.com

## 19 Facility equipment

**MEI, LLC**
3474 18th Avenue SE,
Albany, OR 97322-7014,
USA
Tel: +1 541 917 3626
Fax: +1 541 917 3623
www.marlerenterprises.net

## 20 Facility consumables

**W.L. Gore & Associates**
401 Airport Rd, Elkton,
MD 21921-4236,
USA
Tel: +1 410 392 4440
Fax: +1 410 506 8749
www.gore.com

## 21 Computer hardware & software

**Ansoft Corp**
4 Station Square, Suite 200,
Pittsburgh, PA 15219, USA
Tel: +1 412 261 3200
Fax: +1 412 471 9427
www.ansoft.com

**Crosslight Software Inc**
121-3989 Henning Dr.,
Burnaby, BC, V5C 6P8, Canada
Tel: +1 604 320 1704
Fax: +1 604 320 1734
www.crosslight.com

**Semiconductor Technology Research Inc**
10404 Patterson Ave., Suite 108,
Richmond, VA 23238,
USA
Tel: +1 804 740 8314
Fax: +1 804 740 3814
**www.semitech.us**

## 22 Used equipment

**Class One Equipment Inc**
5302 Snapfinger Woods Drive,
Decatur, GA 30035, USA
Tel: +1 770 808 8708
Fax: +1 770 808 8308
**www.ClassOneEquipment.com**

## 23 Services

**Henry Butcher International**
Brownlow House, 50–51
High Holborn, London WC1V 6EG,
UK
Tel: +44 (0)20 7405 8411
Fax: +44 (0)20 7405 9772
**www.henrybutcher.com**

**M+W Zander Holding AG**
Lotterbergstrasse 30,
Stuttgart,
Germany
Tel: +49 711 8804 1141
Fax: +49 711 8804 1950
**www.mw-zander.com**

## 24 Consulting

**Fishbone Consulting SARL**
8 Rue de la Grange aux Moines,
78460 Choisel,
France
Tel: + 33 (0)1 30 47 29 03
E-mail: jean-luc.ledys@neuf.fr

## 25 Resources

**Al Shultz Advertising Marketing for Advanced Technology Companies**
1346 The Alameda,
7140 San Jose, CA 95126, USA
Tel: +1 408 289 9555
**www.alshuktz.com**

**SEMI Global Headquarters**
3081 Zanker Road,
San Jose, CA 95134, USA
Tel: +1 408 943 6900
Fax: +1 408 428 9600
**www.semi.org**

**Yole Développement**
45 rue Sainte Geneviève,
69006 Lyon, France
Tel: +33 472 83 01 86
**www.yole.fr**

# event calendar

**If you would like your event listed in *Semiconductor Today*'s Event Calendar, then please e-mail all details to the Editor at mark@semiconductor-today.com**

**28 January – 2 February 2017**
**SPIE Photonics West 2017**
Moscone Center, San Francisco, CA, USA
**E-mail**: customerservice@spie.org
**http://spie.org/SPIE-PHOTONICS-WEST-conference**

**31 January – 2 February 2017**
**14th annual DOE SSL R&D Workshop**
Long Beach, CA, USA
**E-mail**: JoAnn.DiDomenico@netl.doe.gov
**www.energy.gov/eere/ssl/2017-ssl-rd-workshop**

**5–9 February 2017**
**IEEE International Solid-State Circuits Conference (ISSCC 2017)**
San Francisco, CA, USA
**E-mail**: m.figueroa@ieee.org
**www.isscc.org**

**27 February – 1 March 2017**
**PHOTOPTICS 2017 — 5th International Conference on Photonics, Optics and Laser Technology**
Porto, Portugal
**E-mail:** photoptics.secretariat@insticc.org
**www.photoptics.org**

**28 February – 2 March 2017**
**Strategies in Light 2017 (co-located with The LED Show and Lightspace California)**
Anaheim Convention Center, Anaheim, CA, USA
**E-mail:** registration@pennwell.com
**www.strategiesinlight.com/conference.html**

**28 February – 2 March 2017**
**IEEE Electron Devices Technology and Manufacturing Conference (EDTM 2017)**
Toyama International Conference Center, Japan
**E-mail:** edtm@jtbcom.co.jp
**http://ewh.ieee.org/conf/edtm/2017**

**14–16 March 2017**
**SEMICON China 2017**
Shanghai New International Expo Centre, China
**E-mail:** semichina@semi.org
**www.semiconchina.org**

**19–23 March 2017**
**Optical Fiber Communication Conference & Exhibition (OFC 2017)**
Los Angeles Convention Center, CA, USA
**E-mail**: OFC@compusystems.com
**www.ofcconference.org**

**3–5 April 2017**
**19th European Conference on Integrated Optics (ECIO 2017)**
Science Park of the Technical University of Eindhoven, The Netherlands
**E-mail**: info@jakajima.eu
**www.ecio-conference.org**

**3–5 April 2017**
**2017 Joint International EUROSOI Workshop and International Conference on Ultimate Integration on Silicon (ULIS)**
Athens, Greece

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**E-mail**: a.nasiopoulou@inn.demokritos.gr
**www.eurosoi-ulis2017.inn.demokritos.gr**

**9–13 April 2017**
**SPIE Defense + Commercial Sensing (DCS 2017)**
Anaheim Convention Center, CA, USA
**E-mail**: customerservice@spie.org
**http://spie.org/SPIE-DCS-conference**

**18–21 April 2017**
**SNEC's 11th International Photovoltaic Power Generation Conference & Exhibition (SNEC PV Power EXPO 2017)**
Shanghai, China
**E-mail**: info@snec.org.cn
**www.snec.org.cn**

**24–27 April 2017**
**SPIE Optics + Optoelectronics 2017**
Clarion Congress Hotel, Prague, Czech Republic
**E-mail**: info@spieeurope.org
**www.spie.org/SPIE-Optics-Optoelectronics**

**1–3 May 2017**
**13th International Conference on Concentrator Photovoltaics (CPV-13)**
University of Ottawa, Canada
**E-mail**: info@cpv-13.org
**www.cpv-13.org**

**14–19 May 2017**
**Conference on Lasers and Electro-Optics (CLEO 2017)**
San Jose Convention Center, CA, USA
**E-mail**: CLEO@compusystems.com
**www.cleoconference.org**

**16–17 May 2017**
**ITF Belgium (Imec Technology Forum 2017)**
Antwerp, Belgium
**E-mail**: Olfa.Marzouk@imec.be
**www2.imec.be/be_en/events.html**

**22–25 May 2017**
**2017 CS ManTech (International Conference on Compound Semiconductor Manufacturing Technology)**
Indian Wells, CA, USA
**E-mail**: lynn_fincher@msn.com
**www.csmantech.org**

**28 May – 1 June 2017**
**29th International Symposium on Power Semiconductor Devices and ICs (ISPSD 2017)**
Sapporo, Japan
**E-mail:** ispsd2017reg@ech.co.jp
**http://eds.ieee.org/eds-meetings-calendars.html**

**30 May – 2 June 2017**
**Intersolar Europe Exhibition and Conference (ISE 2017)**
Messe München, Munich, Germany
**E-mail:** info@intersolar.de
**www.intersolar.de**

**4–6 June 2017**
**IEEE Radio Frequency Integrated Circuits Symposium (RFIC 2017)**
Hawaii Convention Center, Honolulu, HI, USA
**http://rfic-ieee.org**

**5–8 June 2017**
**2017 Symposia on VLSI Technology and Circuits**
Rihga Royal Hotel, Kyoto, Japan
**E-mail**: vlsi@vlsisymposium.org
**www.vlsisymposium.org**

**25–29 June 2017**
**Conference on Lasers and Electro-Optics/ Europe & the European Quantum Electronics Conference (CLEO/Europe-EQEC 2017)**
Munich, Germany
**E-mail**: info@cleoconference.org
**www.cleoeurope.org**

**25–30 June 2017**
**44th IEEE Photovoltaic Specialists Conference (PVSC 2017)**
Marriot Wardman Park Hotel, Washington DC, USA
**E-mail**: info@ieee-pvsc.org
**www.ieee-pvsc.org/PVSC44**

**10–12 July 2017**
**IEEE Photonics Society's 2017 Summer Topicals Meeting Series**
San Juan, Puerto Rico
**E-mail**: i.donnelly@ieee.org
**www.sum-ieee.org**

**10–12 July 2017**
**Intersolar North America**
San Francisco, CA, USA
**E-mail**: info@intersolar.de
**www.intersolar.us**

**15–18 July 2017**
**ALD 2017: 17th International Conference on Atomic Layer Deposition, featuring the 4th International Atomic Layer Etching Workshop (ALE2017)**
Sheraton Denver, CO, USA
**E-mail**: della@avs.org
**www.ald-avs.org**

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