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Nitride resonant tunneling diodes
LED headlamps in the spotlight

Record-brightness white LEDs • GaN power transistor launches
IQE acquires MBE Technology • CSIC Symposium report

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contents

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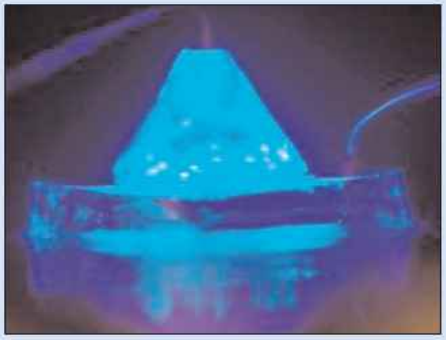
p7 RFMD has opened a customer support center in Shanghai, its fourth location in the Greater China region.



p22 UCSB researchers have found that a pyramid ZnO electrode can double GaN LED light extraction efficiency.

p26 Nichia has developed a lamp-type white LED with 150lm/W efficacy (more than a high-pressure sodium lamp).

Cover: The Lexus LS600h L luxury sedan will be launched in the US this spring as the first series production vehicle with LED headlights for both night-time and low-beam use. Passenger cars have been using LED tail-lights for about five years, and LED daytime running lights since 2004. **p24**

editorial

Complementary technologies

In the last issue (page 11) we reported how RFMD was collaborating with MediaTek to create Bluetooth-enabled cell-phone reference designs using its CMOS-based SiW3500 system-on-chip (SoC). This issue (page 7), we report how RFMD is selling its San Diego-based Bluetooth assets to CDMA-based chipset maker Qualcomm, so that it can focus on its highest-growth wireless markets: cellular transceivers, cellular and WLAN power amplifiers, and GPS (with its first scalable GPS solution due to start shipping in March). However, it has retained the SiW3500 and other SoC and CDMA products, and aims to be a development partner to Qualcomm's entire portfolio for complementary products (e.g. power amplifiers and front-end modules).

In his talk 'Optimizing RF semiconductor choices for mobile devices' at the CSIC Symposium, Jerry Neal, RFMD's co-founder and executive VP of marketing & strategic development, said that, while 2006 revenues should exceed $1bn, it now ships more transmit modules than PAs (page 39) and that, by 2008, most handsets will contain a single-chip quad-band transmit module integrating power amplifiers, a switch and a controller. Stressing that "RFMD is not married to GaAs HBTs", the firm has been developing pHEMT switches, says Neal. But RFMD 'may go to MEMS' [for switches and filters] as it offers lower insertion loss and ease of integration (atop the firm's Integrated Power MOS silicon process).

Similarly, for wideband applications like wireless infrastructure, RFMD is looking beyond GaAs by launching GaN-based power amplifiers (page 13), along with Nitronex and Cree, which are also targeting defense applications. Strategy Analytics forecasts that the market for GaAs devices for defense applications will grow at a compound average annual growth rate of 8% through to 2010, then slow as trends towards wider bandwidth, higher frequency and higher power favor emerging technologies such as GaN. But the high-power, high-frequency capabilities of GaN should allow GaAs device makers also working on GaN to compete in areas that have traditionally been dominated by vacuum tube technology, the firm says: "GaN will provide an additional revenue stream, rather than simply offering a means for replacing lost revenues due to GaAs displacement."

Another possible future application of nitrides is in electronic devices such as resonant tunneling diodes (see feature, page 32) for terahertz signal generation, switching, analog-to-digital conversion and detection, as well as 'functional' logic devices with simpler structures. These include one-transistor SRAM and multi-valued memory cells, and devices that could supersede standard CMOS technology towards the end of the next decade.

Nearer-term applications of GaN of course include white LEDs, which are developing faster than planned (see Nichia's 150lm/W white LED, page 26). The US DOE cautions about their efficacy in luminaires (page 27). Nevertheless, LEDs are making further inroads into automotive applications, with the first LED headlamps on a production vehicle to be launched this spring (page 28). This could drive widespread adoption, it is hoped.

Mark Telford

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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).

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- event calendar and event previews;
- suppliers' directory.

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GaAs defense market to grow at 8% to 2010 before shift to GaN

The market for GaAs devices for defense applications will see continued growth at a compound average annual growth rate (CAAGR) of 8% through to 2010, forecasts the report 'Defense Spending Increases Provide Robust Market for Compound Semiconductors' from Strategy Analytics' GaAs and Compound Semiconductor Technologies service.

GaAs remains a staple ingredient in military and defense systems covering radar, communications, electronic warfare and smart munitions. The value of defense contracts awarded in 2006 for these applications will exceed $16bn, with projects extending through 2015.

"We believe GaAs device demand from the defense sector will increase year-on-year by 9% in 2006 and continue to grow through to 2010," notes Asif Anwar, director of Strategy Analytics' GaAs Service. However, year-on-year growth for GaAs devices will start to slow from 2009 onwards as future trends towards wider bandwidth, higher frequency and higher power favor emerging technologies such as GaN, which will start to be designed into next-generation defense systems. "We believe that the growing power and frequency requirements of defense systems will favor GaN over GaAs as the optimum technology, and therefore predict that GaN will begin to be the underlying technology for military defense systems from 2010 onwards."

Growth for GaAs devices will start to slow from 2009 onwards as future trends towards wider bandwidth, higher frequency and higher power favor emerging technologies such as GaN

"The upside for GaAs device manufacturers also working on GaN is that the high-power, high-frequency capabilities of GaN should allow them to compete in areas that have traditionally been dominated by vacuum tube technology," says Stephen Entwistle, VP of the Strategy Analytics' Strategic Technologies Practice. "GaN will therefore provide an additional revenue stream, rather than simply offering a means for replacing lost revenues due to GaAs displacement."

www.strategyanalytics.net

WiMAX market growth in China depends on dealing with spectrum allocation, product maturity, and 3G

WiMAX has an excellent opportunity to expand China's market for fixed, portable, and mobile broadband access, reports In-Stat in 'WiMAX Market in China: The Next PHS [personal handy-phone system]'.

In early 2006, China Netcom began to deploy WiMAX 802.16-2004 systems (3.5GHz) for fixed wireless access (voice and data) in the Guangdong province, aimed at small- and medium-sized businesses and the residential market. "WiMAX does have many advantages in cost, flexibility, and deployment convenience," says In-Stat analyst Kevin Li.

Although traction in the 802.16-2004 (fixed) market will be important, the real success of WiMAX in China will depend on the much larger 802.16(e) market.

However, WiMAX development in China is still confronting some barriers: uncertain spectrum allocation, immature 802.16e product, and competition from the 3G industry, In-Stat says. Equipment and subscriber forecasts therefore depend on how the industry deals with these issues.

A factor in favor of WiMAX is that it is a data network access technology... no circuit switching domain is required

Nevertheless, In-Stat says that a factor in favor of WiMAX is that it is a data network access technology, which means that no circuit switching domain is required, whereas 3G is divided into circuit switching and packet switching domains, which carry voice and data, respectively.

In-Stat concludes by forecasting that the China WiMAX subscriber base will increase from 8000 in 2005 to 3,525,070 (in an aggressive scenario) or, alternatively, 1,234,120 (in a conservative scenario) by 2010.

www.in-stat.com

WiMAX, Metro Wi-Fi most efficient for mobile broadband

Energy costs represent the third most significant operating expense item for cellular carriers today, and fluctuating energy costs are a significant area of concern for business planners. The introduction of mobile broadband means that the energy required per subscriber arising from increasing data uptake will push per-subscriber energy operating expense for cellular solutions past acceptable barriers — unless carriers move from a traditional cellular-only approach to one that integrates WiMAX and Metro Wi-Fi, says ABI Research.

"From a pure coverage perspective WiMAX is twice as energy-cost-effective and metro Wi-Fi is 50 times more energy-cost-effective than WCDMA," says director of wireless research Stuart Carlaw. "When data traffic is factored into the equation, WiMAX can accommodate 11 times today's average data consumption and still be more energy-cost-efficient compared to WCDMA or HSDPA."

A recent ABI Research study ('Energy Efficiency Analysis for Mobile Broadband Solutions') found that total energy consumption arising from mobile broadband service delivery is forecast to grow from 42.8bn kWh in 2005 to 124.4bn kWh in 2011. The Asia Pacific region will account for most growth.

www.abiresearch.com

Asia GaAs epi suppliers rank highest; Hitachi overtakes FCM for substrates

Strategy Analytics has released the results of two surveys detailing customer ratings for bulk and epitaxial GaAs substrate suppliers, revealing that uniformity and price are the critical parameters used by GaAs device manufacturers and epitaxial wafer suppliers when choosing a substrate supplier.

In its report on semi-insulating GaAs epitaxial substrates, Asif Anwar, director of Strategy Analytics' GaAs Service, notes that "The Asia-Pacific (excluding Japan) epitaxial wafer suppliers have differentiated themselves on cost. Aside from IQE, none of the other epitaxial wafer suppliers could match VPEC and MBE Technology wafer pricing". He adds, "MBE Technology also had the highest rating overall as a result of strong customer ratings in both the technical and commercial parameters."

In its report on semi-insulating GaAs bulk substrates, Stephen Entwistle, VP of the Strategic Technologies Practice, says "Customers rated the top three suppliers of SI GaAs bulk substrates, Sumitomo Electric Industries (SEI), Hitachi Cable and Freiberger Compound Materials (FCM), highly for technical parameters, with little difference between the three."

However, Hitachi Cable overtook FCM and was the clear leader for commercial parameters, rated highly in particular for its delivery, lead times and technical support. Most notable though was the considerable improvement in AXT's commercial ratings, though the company still needs to catch up on technical parameters, Entwistle concludes.

www.strategyanalytics.net

Cellular backhaul point-to-point radio GaAs market to peak in 2007

Point-to-point radio GaAs component revenues for cellular backhaul applications (where information is carried between a wireless base-station and a central wired telephone switch) will peak in 2007 then flatten from 2008 onwards as growth in unit shipment in this market slows, forecasts Strategy Analytics.

The greatest growth in cellular subscribers will be in the Asia-Pacific region through 2010, where infrastructure equipment demand will continue to increase. The traditional frequency segments will continue to dominate point-to-point radios for cellular backhaul, despite the introduction of radios operating at 60GHz and above.

"With revenues expected to flatten, GaAs device manufacturers will have to provide innovative solutions to stay ahead of competitive pressures," says Asif Anwar, Strategy Analytics' GaAs Service Director. "We believe a move toward packaged parts and multifunctional chips and/or multi-chip modules will help GaAs companies offset competitive threats from competing silicon technologies in the near term and provide added value to their customers to secure long-term relationships."

"The next-generation rollout of cellular networks is focused on data, thus point-to-point radios will need to be able to offer high data capacities," adds Stephen Entwistle, VP of the Strategy Analytics' Strategic Technologies Practice. "We believe the growing demand for higher data rates will also lead to replacement of existing links to accommodate higher-capacity radios."

www.strategyanalytics.net

Qualcomm chooses Anadigics' PAs for MSM chipset designs

RFIC maker Anadigics Inc of Warren, NJ, USA says its WCDMA and GPRS/EDGE power amplifiers have been specified by Qualcomm for its Mobile Station Modem MSM7200 and MSM6280 chipset reference designs.

MSM7200 supports the high-speed uplink packet access (HSUPA) standard for peak data rates of 7.2Mbps on the downlink and 5.76Mbps on the uplink. The MSM6280 solution supports the HSDPA standard for enhanced peak downlink rates of up to 7.2Mbps. HSDPA and HSUPA enables wireless broadband speeds that rival wired connections.

Qualcomm's MSM7200 reference design specifies Anadigics' WCDMA and EDGE PAs to support eight frequency bands: four WCDMA bands are enabled by the AWT6273, AWT6278, AWT6279, and AWT6282 PAs; four EDGE bands are supported by the AWT6280 polar EDGE PA.

The MSM6280 reference design specifies the AWT6273, AWT6278 and AWT6279 WCDMA PAs, as well as Anadigics' AND0041 quad-band polar EDGE PA.

The AWT6273, AWT6278 and AWT6279 WCDMA PAs use Anadigics' 3G High-Efficiency-at-Low-Power (HELP3) technology. The performance enables manufacturers to extend battery life in mobile handsets, smart phones, data cards and 3G-enabled notebook computers.

"Qualcomm's MSM7200 and MSM6280 chipsets raise the bar in mobile performance, delivering advanced multimedia and communication capabilities," said Dr Sanjay K. Jha, president of Qualcomm CDMA Technologies. "The evolution of today's 3G networks is enabling mobile users to work and play with functionality that was previously reserved for wired broadband connections, and these two chipsets, together with Anadigics' advanced power amplifiers, represent powerful solutions for the next generations of wireless devices."

These two chipsets, together with Anadigics' advanced PAs, represent powerful solutions for the next generations of wireless devices

"As mobile manufacturers develop advanced 3G devices to take advantage of the data speeds enabled by HSDPA and HSUPA networks, battery life becomes a critical concern," said Anadigics' president and CEO Dr Bami Bastani. "Anadigics' HELP3 WCDMA power amplifiers have been optimized not only to deliver excellent voice clarity and data integrity, but also to significantly improve the operating time of 3G devices."

HELP3 WCDMA PAs offer full compliance with HSDPA and HSUPA requirements, while reducing average current consumption by 75% compared with a conventional power amplifier, says Anadigics. The PAs provide quiescent currents of just 7mA without a DC–DC converter, and eliminate the requirements for external voltage regulation. Such performance and integration of HELP3 products is achieved by using Anadigics' patented InGaP-Plus technology, which combines bipolar and field-effect transistor (FET) devices on the same InGaP-based gallium arsenide die.

www.anadigics.com

Acquicor raises $167m to fund take-over of Jazz

In mid-December Acquicor Technology Inc closed a private placement of $145m worth of its 8% convertible senior notes (due 2011) to qualified institutional buyers. This was followed a few days later by the placement of a further $21.8m of the notes, convertible into shares of the firm's common stock at an initial conversion price of $7.33 per share.

Acquicor is using the proceeds for general corporate purposes and to fund its planned $260m acquisition of CMOS and SiGe BiCMOS wafer foundry Jazz Semiconductor Inc of Newport Beach, CA, USA, which was announced in late September and should be completed in Q1/2007 (pending shareholder approval). Jazz will then become a subsidiary of Acquicor, though it will continue to operate as Jazz Semiconductor.

Acquicor was formed in August 2005 by Apple Computer Inc co-founder Steve Wozniak as chief technology officer, Ellen M. Hancock as chief operating officer and president (former chief technology officer of Apple and chief operating officer of National Semiconductor) and Gilbert F. Amelio as chairman and CEO (former chairman and CEO of Apple and National Semiconductor Corp). The purpose was to acquire — by merger, capital stock exchange, stock purchase, asset acquisition or other similar business combination — one or more domestic and/or foreign operating businesses in the technology, multimedia and networking sectors. The firm subsequently raised $172.5m in its March 2006 initial public offering.

www.acquicor.com

RFMD sells Bluetooth assets to Qualcomm and collaborates on complementary RF products

GaAs RFIC and module maker RF Micro Devices Inc of Greensboro, NC, USA has agreed the $39m sale to Qualcomm Inc of San Diego, CA, USA of most of its Bluetooth assets (specifically those that are based in San Diego working on devices for handsets and headsets, including the intellectual property related to its next-generation SiW1722 and RF4000 series of products based on the Enhanced Data Rate (EDR) Bluetooth specification).

RFMD anticipates a significant reduction in Bluetooth-related expenses. However, the company says it will retain and continue to market and sell its CDMA products SiW1712 and SiW1721 as well as its SiW3000 and SiW3500 system-on-chip (SoC) products, which formed most of its Bluetooth product revenue in Q3/2006.

The deal is expected to give Qualcomm (which provides CDMA-based digital wireless communications technologies and data solutions) access to next-generation Bluetooth technology. Qualcomm will integrate RFMD's Bluetooth EDR technology into its Mobile Station Modem (MSM) reference designs to offer more complete solutions. RFMD's San Diego-based team designs technology for both the mobile handset and headset markets.

Qualcomm is also acquiring WLAN technology provider Airgo Networks Inc of Palo Alto, CA, USA. "As the attach rate for Bluetooth and WLAN features in mobile handsets is poised to grow past the critical tipping point, these acquisitions become very timely," reckons Chris Ambrosio, director of wireless device strategies for market research firm Strategy Analytics.

The deal allows RFMD to increase its focus on its highest-growth wireless business opportunities, including cellular transceivers, cellular power amplifiers, wireless local area network (WLAN) power amplifiers, and global positioning system (GPS) components, as well as gallium nitride high-power amplifiers.

RFMD looks forward to working with Qualcomm with products complementary to their portfolio, such as cellular PAs and WLAN front-end modules

However, the sale will also enable RFMD to accelerate its expansion into new markets while streamlining its cost structure, says president and CEO Bob Bruggeworth. "RFMD also looks forward to working with Qualcomm with products complementary to their portfolio, such as cellular PAs and WLAN front-end modules," he adds. "RFMD hopes to become a broader development partner to Qualcomm's entire product portfolio for complementary products such as power amplifiers and front-end modules."

"The sale of these assets marks the first time the companies have worked together on this scale," says Jerry Neal, RFMD's executive VP of marketing and strategic development. "Our long-term relationship with Qualcomm continues to evolve," he adds. "We look forward to continuing our support of current Bluetooth customers."

www.rfmd.com

Shanghai customer support center opened

RF Micro Devices has opened its new customer support center in Shanghai, its fourth location in the Greater China region.

The center will expand RFMD's capacity to serve wireless customers throughout the Far East by expanding and complementing its sales and support centers in Shenzhen and Taiwan, and its module assembly facility and test and tape & reel facility in Beijing. RFMD employs more than 900 people in the Greater China area.

The facility, which houses technical sales, sales management, application support and customer support, will enable RFMD to better serve regional manufacturers, who are increasingly developing leading-edge handset technology for the world's largest cell phone providers, the company says.

"This new location will expand and strengthen our technical and systems support, while helping to advance the integration of complementary radio functions and applications in cellular handset designs," says Greg Thompson, VP of worldwide sales and applications.

Skyworks launches Helios II-Plus EDGE radio for quad-band handsets incorporating multimedia features

Skyworks Solutions Inc of Woburn, MA, USA is sampling its Helios II-Plus EDGE radio. The firm says that its high level of integration and robust performance is suited to next-generation quad-band handsets incorporating multimedia features such as DVB-H, FM radios, MP3 players, digital cameras, and web browsing.

RF board space is reduced by 25% from the previous Helios design. Helios II-Plus also interfaces with virtually any analog baseband and simplifies factory calibration, allowing OEMs to increase production throughput, it is claimed. Also, it surpasses GSM and EDGE specifications under real-world conditions such as extreme temperature, low-battery voltage and antenna mismatch. It also enables longer user talk-times by exceeding transmitted radiated power (TRP) specifications for improved current consumption.

Skyworks' Helios II-Plus EDGE radio.

Helios II-Plus condenses EDGE RF functionality into two devices.

The SKY74138 RF transceiver is highly integrated for multi-band GSM, GPRS and EDGE applications. The receive path implements the firm's direct conversion architecture (four integrated low-noise amplifiers, a quadrature demodulator and selectable baseband filter). Like the Helios, the transmitter path uses its closed Polar Loop EDGE architecture, so it can be combined with almost any standard GSM/EGPRS baseband without special processing interfaces.

The SKY77523 is a transmit/receive (Tx/Rx) front-end module with integrated coupler for quad-band GSM and EDGE. Also, a CMOS IC provides the internal PAC function, interface circuitry, and decoder circuitry to control the RF switches.

Feedback signals from the devices form an integral part of the Polar Loop transmit architecture, which automatically adjusts amplitude and phase, providing very robust performance, and not relying on blind corrections of the power amplifier process variation like other EDGE transmit architectures.

www.skyworksinc.com

IN BRIEF

Microsemi ships PAs for 802.11n WLAN platforms

Microsemi Corp of Irvine, USA is shipping production volumes of its LX5511 InGaP HBT-based 2.4GHz WLAN power amplifiers designed into draft 1.0 802.11n WLAN platforms from Atheros Communications. It supports the new-generation Atheros XSPAN AR5008E-3NG draft 802.11n WLAN chipset, and is used in Atheros-based reference designs for access point, card bus, PCI and PCI-Express WLAN applications.

The new PA is a two-stage MMIC device, 3mm square, with active bias and output prematching. It operates from a single 3.3V supply. With 26dB power gain between 2.3 and 2.5GHz, it offers a low 90mA quiescent current.

www.microsemi.com

WJ launches 4W 28V InGaP HBT PA module for WCDMA infrastructure

RFIC maker WJ Communications Inc of San Jose, USA has launched a 4W power amplifier module for WCDMA infrastructure systems. Building on its AP60x family of 28V InGaP/GaAs HBT PAs, the highly integrated 2-stage AP622 is designed for the pre-driver and driver stages in WCDMA base-stations and PA modules, and the output stage in repeaters.

The AP622 is housed in a small, 13mm x 29mm x 4.1mm flange mount package and operates at 2110–2170MHz. It has a P1dB of 35dBm, 28dB of power gain and ACLR of –55dBc at 23dBm power output for WCDMA applications and operates from a +28V supply at 130mA operating current when configured for class AB operation, though it is usable over 24V to 32V.

The AP622 embodies the requirements for high linearity, high power gain, low operating current, 28V supply voltage, and design flexibility in a single package.

The AP622 incorporates the same features as the AP60x products, including the active bias circuitry to achieve improved linearity performance and adjustable quiescent bias, while providing design flexibility for demanding system requirements. The fully matched 50Ω input and outputs simplify the design and PCB layout of wireless infrastructure equipment. It also enables designers to 'plug and play' the module into their system designs, reducing implementation time and resources.

The need for higher power products and market demands has encouraged WJ to develop a 7W PA module for WCDMA, as well as future power amplifiers with power levels greater than 7W.

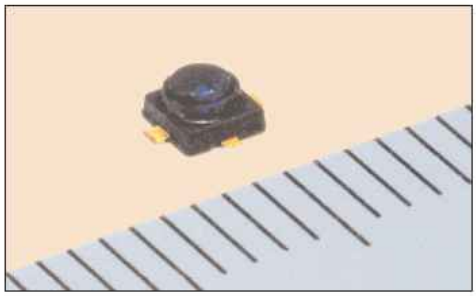
www.wj.com

Ku-band low-noise GaAs HEMTs

Japan's Mitsubishi Electric Corp has developed the MGF4941AL Ku-band low-noise GaAs high-electron-mobility transistor, for use in low-noise amplifiers for 10–12 GHz direct broadcast satellite (DBS) and very small aperture terminal (VSAT) reception systems. Sample shipments will begin in mid-February.

The HEMT is used in first-stage LNAs for down-converters in receiver systems that convert 12GHz signals from broadcast and/or communications satellites into intermediate frequencies in the 1–2GHz band.

An improved surface treatment process improves the noise factor by 0.05dB (compared to previous models) to 0.35dB, contributing to the improved productivity and functionality of satellite communications equipment, the firm says. Also,



Mitsubishi Electric's MGF4941AL Ku-band low-noise GaAs HEMT.

users can choose either the existing small-footprint leadless type of package or an industry-standard Micro X Type 6 package, which makes it easier to mount to the motherboard, improving productivity.

Mitsubishi Electric also plans to produce plastic package HEMTs for Ka-band (18–20GHz) DBS.

www.mitsubishichips.com

IN BRIEF

Anadigics ships dual-band CDMA PAs to Nokia

Anadigics is shipping production volumes of its ultra-compact 3mm x 5mm AWT6314 dual-band CDMA power amplifiers (PA) for Nokia's new 6215i lightweight clamshell handset, which features two-color displays, camera with flash, and a built-in speakerphone.

The small footprint reduces external components and achieves a 25% space saving compared with solutions needing two single-band PAs, helping the design of ultra-thin handsets.

The AWT6314 features 39% efficiency, 50mA of quiescent current, and a common VMODE line to simplify the control interface and support single-mode operation up to full antenna power.

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ST and Velox partner on GaN Schottkys for power supplies

STMicroelectronics (ST) of Geneva, Switzerland and Velox Semiconductor Corp of Somerset, NJ, USA, a vertically integrated manufacturer of GaN transistors and diodes, have teamed to jointly introduce GaN Schottky diodes into the market, with the long-term aim of establishing both companies as dual-source suppliers.

GaN-based diodes can be used to manufacture switch mode power supplies (SMPS) for smaller, more efficient and lower-cost computers, consumer applications, and industrial products. In SMPS applications GaN enables the implementation of higher-frequency power-factor correction circuits that offer benefits in efficiency, product size, low noise, smaller heat-sink requirements, and higher yield.

The reduction in switching losses in GaN devices can be applied to optimize circuit design; by increasing efficiency, reducing heat-sink requirements, or reducing the current rating of the transistor. The operating frequency can be increased to allow the use of smaller passive components, or to achieve acoustic requirements. The absence of high-frequency oscillation at turn-off reduces RFI filter requirements.

Velox is in the final stages of developing 600V GaN Schottky diodes before transition to production. In the first phase of the agreement, ST will help complete the development, test and qualify the diodes, and use its global network to market and distribute them under the Velox brand name. In the second phase, Velox and ST aim to become full dual sources. Velox will license its diode production technology to ST to enable second-source manufacturing; both companies are working together to synchronize manufacturing and quality systems. The companies caution that the synchronization efforts may delay the start of production originally planned by Velox, although the resulting delay should ensure an "agile and consistent supply of GaN devices".

"Both companies believe that the GaN devices will provide one of the best trade-offs for the 600V power device market in the medium term," said Ricardo de Sa Earp, ST's general manager, Application Specific Discretes Division. "We believe that the deal with Velox enables ST to introduce a new and fast-growing product line, quickly, and with the minimum of R&D and capital investment."

"Our agreement with ST will help Velox to answer our customers' needs for reliability of supply, and will enable faster qualification at a larger number of customers," said Velox's CEO Thomas Hierl. "Combining ST's manufacturing, reliability and quality expertise with Velox GaN technology will create a true dual-source supply for GaN devices."

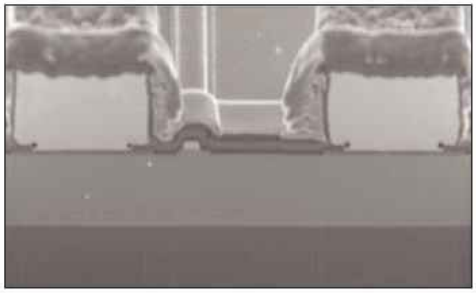
ST and Velox say that they offer complementary skills that should accelerate development of the critical technologies — leveraging the capital costs required, and increasing the quantity and quality of products available.

www.st.com
www.veloxsemi.com

Normally-off GaN power transistor with low R_{on}

At December's International Electron Devices Meeting 2006 in San Francisco, Panasonic (Matsushita Electric Industrial Co Ltd) of Osaka, Japan announced the development of a GaN power transistor with normally-off operation. The firm claims it is the first demonstration of conductivity modulation in GaN as a novel operating principle leading to low on-state resistance. The new transistor enables low-loss and high-voltage power switching devices.

Normally-off operation has been strongly desired for GaN power transistors, but previously reported approaches have resulted in high on-state resistance. In the new 'gate injection transistor', a normally-off positive threshold voltage of 1V is achieved by using a pn-junction gate structure instead of a conventional metal gate. In addition, the injection of holes from the p-type gate layer drastically increases the drain current, resulting in a low specific on-state resistance (R_{onA}) of 2.6mΩcm^2.



Cross section of Panasonic's normally-off GaN power transistor.

The high breakdown voltage of 640V is obtained on cost-effective silicon substrate. The transistor is applicable to future high-efficiency power switching systems replacing silicon-based power devices, the company claims.

Applications have been filed for 89 domestic and 52 international patents.

http://panasonic.net

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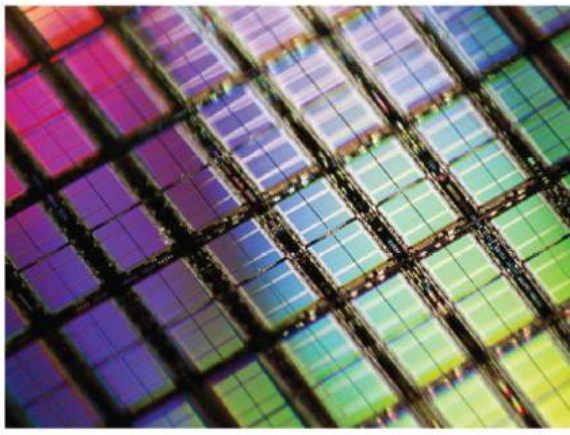

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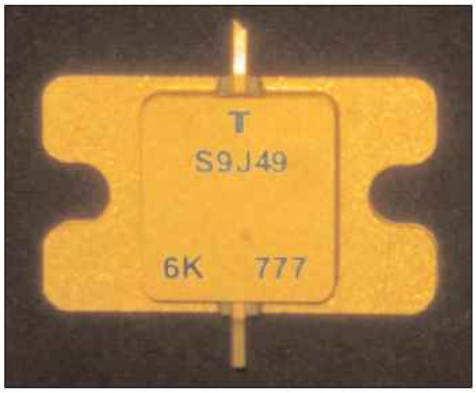
Record-output-power X-band GaN power FET gives 81.3W

At November's IEEE Compound Semiconductor IC Symposium (CSIC) in San Antonio, TX, USA, Toshiba Corp presented GaN power field effect transistors (FETs) that exceed the operating performance of GaAs FETs used in microwave solid-state amplifiers for radar and satellite microwave communications in the 8–12GHz X-band frequency range. The new transistor achieves record output power of 81.3W at 9.5GHz, and six times the power density of a GaAs FET.

Ever increasing communications flows are driving demand for higher output power in the amplifying devices used in radar and satellite microwave communications. Until now, Toshiba has met this demand with GaAs-based FETs offering 90W at 6GHz and 30W at 14GHz. However, balancing heat dissipation and performance characteristics at high frequencies is a critical issue with GaAs, and is reaching the point where the material is fast approaching the upper limits. GaN shows promise for application in high output power amplifiers that support higher frequencies above the microwave frequency band, since it offers higher saturation electron velocity, higher dielectric breakdown voltage and a higher operating temperature range than GaAs.

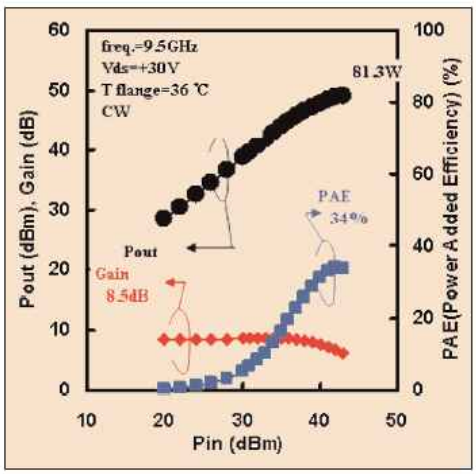
Toshiba initially concentrated on developing a GaN power FET for the 4–8GHz (C-band), and last year announced a GaN power FET with 174W output in the 6GHz band. It has now built on that with structural optimization that has achieved a device supporting higher X-band frequencies and that achieves the highest power output yet obtained by a GaN power FET operating at 9.5GHz. This progress should allow integration of devices in solid-state amplifiers and their downsizing, while giving higher output power.



Toshiba's 21.5mm x 12.9mm GaN Power FET (photo: Business Wire).

The breakthrough was achieved by optimizing the epilayer and chip structures for X-band operation. The FET has a HEMT structure. First the composition and thickness of the AlGaN and GaN epilayers were optimized. Then the FET unit structure (including gate length and the distance between the source and drain electrodes) was optimized. This not only assures heat dissipation but also high performance at X-band frequencies (9.5GHz).

Toshiba's heat treatment technology achieves low contact resistance at the source and drain electrodes, allowing maximization of the GaN material characteristics. To produce high performance at X-band frequencies, the FET requires a gate electrode under 0.5 microns. Also, as a high voltage is applied, suppression of current leakage at the gate electrode is essential. A unique gate electrode structure and overcoat process helps suppress gate leakage to 1/30th of conventional technology.



Transistor characteristics.

The conventional approach to boosting output power in GaN devices has been to fabricate a large chip with high power capacity in a large package. Such devices ran very hot, which could cause components to deteriorate and also damage the amplifiers into which the devices were integrated. GaN is a difficult material to work with and achieve uniformity of chip characteristics, and tends to suffer power losses when combining the power of multiple chips in a package.

Toshiba's process technology achieves chip uniformity across the wafer, while power management reduces power dissipation inside the package. These approaches disperse heat and reduce potential component deterioration, and support the achievement of a high power output of over 80W in the X-band.

Instead of the electron-beam exposure technology often used in lithography for GaN power FETs at C-band and higher frequencies, Toshiba has adopted stepper exposure that it claims is better suited to the mass production of X-band FETs, which require a gate length of less than 0.5 microns.

Toshiba has established manufacturing technology for GaN power FET in the 50W range and started to release samples. It expects to start mass production within six months.

Toshiba is confident the breakthrough opens the way to even higher frequencies of 12–18GHz (Ku-band).

www.toshiba.co.jp

RFMD sampling GaN wideband PAs

RF Micro Devices Inc of Greensboro, NC, USA is sampling its GaN wideband power amplifier ICs, for Tier 1 WiMAX, cellular base-station and public mobile radio (PMR) applications, for production shipments starting in early January.

"Our GaN process technology positions RFMD to provide the high-power, broadband solutions needed to meet growing customer demand for more cost-effective and more efficient deployment of next-generation wireless infrastructure," said Jeff Shealy, VP, Infrastructure Product Group. "RFMD's GaN power ICs deliver a simple, single-amplifier solution for wideband applications dependent on maximizing power, bandwidth and efficiency."

The range includes multiple PAs: RF3820 (8W P1dB cellular, 1.8-2.2GHz), RF3821 (8W P1dB WiMAX, 2.3-2.7GHz), RF3823 (8W P1dB WiMAX, 3.3-3.8GHz), RF3822 (14W saturated power PMR, 100-1000MHz). Both WiMAX PAs provide 29dBm linear output power with 2.5% EVM and flat gain of 11dB across multiple bands. The cellular PA provides 27dBm linear output power with –50dBc ACPR and flat gain of 13dB across DCS/PCS/WCDMA frequency bands. The PMR PA provides 14–12W saturated output power and flat gain of 11.5dB with PAE of 65% mid-band at 500MHz. The designs operate on a 28V rail and include internal-matching elements to deliver a 50Ω interface over the band of operation. They are packaged in a thermally enhanced AlN package for efficient heat removal.

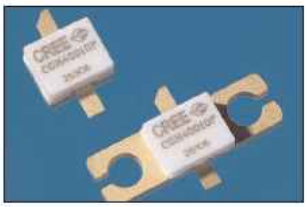
RFMD's GaN wideband PAs.

www.rfmd.com

GaN HEMTs for broadband

Cree Inc of Durham, NC, USA is producing sample quantities of two general-purpose high-power GaN HEMTs for broadband applications. The 10W CGH40010 and 45W CGH40045 operate at up to 4GHz with 14dB of associated power gain and 65% drain efficiency at 28V.

Their efficiency, high gain and broad bandwidth suit linear and compressed amplifier circuits, says Cree. Target applications include general-purpose broadband amplifiers and critical communications systems used by police, fire departments and homeland security. The GaN HEMTs can "significantly outperform existing GaAs or Si LDMOS technology in broadband systems that need wide-bandwidth, low-power or high-efficiency performance," said Jim Milligan, product manager for wide-bandgap RF products.

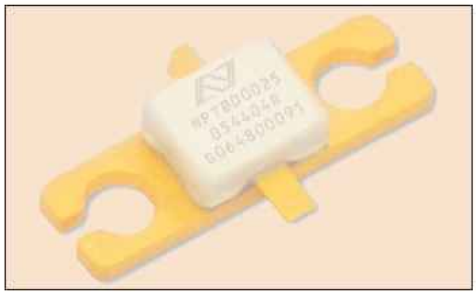


www.cree.com

Nitronex launches broadband RF power transistors

Nitronex of Raleigh, NC, USA has made available the first two in a series of parts from its broadband product line of RF power transistors. The NPTB00025 and NPTB00050 are suited to applications requiring high power and broad bandwidth, e.g. public safety radio networks, medical instrumentation and military systems.

At 3GHz and 28V, the NPTB00025 delivers saturated power of 25W, with small-signal gain of 13.5dB and drain efficiency of 65%; the NPTB00050 provides 50W, with small-signal gain of 11.5dB and drain efficiency of 60%. A large-signal, nonlinear model is also available for both in either ADS- or Microwave Office-compatible formats. Both operate at frequencies from as low as 125MHz up to 3.8GHz.



Nitronex's 25W NPTB00025 GaN broadband RF power transistor.

"These RF transistors are designed to exploit the larger impedances offered by our GaN-on-Si HEMT technology, allowing our customers the design ease and freedom to optimize for power, gain and high efficiency over very wide bandwidths," says Kevin Linthicum, chief technology officer and VP of Engineering.

"Nitronex is committed to the RF power market. In the coming months we will unveil higher-power versions of these parts, including devices developed in Gemini packages."

These latest products are made possible partly by Nitronex's NRF1 SIGANTIC GaN-on-silicon manufacturing process, which Nitronex announced as being fully qualified for volume production at October's WiMAX World event in Boston, while making available the first three members of its family of discrete high-performance RF power transistors for power amplifiers in WiMAX infrastructure: the 50W/28V 3.3–3.8GHz NPT35050 and the 15W/28V 3.3–3.8GHz NPT35015 and 2.3–2.7GHz NPT25015

www.nitronex.com

IQE acquires MBE Technology

IQE plc of Cardiff, UK has closed the acquisition of Singapore-based rival epiwafer foundry MBE Technology for S$23m (£7.5m): half in an initial cash payment plus half in loan notes (bearing 6.5% interest) repayable in three instalments in January 2008, June 2008 and January 2009.

To finance the cash payment plus working capital, on 27 December IQE placed 25 million new ordinary shares at 18p per share (about 6% of the company's enlarged ordinary share capital) on the London Stock Exchange's AIM market (on which IQE's existing shares trade), raising about £4.5m before expenses.

As MBE Technology is profit-making, the acquisition will be immediately earnings enhancing, reckons IQE.

Following August's acquisition of Emcore's Electronic Materials Division (EMD) in Somerset, NJ, USA (now IQE RF), MBE Technology completes IQE's strategy to become the largest outsource supplier of epiwafers to chip manufacturers for the wireless industry, with the industry's broadest range of products, says IQE's chief executive Dr Drew Nelson.

MBE Technology was incorporated in Singapore in 1993 and is a manufacturer of epiwafers for high-speed electronic components in the wireless and optical telecoms industries. It is expected to generate 2006 revenues of US$15m and earnings before interest, taxes, depreciation and amortization (EBITDA) of over US$3.2m. IQE says that MBE has a strong customer base across the Far East, including a strategic supplier agreement with "a substantial Japanese electronics manufacturer" and excellent links into Taiwan, China and Korea. The acquisition provides opportunities to use the new base in Asia to accelerate sales into the Pacific Rim wireless industry, the firm says. "The addition of a manufacturing and formal sales base in the Far East significantly increases our profile in the region and establishes a truly global presence for the group," adds Nelson. As part of a larger group, MBE has the support necessary to exploit the regional opportunities by meeting the rapidly increasing demands of the mobile communications sector.

IQE says it now has a dual-source manufacturing capability for all its wireless products, with facilities in Singapore, the USA, and the UK qualified for the production of epiwafers for RF components. "This brings significant manufacturing synergies, allowing us to more fully leverage our global purchasing power [of raw materials] and excess manufacturing capacity at our facilities in the US [as demand, particularly from the Pacific Rim, continues to grow, particularly for RF/wireless products]," says Nelson.

According to Strategy Analytics, the amount of GaAs wafers used in mobile phones alone is expected to at least double between 2005 and 2009, driven by increasing mobile handset sales and consumer demand for increased functionality, higher-data-rate access, and more comprehensive interactive content, plus the addition of WiFi, WiMAX and wireless media. "IQE is the only wafer company capable of supplying products for the full spectrum of the wireless market, from handset to infrastructure," claims Nelson. "We can provide our customers with complete assurance of supply and a one-stop shop for all of their wafer requirements."

IQE now has about 320 staff and operate six manufacturing facilities: MBE-based epiwafer manufacturing at IQE Singapore and IQE Inc (in Bethlehem, PA, USA) and MOCVD-based epiwafer manufacturing at IQE RF (in Somerset, NJ) and IQE (Europe) Ltd and IQE Silicon Compounds Ltd at its Cardiff headquarters, plus substrate manufacturing Wafer Technology Ltd (in Milton Keynes, UK), as well as nine sales offices worldwide.

Following the EMD acquisition, Strategy Analytics predicts that the addition of MBE Technology will increase IQE's market share by at least 123% in 2007. "There remains the not insignificant challenge of integrating two smaller companies, but if IQE can overcome this challenge, Strategy Analytics believes IQE can use the acquisition of MBE Technology to improve its customer ratings and cement a sustainable position as the world's number-one supplier of GaAs epitaxial substrates," the firm adds.

www.iqep.com

In a trading update for full-year 2006, IQE said it had continued to perform well in the second half, with the overall business performing in line with expectations. Demand for its wafer products continued to be strong in all sectors.

The weak US dollar impacted revenues, but the natural hedging from a significant proportion of group costs being in US dollars has reduced the impact on profitability.

The integration of the former EMD facility has been successful, with demand for its wireless products exceeding expectations. The ability to 'multi-source' wireless products from within the group is proving to be a major benefit, says IQE. It has also provided the opportunity to qualify new and existing customers with additional wireless products and to accelerate development of next-generation products such as BiFET epiwafers.

These developments have resulted in some additional costs during second-half 2006, but are expected to benefit the group significantly in 2007. IQE will report preliminary results for full-year 2006 in March.

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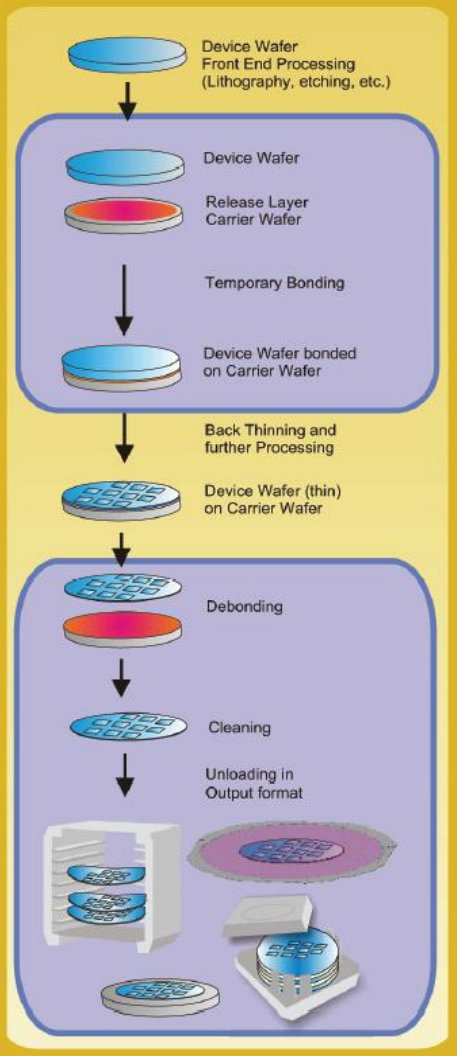

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Tegal gets etch order from Skyworks

Plasma etch and deposition system maker Tegal Corp of San Jose, CA, USA has received an order for a 6500 Advanced Etch cluster tool from GaAs IC maker Skyworks Solutions Inc of Woburn, MA, USA for shipment to its 4" fab in Newbury Park, CA. The high-vacuum system will be used to etch SiN and other critical thin films for devices to be incorporated in wireless handset, automotive, broadband, cellular infrastructure, industrial and medical applications.

"The 6500 Advanced Etch system was selected on the basis of the unique capabilities of our innovative HRe- (High-density Reflected electron) source," says president and CEO Thomas Mika. "A key focus area for our company is the compound semiconductor space, which is seeing renewed growth due to the ubiquitous usage of wireless electronics."

"The HRe- chamber enables us to etch films on GaAs substrates at a low temperature with suitable etch rate, etch profile and selectivity to mask and underlayer," says Dr Nercy Ebrahimi, Skyworks' director of Process Technology. "These etch characteristics are important for us to manufacture our advanced wireless devices [AlGaAs and InGaP HBTs, and GaAs BiFETs]," he adds.

www.tegal.com

BOC Edwards opens new European headquarters in Grenoble

To be closer to key customers in Grenoble's 'cluster of competence', BOC Edwards, a supplier of vacuum, abatement, chemical management equipment and services, has opened a 900m^2 European semiconductor headquarters in Grenoble, France (in the Bernin Industrial Zone next to STMicroelectronics' Crolles fabs) and transferred its European semiconductor team from Crawley, West Sussex, UK.

The firm has initially relocated 50 staff from its sales, business management and applications engineering functions. It also intends to leverage the R&D concentration in the area to hire for technical positions in engineering, project management, and service and support.

BOC Edwards has more than doubled in size over the past decade to well above $1bn, due to "organic growth and a series of strategic mergers and acquisitions, mainly focused on on-tool vacuum, gas and liquid extraction, and treatment technologies," says Olivier Blachier, general manager, Europe semiconductor business. The move will support this growth. "We intend to increase our presence in key markets such as the photovoltaic industry, compound semiconductor devices and outsourcing services."

www.bocedwards.com

Veeco gives APAC VP global role

Veeco Instruments Inc has appointed Benjamin Loh Gek Lim to the new position of executive VP of Global Field Operations, which includes managing the firm's global sales and service organization.

Loh was formerly senior VP, Asia Pacific Operations. Asia is now about 40% of Veeco's revenues and its fastest growing region. "We intend to leverage Benjamin's skills to a more significant role," said chairman and CEO Edward H. Braun. "He will have a particular focus on enhancing our market penetration, accelerating new product sales, and increasing customer satisfaction."

Loh is the first senior Veeco corporate executive to reside in the APAC region. Prior to joining Veeco in 2005, he was SVP of Asia at Unaxis and president of Unaxis Shanghai.

Also, John Bulman, former head of worldwide sales, takes on the role of senior VP, North American and Worldwide Sector Sales. "Bulman's experience and industry relationships will continue to benefit Veeco as he focuses on extending Veeco's relationships with key customers in our data storage, HB-LED/wireless, semiconductor and scientific research markets," Braun added.

www.veeco.com

Aviza Japan president appointed to expand presence

Etch and deposition system maker Aviza Technology Inc of Scotts Valley, CA, USA has appointed Dr Masaaki Yashiro as president of Aviza Technology Japan K.K., responsible for managing day-to-day operations. He will support Aviza's current client base in Japan, and further broaden and strengthen Aviza's market presence in the region.

Yashiro will report to Rick O'Malley, VP Worldwide Sales and Customer Support. "Aviza remains committed to supporting our existing Japanese customers and expanding our presence in this important region," said O'Malley. "We believe that he will play an important role in our efforts to further expand the company's business in the Japanese market."

Yashiro has held positions in executive management, operations, program management and process engineering. He joins from SEZ Group where he was president and chief operating officer of SEZ Japan. Previously, he was VP, Corporate Development and Technology at Tokyo Electron Ltd. He also worked at Texas Instruments for about 15 years.

www.avizatechnology.com

Veeco receives four orders for R&D MBE systems

Veeco Instruments Inc of Woodbury, NY, USA has received four orders for its R&D molecular beam epitaxy systems, extending across its R&D product line including a GEN20, GEN930, GEN II, and a GEN III.

The systems are planned for a range of development efforts by research groups in Europe, Japan, and the USA. The GEN20, the latest development platform addition to the product line, will manufacture quantum dots. Similar to other systems operating in oxides, the GEN930 will support a 'leading institute' in the development of next-generation logic devices. The GEN II and GEN III systems will support III-V and high-mobility developments, respectively.

"The GEN20 system order further solidifies the success of this product as a scalable platform from development through pilot production," says Jeffrey Hohn, vice president, general manager Veeco MBE Operations.

The GEN20 is the only 4" system in the industry that can be upgraded from a manual wafer transfer configuration to a system with an automated cluster tool, enabling 24x7 operation, claims Veeco. The flexibility of the pumping configuration, wafer handling options and high-wafer throughput suit both government labs and pilot production environments. The continued development and advancement of the GEN II and GEN III systems, with their large installed base, suits high-mobility devices and general III-V research. The GEN930 configured for oxides is a powerful and affordable system for emerging oxide applications, Veeco adds.

www.veeco.com

Riber receives second order for Compact12 MBE reactor

MBE reactor maker Riber of Bezons, France has received a second order for its Compact12 research machine (introduced in 2005), to be delivered in Europe in the next fiscal year.

The Compact12 is at the entry level of Riber's range. It is targeted at research labs and institutes carrying out academic or basic research in nanotechnology, as well as feasibility work on new materials or processes, in fields such as semiconductors, metals, oxides and organic semiconductors. It benefits from attractive cost of purchase and operation, as well as ease of use and flexibility, says Riber.

"We expect sales development of this product in the years to come, as we have good feedback on our market target and high interest from our customers for this machine," said Michel Picault, president of Riber's executive board.

- Riber has received an order for a Compact21HM MBE research system (a variant of the Compact21) from an unnamed research institute in China.

Riber says it currently has 14 research machines installed with 10 clients in China, which it views as an important market due to its considerable investment in R&D.

www.riber.com

IN BRIEF

Arima buys Veeco TurboDisc E450 MOCVD system to ramp up auto LED production

Taiwanese high-brightness LED maker Arima Optoelectronics Corp has bought a TurboDisc E450 As/P MOCVD system from Veeco Instruments Inc (its largest-capacity system) to produce epiwafers for automotive LED applications, as it expands production of red, orange and yellow (R/O/Y) LEDs.

Veeco's TurboDisc As/P tools offer integrated RealTemp 200 technology for direct wafer temperature control, and fast gas switching for control of interface abruptness. The E450 is Veeco's largest capacity MOCVD production system, and can be used for the mass production of R/O/Y HB-LEDs, HBTs, pHEMTs, and multi-junction solar cells.

www.veeco.com

Largest-capacity MOCVD system ready for production

Aixtron AG of Aachen, Germany says that the world's largest-capacity MOCVD system for nitride production, the new Aixtron 42x2-inch AIX 2800G4 Planetary Reactor system, is now operational at one of its long-term customers in Asia (the launch customer for the AIX 2800G4 mass-production system).

The system was signed off within just a few weeks from delivery, and has already been put into production. Due to the new Yield-Plus features, it is performing better than previous systems, says Aixtron.

www.aixtron.com

IN BRIEF

Metryx gets order from US GaAs maker

Metryx Ltd of Bristol, UK says that a leading US-based GaAs volume manufacturer of surface acoustic wave (SAW) and bulk acoustic wave (BAW) devices for the communications industry has placed an order for its Mentor OC23 Mass Metrology system, for measuring both deposition and etch processes on product wafers in volume production.

The order highlights the broad range of applications where mass metrology can be implemented to monitor and characterize processes, says the company. Metryx's technology can be used to monitor product wafers in volume production environments for dielectric and conducting materials in etch, deposition and chemical-mechanical planarization (CMP) process applications.

www.metryx.net.

SEMATECH's VP of Strategy becomes Rudolph's COO

Rudolph Technologies Inc of Flanders, NJ, USA, which supplies process control metrology, defect inspection and data analysis systems, has appointed Alex Oscilowski chief operating officer.

"He comes to us directly from SEMATECH [the R&D consortium in Austin, TX] where he has been VP-Strategy," says chairman and CEO Paul F. McLaughlin. "His strong leadership and global network of relationships within our customer base make Alex an excellent choice."

Oscilowski spent his early career at Texas Instruments and Digital Equipment Corp, and has been president of assembly equipment maker Kulicke & Soffa Industries, responsible for global business.

www.rudolphtech.com

TEM sample prep system with adaptive ion milling technology

At the Electronic Device Failure Analysis Society's 32nd International Symposium for Testing and Failure Analysis (ISTFA) in Austin, TX, USA in November, SELA Ltd of Upper Yokneam, Israel, which has supplied over 250 engineering and failure analysis systems since 1992, launched the Xact, the first transmission electron microscopy sample preparation system using new AIM (Adaptive Ion Milling) technology.

The new system was developed to overcome the limitations of focused ion beam (FIB) technology regarding artifacts, size of selected area, lamella thickness and productivity.

The Xact incorporates a scanning electron microscopy and scanning transmission electron microscopy unit. The twin-beam technology is uniquely configured to enable artifact-free sample clarity and automated, in-line, precise end-point detection.

A key feature of AIM is a versatile ion gun assembly with controllable energy for not just aggressive milling but also gentle milling, and a controllable dynamic beam that can impact a specimen at a multitude of angles.

AIM reduces sample widths to <50nm over a large area with high precision, artifact-free (wedge-like) quality, high throughput, and low cost of ownership, SELA claims. The system incorporates a five-axes positioning and micro-positioning manipulator for loading/unloading, alignment, calibration and movement of the sample holder. An optimized air lock allows rapid sample loading and vacuum readiness. The Xact is also recipe driven for accuracy and ease of use.

"The Xact addresses engineering and FA problems linked to the semiconductor and nanotechnology industry roadmap for at least the next two to three generations," says CEO Colin Smith. "Our AIM technology is incorporated in a twin-beam system engineered specifically for sample preparation."

Sela is already working on customer samples and is processing a new tool order for delivery within the next quarter.

www.sela.com

Vistec consolidates in Weilburg

Vistec Semiconductor Systems GmbH, which makes wafer process control systems and mask metrology systems, has consolidated all of its operations (including its headquarters in Wetzlar and about 160 marketing, administrative and R&D staff will move to Weilburg) to a single location in Weilburg, Germany (where it already had a production site with 80 staff).

A €5m investment program has expanded the facility to 12,000m^2, including new IT infrastructure, cleanrooms (enlarging the total area to 1700m^2) and a 250m^2 equipment demonstration cleanroom.

General manager Gerhard Ruppik expects "optimized processes by concentrating our activities in a single site...we can now easily expand to accommodate future growth in demand."

Vistec's cleanroom in Weilburg.

Vistec was previously Leica Microsystems Semiconductor GmbH until being bought from Leica by US capital investment company Golden Gate Capital in 2005.

www.vistec-semi.com

K&S appoints GM for Alphasem die bonder operation

In November, wire bonding equipment maker Kulicke & Soffa Industries Inc of Fort Washington, PA, USA paid Dover Technologies International Inc $27.1m to acquire the die bonding equipment maker Alphasem in Berg, Switzerland. Alphasem has 260 staff and in 2005 had sales of $60m and a 10% share of the $520m die bonder market, according to VLSI Research.

K&S has since appointed Richard Boulanger as general manager of what is now K&S Switzerland, responsible for manufacturing, R&D, product development and business operations (including developing a next-generation die bonder platform and expanding into new markets). "Richard will ensure a smooth transition among K&S, Alphasem employees and our worldwide customer base," added equipment segment VP Christian Rheault.

Most recently, Boulanger was VP of the Advanced Semiconductor Assembly Division of Universal Instruments Corp, which provides solutions for the precision placement of flip chips and bare die. He also worked at IBM's assembly & test plant in Bromont, Quebec, Canada.

"This acquisition is a step forward in our strategy to extend our core products and technologies...as we expand the K&S role in semiconductor assembly," said CEO Scott Kulicke. "Alphasem is a natural extension of K&S's core equipment business into die bonding equipment," added Rheault. "Wire bonders and die bonders share many common functions, software features, sub-assemblies, and components...joining the engineering and manufacturing expertise of Alphasem and K&S will yield superior equipment platforms." The acquisition is "an investment in growth at a reasonable price".

For its fiscal Q4/2006 (to end-September), K&S' revenues were $161.4m, down slightly on $162m a year ago. Equipment revenue fell from $71.1m the prior quarter to $54.9m, but exceeded the high end of guidance by $4m. "Our customers did not over-spend for capacity during previous peak periods, so we did not see a marked correction for excess capacity, as some industry analysts had predicted," says Kulicke. Gold wire revenue rose (from $52.1m and $75.3m the prior quarter to $80.4m).

So, despite the Equipment segment maintaining a gross profit margin of 43.1%, higher gold metal cost cut total gross profit margin by 1.5% to 24.2%. Despite the 12th sequential quarter of profitability, net income was down from $20.6m to $9.3m.

For fiscal 2006, revenue rose from fiscal 2005's $475.5m to $696.3m, and income from $33.3m to $73.4m.

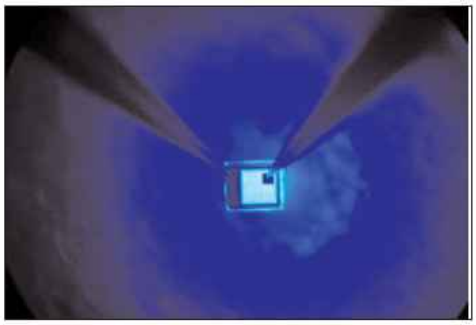
For the December quarter, K&S expects lower gold metal sales and a further drop in wire bonder sales to yield revenue of $140–150m (including about $7m in two months of Alphasem die bonder revenue).

www.kns.com

Record-efficiency nonpolar and semipolar GaN LEDs

Researchers at the Solid State Lighting & Display Center (SSLDC) of University of California, Santa Barbara (UCSB) and the Japan Science & Technology Agency's Exploratory Research for Advanced Technology program (JST ERATO) have set new records for external quantum efficiency in LEDs based on nonpolar and semipolar orientations of gallium nitride.

For standard sizes (300μm x 300μm) and operating current (20mA), the new nonpolar LEDs have an external quantum efficiency of 41% and radiant powers as high as 25mW; the semipolar LEDs exhibit external quantum efficiency of 30% and radiant powers as high as 18mW.



Blue light emission from GaN. Photo © 2006 Randall Lamb (UCSB).

The polarized light emission should enable a new class of light sources and will be useful in applications such as the backlights of liquid crystal displays, since the polarized light emission from nonpolar and semipolar LEDs does not necessitate a polarizing filter (unlike conventional LEDs). The commercial applications of non-polar LEDs also include projection televisions, medical imaging and general illumination.

The groups, led by professors Shuji Nakamura (formerly of Nichia), Steve DenBaars and James Speck, have also achieved conventional c-plane LEDs with external quantum efficiencies of 66% and power output of 35mW. These have been used to make white LED lamps with a luminous efficacy of 116lm/W (more than both incandescent bulbs and fluorescent lamps).

Funding for the research was jointly provided by JST ERATO and the SSLDC's member companies.

www.ssldc.ucsb.edu

BluGlass boosts team to prepare for commercialization

BluGlass Ltd of Sydney, Australia, which was spun off from Macquarie University in June 2005 and raised $7.7m in an initial public offering this September, has appointed three industry specialists to assist in developing and commercializing low-cost gallium nitride-on-glass manufacturing technology (which it demonstrated on 4-inch substrates in November).

Alistair Mitchell has been appointed Operations and Project Engineer, Dr Nancy Lumpkin becomes Operations Engineer, and Stuart Craig joins the firm as Business Development Manager.

Craig brings experience in driving commercialization in high-technology industries, including as CEO of Sydney-based epiTactix Pty Ltd, which was spun off from Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) in 2004 and develops compound semiconductor devices, low-cost wafer fabrication processes and custom ICs for radio systems. Craig has been responsible for the structuring of a number of start-ups, says BluGlass.

Lumpkin has more than 25 years experience in the start-up of semiconductor device production plants and was a key member in the establishment of another Australian semiconductor fabrication facility (including developing and fabricating HEMTs and HEMT-based amplifiers at the CSIRO GaAs IC Facility). She specializes in process design and training.

Mitchell has more than 20 years experience in the semiconductor industry, specializing in the development of process efficiencies, specifically in minimizing environmental impact while maximising cost efficiencies. Mitchell has established several pilot- and commercial-scale technology development and manufacturing plants, and has authored two patents for semiconductor device processes.

"These appointments bring to BluGlass a unique skill set that will be instrumental in the set up and running of the BluGlass pilot manufacturing plant," says CEO David Jordan. "Part of the process of achieving the full potential of our technology is to build a powerful and robust professional team," he adds.

● Macquarie University has given BluGlass its Commercial Innovation Award. The research team, led by Dr Scott Butcher, was recognized for inventing its GaN process.

"The award represents not only the commercial potential of the invention, but also its potential to reduce greenhouse gas emissions through the use of GaN-based energy-efficient lighting", says Jordan. It also congratulates the team responsible for driving the commercial strategy, he adds.

The award was judged on inventiveness, exploitation, and alignment with community values.

www.bluglass.com.au

Reduced-bowing GaN on sapphire-on-AlN substrates

Sandia National Laboratories has demonstrated the growth of GaN structures on the A-Sapph sapphire-on-AlN substrates of Aonex Technologies Inc, a majority-owned subsidiary of Arrowhead Research Corp of Pasadena, CA, USA.

Aonex was founded in 2004 by chief scientific officer Harry Atwater (the Howard Hughes professor of Applied Physics and Materials Science at Pasadena-based California Institute of Technology). Aonex has an exclusive license to a suite of intellectual property developed at Caltech.

Aonex claims its substrates provide a way to cut the manufacturing cost of III-nitride LEDs via production on larger-diameter substrates, simplifying the fabrication of more efficient vertical LEDs, and increasing process uniformity and yield.

A-Sapph substrates consist of a thin layer of single-crystal sapphire (less than 500nm thick) bonded to a polycrystalline AlN support substrate. This offers an industry-standard sapphire growth surface (in either c- or r-plane sapphire orientations) suitable for growth of epilayers by MOCVD or HVPE. The AlN substrate is subsequently removed due to its undesirable optical properties.

Sandia grew GaN on both A-Sapph and bulk sapphire reference substrates using MOCVD. It then characterized the GaN using an x-ray diffraction (XRD) defect estimation technique developed at Sandia. This indicates that GaN grown on A-Sapph substrates has a defect density within 60% of that grown on the bulk reference. Ongoing efforts at Aonex to optimize the growth surface of the A-Sapph substrate are focused on achieving GaN quality that meets or exceeds GaN grown on conventional sapphire substrates.

XRD also showed that the GaN grown on A-Sapph substrates had reduced residual strain relative to GaN grown on conventional sapphire substrates. Unlike conventional sapphire substrates, the A-Sapph sapphire-on-AlN substrate has a coefficient of thermal expansion (CTE) that is nearly identical to the GaN epilayers of the device structure, reducing substrate bowing during device growth. This verifies that the substrates can address the processing challenges encountered with GaN growth on conventional sapphire, claims Aonex. This could result in higher-yield post-growth device processing, especially for HEMTs or other device structures where submicron features are desired.

GaN grown on A-Sapph has a defect density within 60% of that grown on the bulk reference... and reduced residual strain relative to GaN grown on conventional sapphire substrates

Also, A-Sapp substrates offer substantially higher thermal conductivity than bulk sapphire, which may significantly improve growth uniformity through improved substrate temperature uniformity, says Aenox.

III-nitride materials on A-Sapph substrates have sufficient optoelectronic performance to fabricate LED devices

Reducing wafer bow via these improved thermal characteristics could enable the scaling of high-yield GaN device production to much larger-diameter wafer diameters, correspondingly reducing production cost for GaN-based optoelectronic devices. Aonex currently uses 2″ substrates, but its long-term goal is 4″ in diameter.

Sandia also grew 430nm InGaN multi-quantum well (MQW) structures on both substrates. Comparable photoluminescence intensities indicate that III-nitride materials on A-Sapph substrates have sufficient optoelectronic performance to fabricate LED devices, says Aenox. Efforts are currently underway to fabricate functional LEDs for additional characterization. Aonex says it has also designed A-Sapph substrates to enable vertical LED fabrication without laser lift-off.

In addition to A-Sapph, Aonex also offers A-GaN substrates, which consist of thin layers of single-crystal GaN bonded to a polycrystalline AlN support wafer. A-GaN substrates offer a lower-cost alternative to bulk GaN wafers for devices such as blue-violet laser diodes and high-brightness blue and white LEDs, claims Aenox. The market for A-GaN substrates is more near-term than that for A-Sapph substrates, says Aonex's president Sean Olsen.

Aonex is currently sampling its substrates to select device and wafer manufacturers.

● Aonex also has a research program developing substrates for the solar industry. "For photovoltaic devices, we transfer layers of Ge and InP onto silicon support substrates," says Olsen. "We also look to layer transfer to integrate non-lattice-matched materials for high-efficiency, multi-junction cells.

However, the solar effort is secondary compared to that for nitride products, for which there is "more near-term demand", says Olsen.

www.arrowheadresearch.com

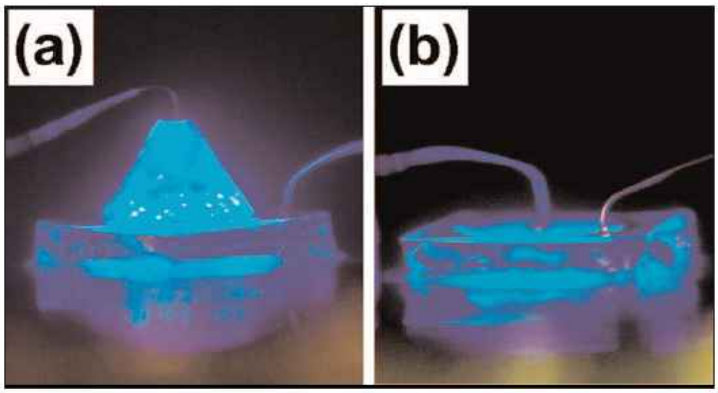
Pyramid ZnO electrode doubles GaN LED light extraction

Researchers led by Shuji Nakamura and Steven P. DenBaars at the University of California, Santa Barbara, supported by the Solid State Lighting and Display Center (SSLDC), have reported 'Hexagonal pyramid-shaped light-emitting diodes based on ZnO and GaN direct wafer bonding' (Murai et al, Appl. Phys. Lett. **89**, 171116) to improve LED efficiency by fabricating a highly transparent and shaped p-type electrode.

A highly transparent, 500μm-thick n-type ZnO substrate (with an electrical resistivity of 0.2Ωcm) grown by a hydrothermal method was wafer bonded directly to a III-nitride LED wafer grown by MOCVD on a sapphire substrate. Then selective chemical etching with diluted HCl of the O face of the ZnO wafer formed an electrode with a truncated hexagonal pyramid shape about 800μm across its base, with faces formed by the {10–11} plane, inclined at an angle of about 60° to the Ga-face c-plane GaN. Ti/Au contacts were deposited on the n-type GaN and n-type ZnO to form the n-pads and p-pad, respectively.

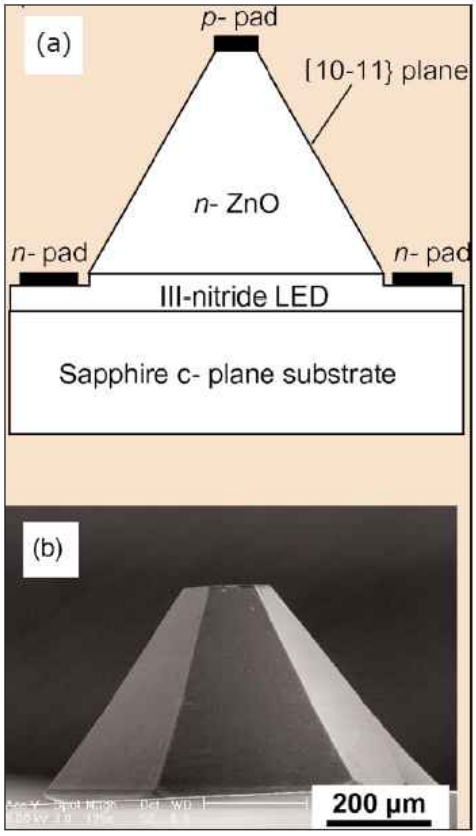
The optical output power of the wafer-bonded LED chip was evaluated as a function of forward current under direct current dc injection using an integrating sphere and spectrometer system. Compared to a conventional LED chip with a thin Ni(5nm)/Au(10nm) semi-transparent p-type electrode (fabricated from the same GaN wafer), the optical output power was found to be 3.3 times higher at a forward current of 5mA and 2.2 times higher at a forward current of 20mA. For both LEDs, the junction area was a hexagon of 0.46mm^2.

The peak wavelength of emitted light was 460nm, emitted mainly from the truncated hexagonal ZnO pyramid to air and partially from the sapphire substrate. So, it is considered that this transparent and shaped ZnO electrode is effective for light extraction improvement.



SEMs of LED chips with: (a) pyramid-shaped ZnO; (b) thin Ni(5nm)/Au(10nm) p-type electrode.

It is known that, for AlGaInP/GaP LEDs, the truncated-inverted-pyramid geometry decreases the mean photon path length within the crystal, reducing the effects of internal loss mechanisms. The ZnO wafer-bonded LED is therefore considered to have a light extraction efficiency advantage over conventional LEDs due to a reduction of internal light reflections and absorption at the p-type electrode.



(a) Cross-sectional schematic and (b) SEM of wafer-bonded GaN LED with truncated hexagonal ZnO pyramid.

The external quantum efficiency (EQE) as a function of forward current was much higher at relatively low current (4.3 times higher at 1mA) than that of the conventional LED. However, it decreased at higher current compared to the conventional LED, which saturated. Imperfect wafer bonding in some places may be causing inhomogeneity in the current density at the ZnO/GaN interface and therefore in the accompanying additional heat generation. Heat generation near the active layer can decrease the internal quantum efficiency, which can cause a decrease in EQE.

However, the EQE values at low current injection indicate room for improvement at high current, the researchers say. Improvement of the wafer bonding process should solve this problem, it is reckoned.

The current-voltage characteristic exhibited good rectification, with a threshold voltage of around 3V, despite the additional GaN-ZnO pn junction. In the forward bias voltage region, the series resistance was about 90Ω (compared with 13O for the conventional LED), due mostly to the wafer-bonded interface. This will be decreased by improving the device fabrication process, say the researchers.

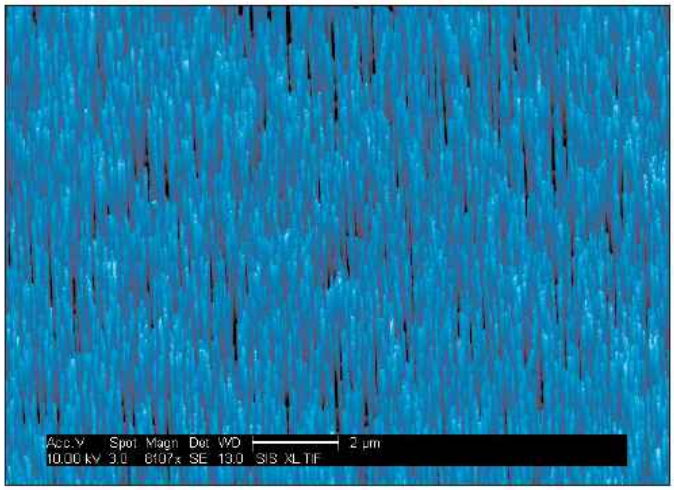
www.ece.ucsb.edu

First p-type ZnO nanowires could lead to cheaper LEDs

Funded by the US Office of Naval Research (ONR-nanoelectronics), the National Science Foundation, and Sharp Labs of America, scientists at University of California, San Diego, in collaboration with Peking University's Electron Microscopy Laboratory, have reported the synthesis of the first high-quality p-type zinc oxide nanowires ('Rational Synthesis of P-type Zinc Oxide Nanowire Arrays Using Simple Chemical Vapor Deposition', Xiang et al, Nano Letters; doi: 10.1021/nl062410c). Their use of a simple, low-cost ZnO CVD growth technique could pave the way for a new type of LED that could be less expensive than current blue, green and white LEDs fabricated using more costly GaN-based materials and the MOCVD growth technique, it is claimed.

For years, researchers have been able to make electron-rich, negatively charged n-type semiconducting ZnO nanowire crystals, but have not been able to make the hole-rich, positively charged p-type semiconducting ZnO nanowires that are also needed to form pn junctions in many electronic and optoelectronic devices, including LEDs. "ZnO is a wide-bandgap semiconductor, and generating p-type doping impurities that provide free holes is very difficult — particularly in nanowires," says Deli Wang, who is the senior author of the paper and an electrical and computer engineering professor in UCSD's Jacobs School of Engineering.

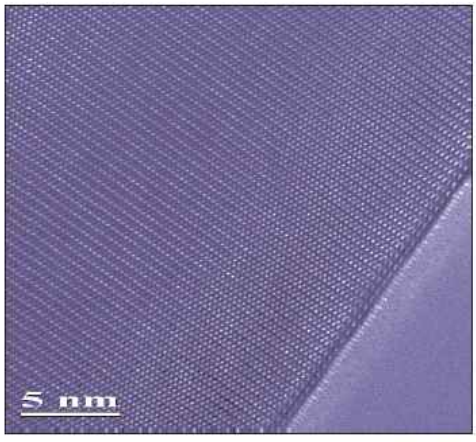
Previously, p-type conduction in ZnO thin films has been demonstrated and ZnO thin-film LEDs have been fabricated. But using ZnO nanowires rather than thin films could be less expensive and lead to more efficient LEDs, reckons Wang. "ZnO nanostructures are incredibly well studied because they are so easy to make," he adds.



SEM image of p-type ZnO nanowires. N.B The blue color has been added. (Photo: Deli Wang/UCSD)

To make the p-type ZnO nanowires, the scientists doped ZnO crystals with phosphorus. Adding phosphorus atoms to the ZnO crystal structure leads to p-type semiconducting materials through the formation of a defect complex that increases the number of holes relative to the number of free electrons. The starting materials and CVD manufacturing costs for ZnO LEDs are far less expensive than those for MOCVD-grown GaN-based LEDs. In future, Wang expects to cut costs even further by making p-type and n-type ZnO nanowires from solution.

p-type doping in nanowires could make complementary ZnO nanowire transistors possible



High-resolution TEM image of ZnO:P nanowires: high-quality single crystal with clean and smooth surface, with no amorphous layer coating.

Wang has filed a provisional patent for p-type ZnO nanowires. His lab is currently working on a variety of nanoscale applications. "Now that we have p-type ZnO nanowires, the opportunities for LEDs and beyond are endless," he says. "ZnO is a very good light emitter. Electrically driven ZnO single-nanowire lasers could serve as high-efficiency nanoscale light sources for optical data storage, imaging, and biological and chemical sensing," adds Wang.

Having both n- and p-type ZnO nanowires — complementary nanowires — could also be useful in a variety of applications including transistors, spintronics, UV detectors, nanogenerators, and microscopy. Transistors that rely on the semiconducting properties of ZnO are now on the horizon: "p-type doping in nanowires could make complementary ZnO nanowire transistors possible," says Wang. In spintronics applications, p-type ZnO nanowires could be used to make dilute magnetic semiconductors by doping ZnO with magnetic atoms, such as manganese and cobalt, he adds.

http://pubs3.acs.org/acs/journals/doilookup?in_doi=10.1021/nl062410c

Cree extends patent litigation against BridgeLux

LED chip maker Cree Inc has expanded its patent litigation against BridgeLux of Sunnyvale, CA, USA (which was founded in 2003 as eLite Optoelectronics Inc) with claims of infringement of US patents 6,614,056 and 6,885,036 (both of which are titled 'Scalable LED With Improved Current Spreading Structures').

The latest litigation is a counter-claim in response to BridgeLux's complaint filed in October in the US District Court for the Eastern District of Texas alleging infringement of BridgeLux's US patent 6,869,812 (see October/November issue, page 29). This followed Cree's initial claim filed in September alleging infringement by BridgeLux of Cree's US patents 6,657,236 and 5,686,738 ('Enhanced Light Extraction in LEDs through the Use of Internal and External Optical Elements' and 'Highly Insulating Monocrystalline Gallium Nitride Thin Films') — see September issue, page 19.

In addition to seeking an injunction to stop on-going infringement, Cree has now also requested a declaration that BridgeLux's 6,869,812 patent is invalid over Cree's earlier patents 6,614,056 and 6,885,036.

BridgeLux's 6,869,812 patent relates to a structure for elongated geometry, which is the basis of its BSV Series side-view LED chip product line for thinner mobile displays, launched in October (see November/December issue, page 22).

Cree is also seeking a declaration that BridgeLux's patent is not infringed and that it is unenforceable due to fraud and/or inequitable conduct committed before the US Patent Office.

www.cree.com

Cree cuts forecast on lower LED chip sales

Due to lower-than-expected orders for LED chips for mobile phones, Cree Inc of Durham, NC, USA has cut its revenue forecast for fiscal Q2/2007 (to 24 December) from October's forecast of $105–109m to $90–92m (down from $103.9m last quarter and $105.6m a year ago).

Cree also forecasts gross margin of 34–35% (down from 41% last quarter and 49% a year ago). This is mainly due to lower factory utilization associated with the fall in LED chip orders, increased pricing pressure for LED chips, and higher start-up costs related to new product lines. Cree continues to expect operating expenses of about $28m.

"The LED chip market remains challenging, particularly for our mid-brightness products in mobile applications," said chairman and CEO Chuck Swoboda. "Despite the slowdown in the LED chip business, we are pleased with the growth in new product sales from our recently introduced lighting-class XLamp power LEDs [designed for use in outdoor lighting, industrial lighting, and emergency vehicles] and our ability to attract a global distributor such as Arrow Electronics," he adds. "These are important steps in our long-term strategy of growing the company through increased sales of higher-value components."

Based on its preliminary outlook for its Q3, Cree says its LED chip business will be in a similar range to Q2, with incremental growth coming from new product lines.

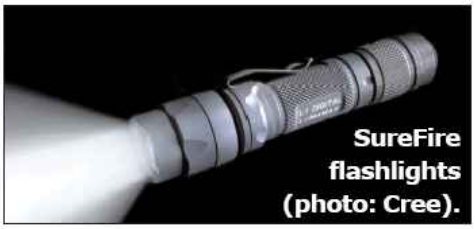
www.cree.com

Cree XLamp LEDs used in flashlights

Cree's XLamp 7090 XR-E Series of power LEDs (launched in October) has been chosen as the light source for new models of handheld flashlights by two US manufacturers: SureFire LLC of Fountain Valley, CA and ASP Inc of Appleton, WI (for its high-precision Triad flashlights for law enforcement and military use).

The new white XR-E Series LEDs produce typical luminous flux of 80lm at 350mA (an efficacy of 70lm/W). High brightness and efficiency are critical for battery-powered, portable lighting applications, says Cree. XR-E Series LEDs also produce the high-quality, uniform white light required, it adds.

"XLamp LEDs measure 40% brighter and 50% more efficient than other LED solutions," says SureFire's founder and president John Matthews. "They are easy to design into our new flashlight models and provide a pure, brilliant beam of light...we are able to design LED flashlights with far longer battery life," he adds.



SureFire flashlights (photo: Cree).

"Our customers literally stake their lives on the performance of our lighting products," says ASP's CEO Kevin Parsons. "Our new Triad product line is now a unique new class of high-performance, high-reliability safety flashlight."

● In November Cree signed a global distribution agreement for its high-power packaged LED products to be sold and supported by Arrow Electronics Inc, a "milestone in our strategy to grow global sales, marketing and distribution capabilities," said Bob Pollock, senior VP of sales.

www.surefire.com
www.asp-net.com

Noctron aligns with Chinese solid-state lighting manufacturer

After presenting prototypes of its patent-pending Noctrix and Noctrel high-power LED solid-state lighting technology during the Luxembourg Trade Mission to the People's Republic of China in September, at the end of November Luxembourg-based Noctron SARL (which was founded in 2005 and develops digital night vision, LED and optical filtering technology) signed a Memorandum of Understanding with a major Chinese solid-state lighting (SSL) manufacturer.

Noctron was offering Chinese manufacturers a joint venture (including internationally recognized intellectual property rights for worldwide production and distribution) as a corner-stone of its strategy for competitively entering the international marketplace. But Noctron is currently evaluating whether a partnership or a take-over is best. "Noctron is open for both scenarios, but we are in favour of being taken over by the right company, since this speeds up the process of bringing our newest invention in large quantities to market", said Paul Moody, director of business development.

Noctron holds the intellectual property rights for Noctrel, which it claims is the first encapsulated high-power solid-state light element providing double-sided light output like an incandescent light bulb. This first true transparent solid-state lighting element can be used in almost any light fixture designed for 360 degrees light emission.

Noctron's Noctrel SSL element.

Together with Chinese manufacturing resources, Noctrel could be produced and supplied in large quantities this year at a competitive price, initially to China and later to the rest of the world.

"We will offer our element at a price that allows the final Noctrel light bulb to compete with most of the fluorescent light bulbs in the stores," reckons managing director Frederic Tonhofer. "For 2007 we plan a test run of around 10m light bulbs with the Noctrel element, after that we will get serious." Moody adds, "In mass production by 2008, we are confident of manufacturing our basic Noctrel element for only €0.10 a piece". This, he reckons, will "shake-up the industry".

For China, this could be a fast and revolutionary way to partly solve their primary resource problem — energy consumption. "If only half of China's residents replace one incandescent light bulb with a Noctrel bulb, we are looking at an immediate demand of 650m units," says Richard Witter, head of marketing, adding "...there are not many households with only one light bulb."

Noctrix is a multi-chip white high-power LED element. Using a common phosphor mix, light output was 200lm at a drive current of 350mA and forward voltage of 10V (3.5W), i.e. a luminous efficacy of 60lm/W. However, using Noctron's patent-pending phosphor-crystal mix increases output by at least by 10%, says Tonhofer.

www.noctron.com

SDK ramps red/orange/yellow AlGaInP HB-LED capacity

To meet growing demand for use in LCD backlighting and automotive parts, Tokyo-based chemicals manufacturer Showa Denko K.K. (SDK) is investing about ¥1.5bn (about $13m) to increase production capacity of its AlGaInP red, orange and yellow ultra-bright LED chips from 30m to 100m units per month between February and Q3/2007, focusing on expanding MOCVD reactor epiwafer capacity, chip-making facilities, and cleanrooms.

While AlGaInP ultra-bright LED chips are mainly used in displays, automotive parts and traffic lights, development is underway for applications such as LCD backlighting and light sources for sensors (e.g. in auto-focusing digital camera), says SDK. The AlGaInP ultra-bright LEDs market is expected to grow at an annual rate of about 40% over the next five years, it adds.

SDK says it is seeing a sharp increase in the amount of orders it is receiving from overseas customers, and expects more to start using its product from this year onwards. The firm aims to expand its ultra-bright LED business as a new 'growth driver' by developing brighter chips for LCD backlighting and automotive applications such as car headlights, and accelerating development for general lighting. Currently, SDK aims to sell LEDs worth ¥2bn (about $17.3m) in 2007, and double that in 2008 following completion of the expansion.

www.sdk.co.jp

Record 240lm from single-die white LED

Seoul Semiconductor Co Ltd (SSC) has launched the P4 LED, which emits a luminosity of 240lm at 1A (its maximum drive current), and offers what it claims is the industry's highest luminous efficacy (100lm/W at 350mA) with just a single die. This makes the P4 brighter and more cost-effective than both conventional incandescent lighting (15lm/W) and fluorescent lighting (70lm/W), the firm claims.

"Conventional LEDs have been known to emit more than 100lm with several dies. Seoul Semiconductor's P4 is the only LED product in the world with 240lm via a single die," claims CEO Jung Hoon Lee.

SSC says the P4's the luminosity, as well as the reliability characteristics needed to meet thermal management requirements, are achieved through patented phosphor and packaging technologies.

The P4 is available in two types with different typical efficacies at 350mA (80lm and 100lm) and is designed for operation in a wide variety of lighting applications and industries, including automotive, torches, LCD TV monitor back-lights, projectors, home appliances, traffic signals, mobile phone flashes, street lights, decorative and architectural lightings, and general illumination.

P4 gives 240lm from a single die.

SSC says it plans to improve the P4's luminous efficacy to 135lm/W in 2007 and 145lm/W by the first quarter of 2008 (more than double the efficiency of standard compact fluorescent lighting).

www.seoulsemicon.com

Nichia's record 150lm/W white LED

Japan's Nichia Corp has developed a lamp-type white LED (part no. NSPWR70) with an efficacy of 150lm/W (a luminous flux of 9.4lm) and a color temperature of 4600K at a drive current of 20mA in the lab. The prototype is packaged in the same lamp-type package used for Nichia's high-flux lamp-type LED.

The efficacy is 11.5 times that of an incandescent lamp (13lm/W), 1.7 times that of a three-wavelength fluorescent lamp (90lm/W), and even better than a high-pressure sodium lamp (132lm/W), regarded as the highest-efficacy conventional light source.

In March Nichia developed 100lm/W white LEDs (and shipped samples in August). In June rival Cree reported a white LED chip delivering 131lm/W at 20mA, then in November Nichia raised the record to 138lm/W.

Nichia's 150lm/W lamp-type LED.

Nichia's 150lm/W LED has been developed sooner than the 2007 timescale targeted on its development roadmap. The product has not yet been scheduled for commercial release.

www.nichia.co.jp

Nichia loses Korean design patent rights for side-view LED

The Korean Intellectual Property Office (KIPO) has ruled that Korea's Baron Tech Co Ltd has won its 'Design Patent Invalidation' trial against LED maker Nichia of Japan, and has invalidated Nichia's Korean Design Patents for a side-view white LED used in LCD backlighting for mobile phones, PDAs, digital cameras, and navigation devices. Nichia had been supplying about $0.2bn worth annually to Korea.

However, before the ruling, Nichia concluded that maintaining its design patent would be difficult under Korea's unique design patent system, and on 1 December abandoned the patent.

The patent has the same design as the patent for which Nichia filed a lawsuit in January 2006 in the US district court for Northern California against Seoul Semiconductor Co Ltd (SSC), Korea's biggest LED maker and one of the top 10 globally, and its US subsidiary Seoul Semiconductor Inc, as well as against Creative Technology Ltd and its US subsidiaries Creative Holdings Inc and Creative Labs Inc, which had sold products incorporating SSC's LEDs. However, in late November Nichia settled the design patent litigation with Creative, while continuing the litigation against SSC.

SSC says that the ruling re-establishes fair market competition in the LED industry and strengthens SSC's presence in the backlighting LED industry. SSC also claims that the ruling could have an impact on their lawsuit and on litigation elsewhere. But Nichia has rebutted this. Because the ruling is based on Korea's unique design patent system and procedural requirements, it will not impact the validity of foreign counterparts in the US, Taiwan, Japan or China, where such circumstances do not exist, says Nichia.

DOE study sheds light on commercial LED lamp efficacies

A pilot test of four LED lamps by the US Department of Energy's solid-state lighting (SSL) Commercial Product Testing Program (launched last October) has found that they all fall short of claimed light outputs.

During the program development phase, the pilot tests examined two 'downlights' (a spotlight typically recessed into a ceiling) as well as a task light and an under-cabinet light. The four different products were chosen to represent a range of applications, designs, and manufacturers. The LED makers claimed lighting efficacies of 36–55lm/W, but the pilot test found efficacies of 11.6–19.3lm/W, placing them below compact fluorescent lamps (CFLs) in lighting efficacy.

The study suggests that manufacturers are relying on measurements of how much light an isolated LED produces rather than how much an LED lamp actually delivers. However, the results show that traditional lighting performance metrics (mainly based on lamp efficacy, not overall luminaire efficacy) do not provide an adequate indication of an SSL luminaire's performance; it is inappropriate to suggest that a high LED luminous efficacy (lamp efficacy) indicates that a luminaire using those LEDs has high efficacy. It could therefore be misleading if lamp efficacy is used to compare the light output or energy efficiency of an SSL product to a product using another light source, says the DOE. Lamp efficacies should not be used in luminaire product literature to indicate luminaire performance at this time, it stresses.

Nevertheless, measures of LED efficacy can be useful for manufacturers to evaluate the performance of available lamp components, the DOE adds. Developers of individual LEDs are achieving significant gains in efficacy. In October Cree Inc said that, with funding from the DOE, it had developed a white-light LED that produces up to 85lm/W and can output up to 160lm. White LEDs have since been demonstrated with luminous efficacies of over 100lm/W by Seoul Semiconductor (the P4, launched in early December) and 150lm/W by Japan's Nichia in mid-December. By 2025, DOE's goal is to achieve 160lm/W in cost-effective, market-ready, solid-state lighting products.

Since SSL technologies are undergoing rapid change and improvements, products arriving on the market exhibit a wide range of performance, the DOE says. Industry groups, standards setting organizations, and the DOE are therefore moving to develop the standards and test procedures needed for SSL products. In the meantime, manufacturers could knowingly or unknowingly take advantage of the novelty of SSL, of the public's lack of familiarity with it, and of the lag in appropriate standards and rules to promote products as energy efficient, whereas in fact they perform more poorly than incandescent or fluorescent lamps, the DOE warns.

Until standards and testing procedures are established and rulings are adapted to account for particularities of SSL technologies, industry professionals should use their vigilance to help ensure that product performance data is not used misleadingly, the DOE advises, adding that manufacturers, testing laboratories, energy experts, and regulators have a key role in protecting the potential of SSL. Until SSL technologies and supporting knowledge mature, any claims regarding SSL luminaire performance should be based on overall luminaire efficacy (i.e. from testing of the entire luminaire, including LEDs, drivers, heat sinks, optical lenses and housing), to avoid misleading buyers and causing long-term damage to the SSL market.

Further testing is planned to better understand the discrepancies seen: i.e. to gain a clearer understanding of how to assess the performance of SSL products compared to those using traditional light sources; to identify how different testing procedures affect results; and to clarify how traditional photometric practices apply or not to SSL products.

www.netl.doe.gov/ssl

The DOE SSL Commercial Product Testing Program aims to:

- guide DOE planning for SSL R&D and commercialization support activities, including ENERGY STAR program planning;
- support DOE technology procurement activities and associated technology demonstrations;
- provide objective product performance information to the public in the early years, helping buyers and specifiers have confidence that new SSL products will perform as claimed;
- guide the development, refinement, and adoption of credible, standardized test procedures and measurements for SSL products.

DOE supports testing of a wide, representative array of SSL products available for general illumination, using test procedures under development by standards organizations. Guidelines for selecting products for testing ensure that the overall set of tests provides: insight on a range of lighting applications and product categories; a range of performance characteristics; a mix of manufacturers; a variety of LED devices; and variations in geometric configurations that may affect testing and performance.

IN BRIEF

Philips now sole owner of Lumileds

After buying Agilent's stake in their former joint venture in 2005, Amsterdam-based Philips has taken full ownership of LED maker Philips Lumileds Lighting of San Jose, CA, USA by acquiring the remaining 3.5% of share capital from its staff and management. The 3.5% stake was related to an employee stock option program at Lumileds, which has now been replaced with an incentive program. A one-time charge of about €8m will appear in Philips' Q4/2006 financial results.

"In the last year we have made tremendous progress in aligning Philips' and Lumileds' business and strategy to further strengthen our position in the fast-growing, emerging solid state lighting market," says Theo van Deursen, CEO of Philips Lighting. "Philips now owns the entire new value chain, from technology expertise to in-depth customer knowledge, which provides us with a real competitive edge."

www.philips.com

Osram sues Citizen in US over white LEDs

In late November, Munich-based Osram GmbH (parent company of Osram Opto Semiconductors of Regensburg, Germany) filed a lawsuit in the US District Court in Wilmington, DW accusing Tokyo-based Citizen Watch Co of infringing six US patents for white LEDs used in mobile-phone screen backlights, cameras and car parts. Osram asked for a jury trial, an order to stop use of the inventions, and unspecified damages.

Citizen has continued to show no respect for Osram's US patent rights by importing and selling diodes based on patents awarded since 2001, the complaint states.

www.osram-os.com

LED headlamps enter the spotlight

Production passenger cars have have been using LED tail-lights for about five years, and LED daytime running lights since 2004: first by Audi in its high-end A8 model (five Lumileds Luxeon LEDs) then in 2006 in its S6 and S8, and this year in the R8 sports car for the USA.

Up to now the higher brightness demands of LED headlamps have limited their use to concept cars (for example, the R8 concept car at September's Paris Motor Show). At the 2007 North American International Auto Show in Detroit, Ford's Airstream Concept had an array of 12 LEDs forming each headlamp. In Mercedes-Benz's Concept Ocean Drive four-door convertible (based on the S 600), 35 LEDs (in five banks), each in its own sheath (which acts as a 'directional nozzle' for the light) provide both dipped and main-beam headlights. Also, Honda unveiled its Acura 'Advanced Sports Car Concept' (a preview of the design direction for the Acura NSX's successor) in which slim LED headlights mimic the pop-up headlights on the first-generation NSX.

Despite LEDs now surpassing the luminance of halogen bulbs, regulatory barriers to use in headlamps in Japan and and may not be overcome until 2008. But regulatory clearance has been gained in the US.

LED headlamps of the Lexus LS 600h L to be launched in Spring.

Ford's Airstream Concept (top); Mercedes-Benz's Concept Ocean Drive (middle); Honda's Advanced Sports Car Concept (bottom).

So, in the US this spring the Lexus LS600h L luxury sedan will be launched as the first series production vehicle with LED headlights for both night-time and low-beam use. Audi aims to launch LED headlamps in production after 2007. As costs approach those of high-intensity discharge lights, many more cars are expected to adopt LED headlamps in the next few years.

Audi's Q7 V12 TDI gains LEDs

At September's Paris Motor Show, Audi unveiled the Q7 V12 TDI (which has the same V12 diesel engine that powers Audi's R10 Le Mans race car, producing 500hp). But for its North America debut at January's 2007 Detroit Auto Show the headlights have gained a row of LEDs, the reverse lights have been relocated from the stop lamps into a strip along the

bumper, and the center stop lamp beneath the rear spoiler is now a string of red LEDs.

Osram LEDs used in Audi R8 & Ferrari daytime running lights

In Audi's new R8 sports car, 12 Advanced Power TOPLEDs from Osram Opto Semiconductors are used in each headlight to provide high-visibility daytime running lights that consume far less power than normal low-beam headlights. Osram Opto, based in Regensburg, Germany, claims that the R8 is the first serial production car with LED daytime running lights.

The firm says that the introduction of mandatory daytime running light in many countries throughout Europe is giving vehicle manufacturers a further opportunity to differentiate their products from those of competitors via unique headlight designs. Its Advanced Power TOPLED provides concentrated light from very small dimensions and has an edge length of just 500µm, giving stylists the scope to create imaginative designs. Also, their high-temperature behavior meets the stringent requirements of the automobile industry for this application, the firm adds.

Advanced Power TOPLEDs produce white light via a combination of Osram Opto's ThinGaN technology and chip-level conversion (a yellow converter sited directly on the blue-emitting chip — which is not the case with the usual volume encapsulation method). The result is better optical efficiency and higher luminance (18lm at an operating current of 140mA, ranking between Osram Opto's Power TOPLEDs and Golden Dragon LEDs in brightness).

The LEDs are housed in an SMT package and can be processed further by customers using standard processes. The Advanced Power TopLED will be available on the market with these specifications from mid-2007.

Daytime running lights: Audi R8 (left & inset); Pininfarina's Ferrari P4/5 (right).

● After its ENJOY show car and the Maserati Birdcage 75th concept car, designer Pininfarina has also used Power TOPLEDs in the daytime running lights of its 612 P4/5, a Ferrari Enzo re-modeled in the style of a 1967 Ferrari 330 P3/4 race car for a New York-based collector.

Osram Opto says that each headlight includes daytime running lights formed by 15 separate, clearly distinguishable lighting clusters (each fitted with eight Power TOPLEDs) that follow the bodywork's contours (giving the look of shark's teeth). Each LED incorporates a ThinGaN chip, giving 40lm/W efficiency.

www.osram-os.com

Osram helps VW Chameleon put Microbus in new light

At the AltWheels event in Boston, in September Volkswagen debuted the Chameleon concept vehicle, a refit of a 1964 VW Deluxe Microbus, produced at its Electronics Research Laboratory in Palo Alto, CA.

As well as an electric engine and solar panels (on roof-mounted surfboards), in collaboration with Osram both interior and exterior lighting systems were retrofitted. This is the first vehicle using LEDs for all major exterior lighting, and one of the first with LED headlamps.

Each headlamp integrates 24 LEDs: a horizontal, rectangular bar comprises two Osram Joule modules (each containing five OSTAR LEDs) for the low beam, plus four Golden Dragon LEDs for daytime running lamps; two circular projectors each contain a Joule module (a top projector to boost the low beam; a bottom projector for the high beam).

Unlike conventional headlamps, the forward beams have no reflectors (the advent of clear lenses requires near-perfect reflector quality).

Both front and rear turn signals are lit by Advanced Power TOPLEDs: amber reflector-optic Joule modules (front) and a red direct-view light-guide optic system (rear).

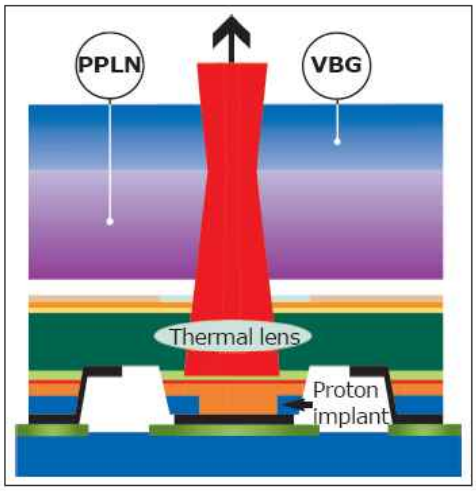
Cabin lighting comes from a single White OSTAR Lighting unit (four co-packaged LEDs) via a flexible fiber-optic bundle. The LCD instrument panel is lit by TOPLEDs via a light guide assembly.

Osram is developing LED headlights similar to the Chameleon's.

Red RPTV laser arrays hit 1.5W

Novalux Inc of Sunnyvale, CA, USA says it has delivered red 1.5W Novalux extended-cavity surface-emitting laser (NECSEL) prototypes to key consumer electronics partners. The 1.5W output is twice the power of the first red NECSEL arrays (demonstrated at the end of August) putting Novalux on track to produce RGB (red/green/blue) NECSEL lasers for integration into high-definition (HD) projection TVs, Novalux says.

"Reaching 1.5W with our red NECSEL arrays is a significant step toward our goal of shipping RGB lasers that produce 3W per color for our initial product," said VP of marketing Greg Niven. Novalux doubled the power output of its prototype 465–532nm blue and green arrays to the targeted 3W in late August. "We've been able to apply what we learned with that product development to our red technology," Niven said. "Customers want all-NECSEL RGB devices for incorporation into laser-based home theater systems. Now that we've met the target with green and blue, red isn't far behind and will soon be at the same level... We are on track to deliver all-NECSEL RGB sources to our consumer electronics partners for integration into HD laser TVs for Christmas 2007."



NECSEL laser structure (PPLN = periodically poled lithium niobate; VBG = volume Bragg grating).

NECSEL-based laser TV offers advantages over competing display technologies, such as plasma and UHP lamp-based projection TV, Novalux claims. "Plasma especially has momentum in the over-50" big-screen marketplace, but NECSEL laser TVs offer twice the color gamut with one quarter the power consumption," claims Niven. "Plasma TVs consume about 1kW of power, so a US consumer could save around $300 per year in electricity cost alone by buying a laser TV."

Early prototype NECSEL-based RPTVs were first introduced at the 2006 Consumer Electronics Show and showed expanded color gamut and striking image contrast over competing display technologies. The latest prototypes, shown at the Society for Information Display 2006 event, demonstrated higher-brightness, color-balanced, speckle-free, high-definition images on 52" screens. Ultimately, Novalux aims to enable home theater systems with over 200% of NTSC color coverage, high-brightness, high-resolution images, a thin, wide viewing angle architecture, and unsurpassed light source lifetime.

All-NECSEL RGB sources provide desirable wavelengths, increase display performance, and allow lower system cost, Novalux claims. Specifically, red NECSEL arrays can produce 615–625nm light, matching existing TV-screen phosphors; competing red edge-emitter lasers can only reach 635nm and have poor lifetime. Also, the same type of laser emits each of the three colors with the same device parameters. This uniformity results in simpler, cost-efficient laser integration from drive electronics to imaging optics.

www.novalux.com

Green lasers power miniature projection displays at CES

After collaborating since last July, at the 2007 International Consumer Electronics Show in Las Vegas, Microvision Inc of Redmond, WA, USA demonstrated a prototype miniature full-color projection display using Integrated Photonics Modules that incorporates Novalux's latest green NECSELs.

Microvision develops high-resolution displays and imaging systems based on proprietary silicon micromirror technology, with applications in consumer, medical, industrial, professional and military products. Its ultra-thin Pico Projector (PicoP) is small enough to be embedded in portable handheld devices, including mobile phones.

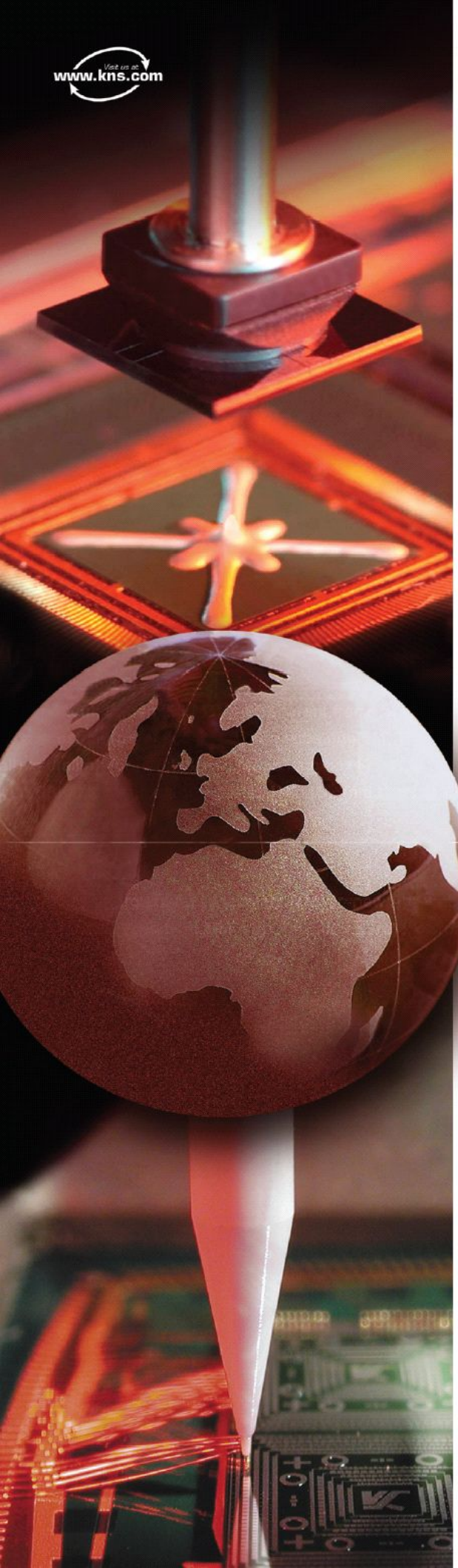
"We mobilized our internal development efforts to accelerate the maturation of the NECSEL green laser technology optimized for such applications," said Novalux's CEO Jean-Michel Pelaprat. "Ultra-thin miniature projectors represent one of the most exciting market opportunities for low-power, low-cost green lasers, and we are ramping up our internal investment in anticipation of growing market demand."

www.microvision.com

● Novalux has also licensed its RGB laser reference design for NECSEL-based illumination devices to Young Optics Inc, an affiliate of Coretronic Corp of Hsinchu Science-Based Industrial Park, Taiwan, for use in projection display products. It will also supply Young Optics with NECSEL chips.

Young Optics will mass-produce and sell NECSEL laser modules, and integrate them into its OEM projection display light engines. Its aim is to enhance its foothold in markets such as microdisplay-based projection TV and video walls.

www.youngoptics.com



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Kulicke & Soffa

Resonant tunneling barriers in nitrides

The widening of the application base for nitride semiconductors from light-emitting diodes, through laser diodes to high-power-density high-electron-mobility transistors has encouraged researchers to look at more advanced structures. Dr Mike Cooke reports on recent work on GaN/AlN quantum-well-based resonant tunneling diode structures.

There are a number of reasons why resonant tunneling diodes (RTDs) are of interest to the semiconductor community. First, they can be used to test and modify models of semiconductor behavior that take into account quantum effects, such as the envelope approximation based on using effective masses of carriers. Further, the simple vertical transport structure that is used is the basis for more complicated, multilayer devices using quantum interference effects to create new intersubband structures and devices (e.g. quantum cascade lasers and quantum well infrared photodetectors). Finally, RTDs have a number of interesting device applications of their own.

For example, they are among the limited number of electronic devices that can reach towards terahertz frequencies, offering possibilities for signal generation, switching, analog-to-digital conversion and detection. RTDs maintain their position as the fastest large signal semiconductor switching device with slew rates as fast as 300mV/ps [1].

In addition, RTDs can also be used as 'functional' logic devices, combining in one object a number of functions and creating simpler structures. Possibilities include: (i) one-transistor static random access memory (present-day SRAM generally uses either six transistors or four transistors and two resistors; the RTD version typically needs in addition just a field-effect transistor and a resistor) and (ii) multi-valued memory cells.

The same properties can also be used in combination with other semiconductor structures for improved performance, such as in the unipolar resonant tunneling transistor, which has a resonant tunneling double barrier between the emitter and base layers of the device.

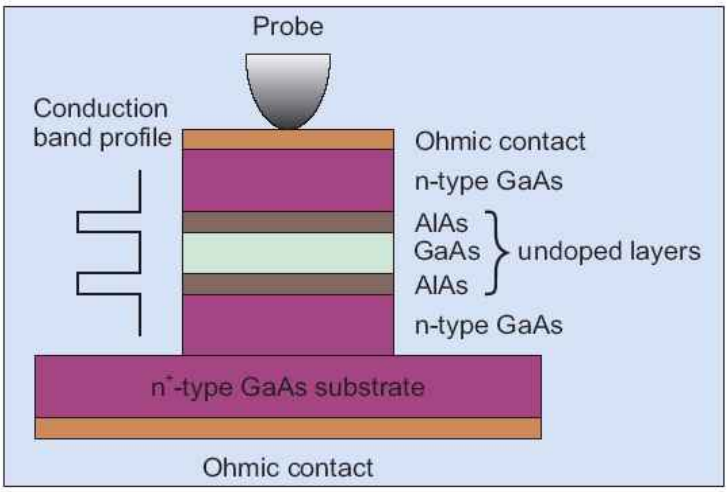

Figure 1: Schematic of a mesa-type AlAs/GaAs/AlAs double-barrier resonant tunnelling diode.

One unipolar resonant tunneling transistor can replace eight MESFETs in providing exclusive-NOR logic functions. Resonant tunneling bipolar and FETs can also be created. Resonant tunneling is also being considered for devices that are being developed to supersede standard CMOS technology, which is due to run out of steam towards the end of the next decade [2].

Formation of resonant tunneling diodes

Resonant tunneling diodes are commonly formed from heterostructures consisting of layers of GaAs and AlAs (Figure 1). For example, the sequence from a GaAs substrate of GaAs/AlAs/GaAs/AlAs/GaAs presents a structure where free electrons in the GaAs layers can exist at energies below the bottom of the AlAs conduction band. Hence, the AlAs layers act as barriers to electron transport.

For thin layers, electrons trapped between the barriers can be considered to be approximately confined to discrete energy levels, as described by a simplistic quantum-mechanical model of a square-well potential. Since the barriers are of finite width, these electrons would tend to leak out via quantum tunneling. Electrons from outside the well that hit the barrier structures will largely be reflected, except those within a very narrow range around the discrete energy levels of the well, which acts as an electron energy filter. The thicker the barriers on each side of the well, the narrower the range of electron energies that the structure transmits.

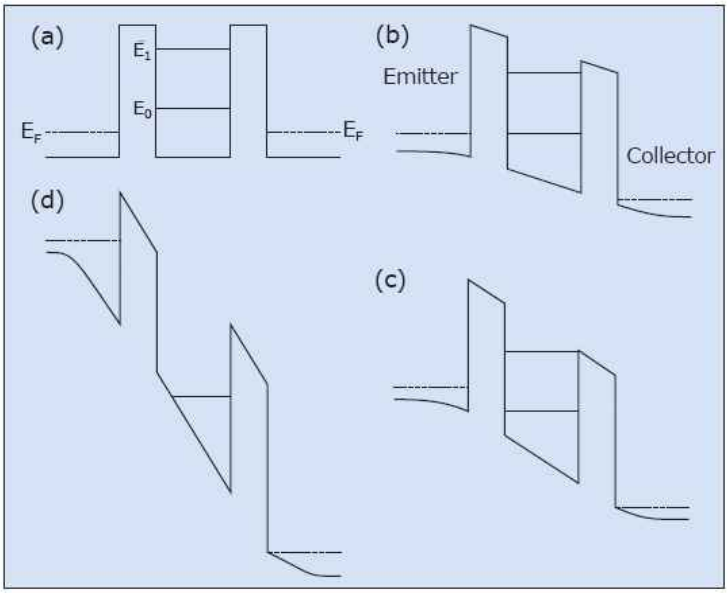

Figure 2: Variations in conduction band energy levels under (a) zero bias; (b) towards the peak current where the energy level of the well lines up with electron states in the emitter; (c) towards the valley current where the energy level falls below the edge of the conduction band into the gap; and (d) where thermionic emission over the barrier begins.

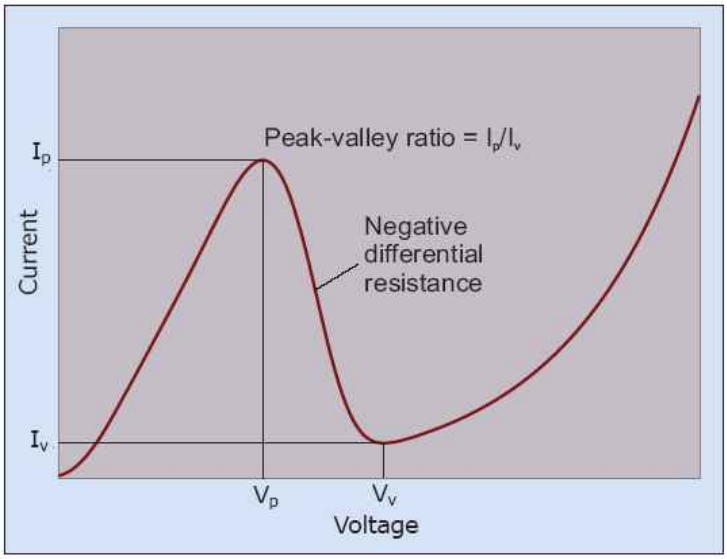

Figure 3: Sketch showing features sought in I–V behavior of RTDs.

In real electronic applications, electrons have a thermally distributed range of energies. Applying an electric potential difference shifts the well's energy levels. As this energy level passes through the peak of the thermal electron distribution, the current peaks, giving a distinctive peak and valley appearance to the current–voltage (I–V) curve (Figures 2 and 3). In the region where the current I decreases with increasing voltage V, one has a negative differential resistance (NDR). Advantages of RTDs include low junction capacitance due to the relatively low doping levels compared with other NDR devices such as ordinary (Esaki) tunnel and transferred-electron devices (TEDs). This enables cut-off frequencies for RTDs to encroach on the terahertz range (10^{12}Hz). Standard applications of the NDR effect include use in ultra-fast pulse forming, radiation detection and signal generation systems.

The classic RTDs are built using GaAs/AlAs, InAs/AlSb or InAs/GaSb on GaAs or InP substrates, depending on criteria such as lattice matching. At room temperature, GaAs/AlAs RTDs typically have peak-to-valley ratios (PVRs) of around 3, while for InAs/AlSb the PVR can reach 8. However, alternative material systems are possible, including silicon/germanium and nitride semiconductors. The attraction of silicon is possible cost reductions and device integration, while the GaN/AlN combination offers a large conduction band offset of 1.8eV, creating the potential for even larger PVRs and quantum behavior at much higher temperatures than in other III-V systems. Such devices, if practical, could offer higher power at a given frequency or higher frequency at given power, compared with devices built in alternative systems. Lateral transport high-electron-mobility transistor devices are already using the nitride system to produce high-power-density amplifiers for use in mobile phone base-station transmitters.

However, the GaN route for vertical transport devices such as RTDs is beset with some of the usual barriers in the nitride material system, in particular dislocations and strong internal spontaneous and strain-related (piezo) electric fields. The result is that RTDs with AlN/GaN double barriers have yet to demonstrate the predicted benefits in terms of peak-to-valley ratios and current densities. Other vertical devices, such as quantum well infrared photodetectors (QWIPs) built using the same techniques, suffer from similar problems, although paradoxically these more complex architectures often produce more promising results than the basic RTD structure. This suggests that much work needs to be done in comprehending and modeling quantum phenomena in the nitride semiconductor system. For this, understanding the behavior of simpler structures is vital.

Data from fabricated AlN/GaN RTDs tend to be non-reproducible. Some propose that the effects that are seen could also be due to charge trapping rather than resonant tunneling. Current instabilities are also evident. Early GaN RTDs were reported by Kikuchi et al [3], suggesting a massive maximum PVR of 32 in the latter article. A 3ML (monolayer) GaN quantum well was sandwiched between 4ML AlN barriers. The contact layers consisted of n-type silicon-doped GaN. The layers were grown using plasma-assisted molecular beam epitaxy (PAMBE) on sapphire (Al_2O_3). NDR was reported at 2.4V with a current of 2.9mA (a density of 180A/cm^2).

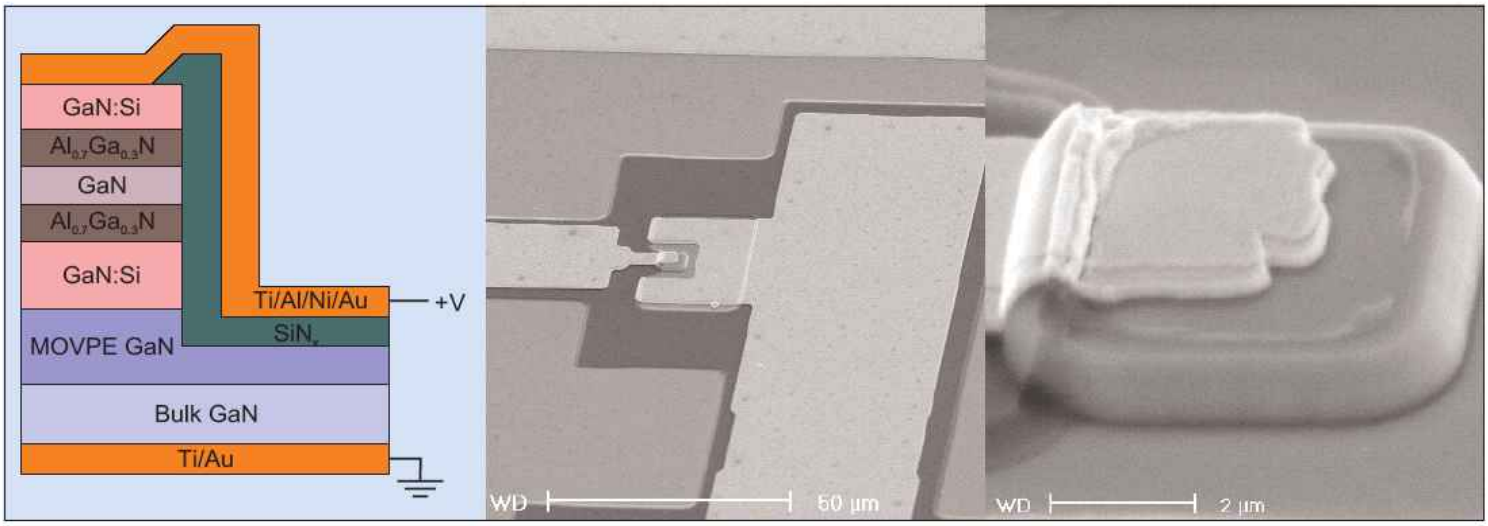

Figure 4: Schematic (left) and scanning electron micrographs (centre and, magnified, right) of GaN RTD device investigated by Golka et al [Appl. Phys. Lett., vol. 88, p. 172106, 2006]. The diagram is not to scale. The MOVPE GaN is 1µm thick and doped n-type to achieve a carrier concentration of $5x10^{18}cm^{-3}$. The silicon-doped GaN layers also have carrier concentrations of $5x10^{18}cm^{-3}$. The layer thicknesses of the wells and barriers (not intentionally doped) are 2nm, while the GaN:Si layer above the MOVPE GaN is 150nm thick and that next to the top contact is 100nm. The SiN_x insulator is 300nm thick. The GaN substrate is doped n+ with a carrier concentration of $5x10^{19}cm^{-3}$.

This article provoked a comment from Belyaev et al [4], reporting the finding that peaks found in similar devices are highly sensitive to the way in which the I–V measurements are made. In particular, the I–V curve varied in a series of up–down voltage sweeps. This behavior prompted Belyaev et al to question the interpretation of Kukushi et al's I–V curves and a simple resonant tunneling explanation. Belyaev et al's experiments showed a peak from sweeping in the down direction at around –6V, but no peak in the subsequent up direction. Moving beyond 0V, a very weak peak is seen at +5V. The peaks that are seen degraded on further sweeps through the voltage range. The behavior was attributed to the strong hysteresis and the degradation to bias-dependent electron trapping, possibly assisted by strong polarization fields in the AlGaN system. This multinational group (UK, Ukraine, Russia, Germany) reported further results in [5].

For their part, Kikuchi et al [6] believed that they had been misunderstood and stressed that they did not claim that a simple RTD model could explain their results due to the presence of a large piezoelectric field in the system. The next year, Hermann et al [7] reported a maximum PVR of 8.3.

Further work by Belyaev et al [8] suggests that the structural quality of GaN heterojunctions and impurity scattering from doping destroys the momentum conservation needed for the successful application of resonant tunneling. Another factor to be considered is the higher effective electron mass — some three times that in GaAs — requiring barriers and wells of about half the thickness, i.e. ~1–4nm for GaN wells and ~1–3nm for AlGaN barriers. Using these values, Belyaev et al produced RTDs on Si-doped GaN/sapphire substrates, again using PAMBE. The resulting device has a peak in the I–V curve in the reverse bias direction. However, sweeping through the I–V curve again causes the peak to degrade, and is only seen in sweeping down and not up. The team's numerical simulations suggest that the double well becomes asymmetrical due to the internal electric fields. The resulting charge structure inhibits resonant tunneling into the ground quasi-bound state of the well. Tunneling is only able to occur successfully (in the model) into excited quasi-bound states. The researchers conclude that the hysteresis and degradation of the peak is due to bias-dependent trapping of electrons, possibly in the quantum well after having made one tunneling transition from the emitter. The resulting charging and discharging creates nonlinear and unstable current behavior.

Leconte et al [9] studied GaN/AlN/GaN single-barrier structures (grown using PAMBE) with a view to intersubband and RTD devices. Vertical transport through varying AlN thicknesses (2–20ML, 0.5–5nm) were compared with simulation results from a self-consistent Schrödinger–Poisson equation solver. Capacitive measurements suggest that a depletion layer is formed in the top GaN layer, while a two-dimensional electron gas forms at the bottom GaN/AlN interface, even for the 2ML barrier. Photoluminescence experiments support this interpretation, since a signal from recombination of electrons from the two-dimensional electron gas (2DEG) into the valence band of the top GaN layer is identified. Conductive atomic force microscopy is used to investigate leakage currents. The density of leakage current dislocations is

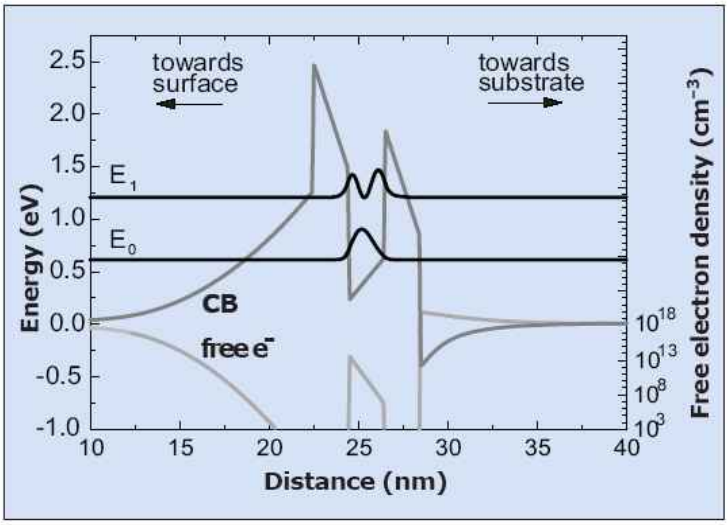

Figure 5: Conduction band diagram resulting from a self-consistent Schrödinger–Poisson equation solver without external bias. The ground-state energy is E_0 = 0.613eV and the excited state, E_1, is at 1.206eV. (From the 2006 Wide Bandgap Semiconductor Quantum Structures summer school, Switzerland presentation by Gottfried Strasser.)

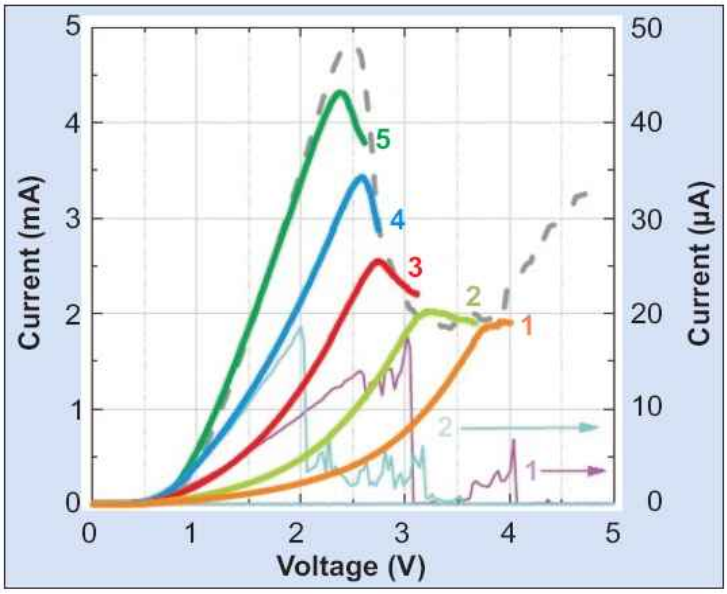

Figure 6: Sequence of traces of two GaN RTDs showing decay of the peak/discontinuity currents. (From the 2006 Wide Bandgap Semiconductor Quantum Structures summer school presentation by Gottfried Strasser.)

~10^7cm^{-2}, about an order of magnitude smaller than the level of dislocations (5x10^8cm^{-2}). Thicker barriers result in degradation in behavior that is assigned to trap-induced phenomena and relaxation of the AlN barrier layer. Leconte et al see these results as promising for micron-scale RTD device applications.

RTDs are not the only devices to be affected by dislocations resulting from the 18% lattice mismatch between GaN and sapphire. Laser diodes (LDs) built in the GaN material system on sapphire tend to have very short reliability lifetimes, on the order of 20 minutes. And yet, GaN blue LDs are now entering the market in optical disk storage video playback and data devices. Indeed, Sony released its Playstation3 (containing a Blu-ray laser disk reader) on 11 November in Japan and 17 November in the USA, and early this year in the rest of the world. LD commercialization has depended on abandoning the less expensive GaN on sapphire or even silicon carbide and using pure GaN crystal substrates to drastically reduce dislocation densities and thus create realistic LD lifetimes.

Golka et al [10] have performed experiments on GaN-based RTDs grown on bulk (0001) single-crystal GaN substrates in order to remove as many dislocation-related effects as possible, such as traps, leakage and carrier scattering. The latter effect destroys the quantum coherence needed for the resonant tunneling mechanism.

In addition to changing the substrate, Golka et al reduced the diode lateral dimensions from the typical 40–100μm to around 6μm. Another change is to move from AlN barriers to AlGaN with a 70% Al content (Figure 4). This is designed to reduce lattice mismatches between the GaN and barrier layers. The GaN substrates used were about 60μm thick and about 5mm in diameter. They were grown using a high-pressure process developed at the Polish Academy of Science UNIPRESS high-pressure research centre. The RTDs were deposited on the Ga polarity side of the substrate using PAMBE. The deposition was performed under Ga-rich conditions using adlayer enhanced lateral mobility (AELD) at 710°C to achieve high-quality 2D growth at lower temperatures than normal. The contacts were Schottky rather than Ohmic, although efforts were made to reduce the resulting rectifying behavior. The I–V curve shows a resonance peak at about 2.2V in the direction of the rectifying contacts and none under reverse bias. A simulation of the structure using a Schrödinger/Poisson solver (Figure 5) suggested a lower bound for the resonance of about 1.2V, which is in reasonable agreement with the measured value, taking into account potential drops away from the double-barrier structure such as at the non-ideal contacts. Further, screening of the barrier occurs due to charge layers that build up in front of the barriers as a result of the strong polarization fields in nitride semiconductors.

The measured peak-to-valley ratio (PVR) is around 2, which is much smaller than the value of 32 reported for the device of Kikuchi et al [3]. In the devices that demonstrated negative differential resistance (about 20% of the total), the width of the NDR region was about 0.3V. Another 20% of the devices showed a sharp discontinuity in the I–V curve, while the remainder showed no more than an exponential background in their I–V characteristic. The diodes are destroyed if they are taken beyond 6V bias in either direction.

In the diodes with NDR, Golka et al see the same degradation of the peak after the first sweep, as reported by other groups. By stopping the sweep close to the peak, one sees a gradual decay that follows an envelope representing a full sweep on a virgin device (Figure 6); i.e. the peak decreases and shifts to higher energy.

Golka et al discuss and dismiss non-resonant tunneling explanations of the NDR such as physical degradation and trap filling. However, traps are seen as having a role in increasing the barrier screening and hence shifting the peak to higher voltages. To test this idea, a 350°C thermal process under a nitrogen atmosphere was applied to the devices, with a view to releasing carriers from traps. The NDR behavior was restored, but with an order-of-magnitude reduction in the current density.

Gottfried Strasser of TU Wien, and part of the research team that includes UNIPRESS, comments: "These are, to the best of our knowledge, the only RTD structures on bulk GaN material. Although this is not an RTD, it is the first measurement that shows reproducible results. This is, as reported in the paper, most probably due to the reduced defect density (bulk substrates and smaller mesa sizes). While this is not yet a workable device, we can now start looking deeper into material properties and separate intrinsic from extrinsic behavior. It is too early to make final statements but, given the remarkable progress in the control of GaN-based materials within the last few years, and assuming continuous progress in improving substrates as well as growth and processing, there is a good chance of succeeding in developing usable RTDs."

The work of Golka, Strasser et al is part of a European project called NITWAVE, carried out between TU Wien and the company TopGaN (Poland). Further work is being carried out to produce RTDs on GaN crystals with a non-polar orientation as developed by UNIPRESS/TOPGaN. Also, lower Al concentration layers are being investigated further to understand vertical transport mechanisms.

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Optimizing technologies

This year's CSIC Symposium showed the continued maturing of wide-bandgap SiC and GaN power devices, as well as the mixing of III-V and silicon technologies for optimum system performance.

The CS Week 2006 event from 12–15 November at the San Antonio Convention Center in Texas attracted the traditional high quality of compound semiconductor executives and senior technologists. However, contrary to the current boom in the GaAs market, the number of delegates was down compared to last year's event. About 250 attended the main event, the IEEE's annual Compound Semiconductor IC Symposium (CSIC, formerly the GaAs IC Symposium). This included 20 or so cross-registered with the co-located Key Conference running in parallel on 13–14 November (which drew about 90 delegates in total).

At the CS Week exhibition, one or two suppliers of both GaAs substrates and epiwafers commented on a current slowdown in orders, despite the continuing growth in the GaAs RFIC market. This is put down to GaAs chip makers having built stockpiles of wafers, leading to inventory corrections. However, one substrate supplier said they expected sales growth to pick up again in second-quarter 2007.

Cree focusing on SiC and GaN transistors

Meanwhile, in the CS IC Symposium, technology trends were illustrated by the composition of the program. Of the 61 presentations, as many as 14 focused on GaN (mainly GaN HEMTs).

In his invited talk, John Palmour, Cree's co-founder and executive VP of Advanced Devices, presented work on wide-bandgap electronic devices, specifically GaN HEMTs for RF switch-mode power amplifiers demonstrating a high combination of output power (63W) and power added efficiency (75%) operating at a frequency of 2.0GHz. This is enabled by the use of Class E circuit topologies (which is not possible at such high frequency and power levels using silicon or GaAs).

A particular focus for Cree is GaN HEMTs for WiMAX base-station and access point applications operating in the 2.3–2.9GHz and 3.3–3.9GHz bands with average power levels of 2–12W, gains of 12–16dB, and drain efficiencies of more than 25% at 2.5% EVM (in either QFN-style surface-mount, leadless plastic packages or ceramic flanged packages).

As well as Cree's 28V GaN HEMT 'release process', the company is also working on a 50V process. Again, a very wide instantaneous bandwidth of more than 500MHz (compared to 200MHz and 18% efficiency for silicon LDMOS) enables a single GaN HEMT amplifier design to cover many different frequency applications. LDMOS and RF CMOS are 'against the wall' in terms of power efficiency, says Palmour. Although WiMAX is just a nascent market at the moment, it is 'definitely taking off', stresses Palmour, with Sprint/Nextel committing to the WiMAX specification and Intel deciding to enable its next Centrino processor for WiMAX.

LDMOS and RF CMOS are 'against the wall' in terms of power efficiency, says Palmour... WiMAX is 'definitely taking off', with Sprint/Nextel committing to the WiMAX specification and Intel deciding to enable its next Centrino processor for WiMAX.

Palmour also highlighted SiC power devices. In power factor correction circuits for switch-mode power supplies (SMPS) in computer servers etc, silicon PiN diodes (which are bipolar devices, with minority carrier recombination current flow) are now being replaced by SiC Schottky diodes (which are unipolar devices, with no reverse recovery current during switching). The 2–5% improvement in efficiency yields up to a 25% reduction in losses (since the average efficiency of a PFC circuit is currently 88–93%. Pairing with a SiC MOSFET as the switch allows the use of higher doping levels (compared to a silicon MOSFET) for the same blocking voltage (due to SiC's higher breakdown electric field), allowing lower on-resistance. A resultant 1.6% improvement in efficiency yields another 22% reduction in losses, giving a total reduction of 47%. For motor control, SiC Schottkys allow a 35% reduction in losses.

If variable-speed drives were widely adopted across all motor control applications, the potential savings, combined with the use of SiC in SMPS and GaN in RF, are estimated to be over $30bn per year

Palmour concludes that, if variable-speed drives were widely adopted across all motor control applications, the potential savings, combined with the use of SiC in SMPS and GaN in RF application, are estimated to be over $30bn per year.

RFMD integrating optimum technologies

In his invited talk 'Optimizing RF semiconductor choices for mobile devices', Jerry Neal, RF Micro Devices' co-founder and executive VP of marketing and strategic development, estimated shipment of over 2bn mm^2 of GaAs into mobile handsets in 2006 (equivalent to 0.5 acres in real estate) as the penetration of GaAs into handsets rises with the increasing adoption of multi-band handsets. RFMD expected the total handset market to grow by 150m units in 2006, and for its revenues to break $1bn annually. Neal reckons that, by 2008, most handsets sold will contain analog functions consolidated into a single-chip quad-band transmit module that integrates power amplifiers, a switch and a controller (indeed, RFMD is now shipping more transmit modules than PAs). Some handset manufacturers are even talking of incorporating up to 11 radios in a handset, he adds.

Handset manufacturers are even talking of incorporating 11 radios in a handset

However, while fine-line silicon CMOS is not good for PAs, switches and filters, it is becoming the technology of choice for the bulk of the other cellular handset functions (integrating a SAW filter and LDO regulator in a CMOS transceiver module). Meanwhile, MEMS is becoming attractive for use in switches and filters as it offers lower insertion loss (compared to a pHEMT switch) and ease of integration. 'MEMS could cause a paradigm shift in the RF section of the transmit module', says Neal. Although RFMD is spending much development effort on GaAs pHEMT switches, it may go to MEMS, he adds. "RFMD is not married to GaAs HBTs", Neal stresses: it is currently working with silicon foundries, and can 'invest in technology for fabs if needed'. He reminded the audience that RFMD originally invested in a 10% stake in Si/SiGe foundry Jazz Semiconductor (now Acquicor) so that it could work with silicon technologies, and is now developing all its silicon technology in-house. Indeed, RFMD's proprietary Integrated Power MOS (IPMOS) process can integrate MEMS on top of it. A quad-band silicon PA, switch and controller will have integrated fully shielded modules.

MEMS could cause a paradigm shift in the RF section of the transmit module... RFMD is not married to GaAs HBTs

Record DHBT f_T of 660GHz

In CSIC's 'Late News' session, Zach Griffith et al of the University of California Santa Barbara reported a record current-gain cut-off frequency (f_T) of 660GHz for a double-heterojunction bipolar transistor (DHBT), using epi growth on 3" InP substrates at IQE Inc of Bethlehem, PA, USA. The f_{max} is 218GHz and the breakdown voltage BV_{CEO} is 2.5V. The InP/InGaAs/InP device was scaled vertically to a 14nm highly doped InGaAs base and a 60nm InP collector to reduce the base and collector electron transit times. The previous record InP DHBT had a 20nm base and a 75nm collector, giving an f_T of 544GHz and an $f_{max}$of 347GHz, with a BV_{CEO} of 3.2V. In comparison, InGaAs-collector InP single heterojunction bipolar transistors (SHBTs) with a 20nm base and 62.5nm collector have demonstrated a 604GHz f_T and 246GHz f_{max}, and 12.5nm base and 55nm collector InP SHBTs have demonstrated a 710GHz f_T and a 340GHz f_{max}, but both had a significantly lower breakdown voltage BV_{CEO} of 1.7V and lower operating power density before failure.

First AlGaN/GaN HEMTs on CVD diamond

Gregg Jessen of the US Air Force Research Laboratories gave the first report on the operation of AlGaN/GaN HEMTs atomically attached to a CVD diamond substrate. Nitride device layers were MOCVD grown on silicon by Emcore's EMD division (now IQE RF) of Somerset, NJ, and transferred to a 25μm-thick polycrystalline CVD diamond substrate via a process developed by Group4 Labs of Menlo Park, CA. Sheet resistance measurements show that the two-dimensional electron gas interface remains intact. At a drain bias (V_{DS}) of 5V, f_T is 8GHz and f_{max} is 11.4GHz at a peak transconductance (g_m) of 70mS/mm; the source–drain current (I_{DS}) is 283mA/mm. In future, mounting the diamond layer directly on thermally conductive packaging (rather than a silicon carrier wafer) should improve performance.

CMOS W-band LNAs at 77 & 94GHz

S T Nicholson and S P Voinigescu of the University of Toronto reported the first experimental demonstration of CMOS W-band low-noise amplifiers at 77 and 94GHz: one-stage and two-stage cascode devices, respectively, fabricated in STMicroelectronics' 90nm general purpose CMOS technology. Voinigescu added that a CMOS W-band LNA operating at about 100GHz will be reported soon.

● The 2007 Compound Semiconductor IC Symposium will take place on 14–17 October in Portland, OR, USA.

The start of CSIC saw the award for the best paper at CSIC 2005 event. This award was presented by CSIC 2006 symposium chair Mitchell Shifrin of Hittite Microwave to Shahmiar Shahramian, Anthony Chan Camisone and Sorin Voinigescu of the University of Toronto, Canada for their paper 'A 40 Gsamples/Sec Track & Hold Amplifier in 0.18μm micron SiGe BiCMOS Technology'.

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