# Compound semiconductor industry continues growth

**This year's CS MANTECH event evidenced the continued economic recovery and technical progress in the compound semiconductor manufacturing industry. Mark Telford reports.**

This year's International Conference on Compound Semiconductor MANufacturing TECHnology (CS MANTECH) in Palm Springs, CA, USA in May drew a healthy attendance, despite the aftermath of the earthquake and tsunami in Japan on 11 March preventing some delegates from that country being able to attend (with consequently a mere six papers stemming from Japan, out of the total of 85, of which 33 were non-US).

It was poignant then that this year's conference chairman was Hitachi Cable's Yohei Otoki, whose family home and company headquarters in Hitachi City are both in the disaster area. In his opening address he spoke movingly about how some family members had been flooded out of their home, but also how — by the time of the conference — most of the functionality of the Hitachi Cable factory had been recovered.

Otoki commented that one thing highlighted by the disaster was the need for information. In that context — along with the power of relatively new media like Skype and Twitter — the impact of a crowded cell-phone network, shortages of electricity, and limited battery life highlighted the need to develop the smart grid, as well as the importance of photovoltaics.

## Wide-bandgap electronics

Fittingly, as has been the trend in recent years, the MANTECH program included many presentations on high-efficiency, energy-saving wide-bandgap microelectronic technologies, as well as a session dedicated to nitride-based LEDs. In fact, over 40% of all papers presented concerned wide-bandgap materials.

In the Rump Session 'Are There Real High Volume Applications for GaN?' (moderated by Yohei Otoki), it was noted by Eric Higham of market research firm Strategy Analytics that the non-optoelectronic gallium nitride device market was just $75m in 2010 (1.6% of the GaAs market, and just 0.8% of the $10bn opto GaN market, which is forecast to rise to $12bn in 2011 and $15bn in 2012).

However, while the GaN microelectronics market is currently still dominated by military applications (driven by DARPA programs), applications such as cable TV are coming in 2012–2014 via manufacturers like RF Micro Devices. Meanwhile, 'green' initiatives will drive applications in wireless infrastructure, especially as the increase in the number of frequency bands leads to narrower bands, and hence a market opportunity. In his presentation in the 'Business Analysis' session, Higham added that he expects a 'big bump' for LTE in the next few years (2011–2012). Consequently, the non-opto GaN market is forecast to increase rapidly at a compound annual average growth rate (CAAGR) of 57% to $376m in 2014 (7% of the GaAs market), says Higham (see Figure 1).

In particular, according to a delegate from NXP, for silicon LDMOS technology (which is now on its 8th or 9th generation) it is increasingly difficult to improve efficiency. By comparison, with efficiency for GaN-based devices rising to about 50%, GaN will increasingly be seen in base-stations. "No firm is not looking into GaN, but it's not yet ready for production," he commented. At a frequency of 2.7GHz, there is a 'clear case' for GaN in Doherty configuration circuits, since there is 'no way' for LDMOS. In addition, since LDMOS represents just a small proportion of silicon production volume, it is very difficult to get it into fabs — "TSMC won't get involved". Consequently, 2013 will see the first significant volumes for GaN, starting on 4" substrates.

One comment from Higham is that 3–4" equipment (for the silicon industry) is currently "going away". There is hence a need to get equipment vendors onside, but this must be done as a group, not individually. As an example, he noted that sub-100nm lithography can only be done economically on electron-beam tools,

## Recovery continues

The recovery in the compound semiconductor industry from 2009 has continued through 2010 into 2011 (see GaAs market values in Figure 1). This was evident at MANTECH, judging from the proliferation day-by-day of job recruitment notices on the conference notice board. These were posted by the likes of TriQuint, Skyworks, Kopin, Avago, M/A-COM, Agilent, Sumika, Northrop Grumman, Cree, Nitronex, Soitec and Hexatech, with a particular emphasis on vacancies for GaAs process engineers.

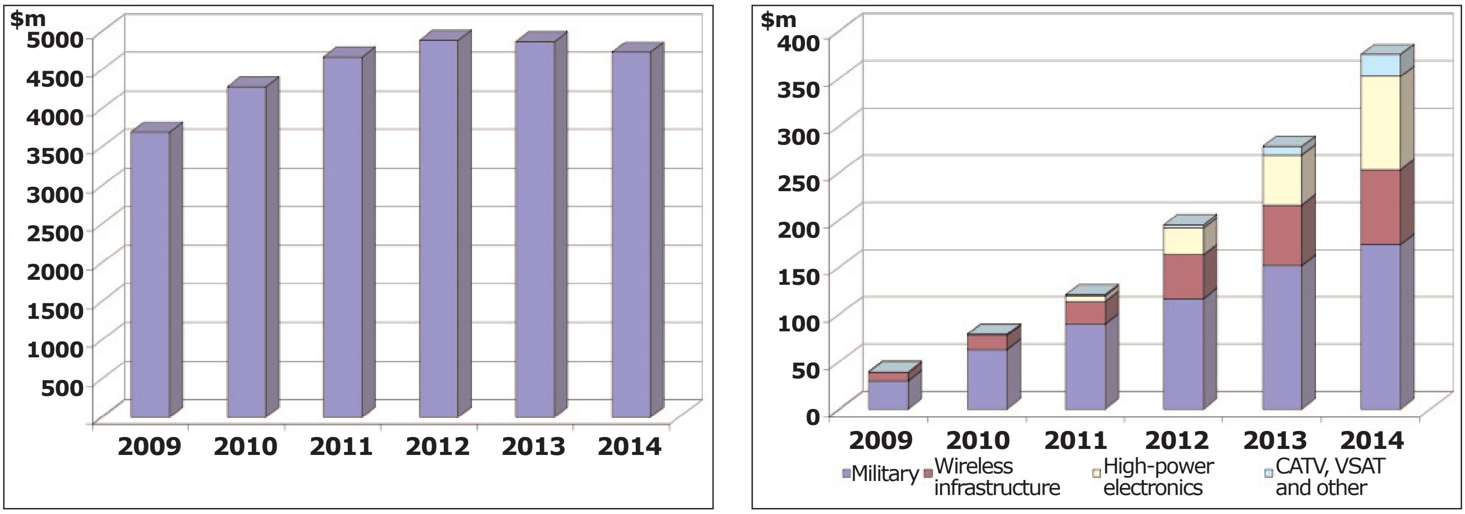

**Figure 1. Value of the microelectronic markets for (left) GaAs and (right) GaN, according to Strategy Analytics.**

because optical lithography exposure systems (such as from ASML) are too high-volume and too expensive.

Also, in the 'Business Analysis' session, Jeff Perkins, general manager (business development) for market research firm Yole Développement, addressed the topic 'Will GaN-on-Si displace Si and SiC in power electronics?', for which a key factor is the compatibility with silicon processing and extendibility to 6" diameter and beyond.

Yole reckons that the total addressable market for GaN power devices was $16.6bn in 2010. However, the actual GaN power electronics market has just started in 2010, with launches by International Rectifier and EPC Corp of products with a maximum commercially available breakdown voltage of 200V (addressing the IT and consumer segments). However, these firms (and other possible entrants like MicroGaN, Furukawa, GaN Systems, Panasonic, Sanken and Toshiba) are rapidly moving to launching 600V and even 900V devices, addressing the industrial and automotive hybrid electric vehicle (HEV) segments.

Taking into account the minimum qualification period required for the implementation of new technology, Yole forecasts that the inflexion point for GaN market ramp-up will occur in early 2012, leading to a market size of $50m+ by 2013 and about $350m by 2015 (equally split between discretes, ICs and modules).

Yole reckons that, of the power electronics market, about 3% is for >3.3kV, 11% for 2–3.3kV, 19% for 1.2–1.7kV, and as much as 67% is in the 0–900V range (mostly cost-driven consumer and IT applications). To address the latter segment requires high-volume manufacturing capability and aggressive market price positioning, so technology involving expensive bulk GaN substrates is not compatible with market requirements, reckons Yole. GaN-on-Si appears to be the most cost-effective option for reaching at least 0–900V applications, it adds, since it has been calculated that GaN-on-Si HEMTs could be 50% cheaper than the same SiC device. However, the existing state-of-the-art remains two or even three times more costly than the equivalent silicon device.

The choice to integrate GaN instead of silicon will be made at the system level, while calculating the overall module cost, says Yole. In particular, implementing GaN will allow a reduction in thermal management costs (fewer fans, smaller heat-sinks); RF filtering costs (higher switching frequency will need small capacitors and inductances), and overall housing costs (30–50% overall module size shrinkage is expected).

Yole adds that, based on the expected price erosion of 6" GaN-on-Si epiwafers, the GaN substrate market should exceed $100m in 2015.

## High-frequency GaN devices

In the session 'High-frequency GaN devices', Colombo Bolognesi's Millimeter-Wave Electronics Group at Switzerland's ETH-Zürich reported what it claims is the first broadband characterization of coplanar waveguides (CPWs) on GaN-on-silicon. Conventional CPWs on commercially available AlGaN/GaN on high-resistivity (HR)-Si HEMT buffer layers (fabricated by Nitronex Corp of Durham, NC, USA) have loss as low as 0.8dB/mm at 110GHz, which is further reduced to 0.47dB/mm by etching trenches between the CPW conductors. The group says this shows that CPWs on GaN-on-Si exhibit performance comparable to those on semi-insulating indium phosphide (SI InP), demonstrating the feasibility of mm-wave interconnects on GaN-on-Si epilayer stacks and hence the viability of a low-cost AlGaN/GaN HEMT MMIC technology on high-resistivity silicon substrates.

The Air Force Research Laboratory's Wright–Patterson Air Force Base and Sensor Electronic Technology Inc (SETi) of Columbia, SC reported the dc/RF characteristics of AlInN/AlN/GaN HEMTs on SiC with novel 5nm ultra-thin atomic layer deposition (ALD) $Al_2O_3$ dielectric passivation for high-frequency operation (thinner than in previous lattice-matched 25nm ALD $Al_2O_3$ in AlInN/GaN and 4nm ALD $Al_2O_3$ in AlGaN/GaN HEMTs) — see Figure 2. ➤

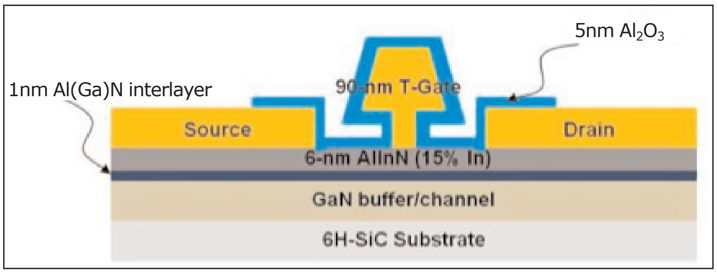

**Figure 2. AFRL/SETi's strained $Al_{0.15}In_{0.85}N$/AlN/GaN HEMTs with 90nm T-Gate and 5nm $Al_2O_3$.**

➤The barrier layer contains a lower indium concentration (15%), which induces a lattice-strain-induced piezoelectric field to boost the two-dimensional electron gas (2DEG). Ideally, one wants a very thin low-k dielectric that can suppress traps and decrease parasitic gate capacitance, increasing small- and large-signal gain. HEMTs were fabricated with 2x150μm gate periphery and a T-gate length of $L_G$ ~90nm. Compared with devices fabricated with 100nm $Si_3N_4$ passivation, using ALD $Al_2O_3$ yields a 25%+ decrease in parasitic capacitance and a 15% increase in small-signal gain. An intrinsic cutoff frequency of up to 130GHz highlights the promise of AlInN/GaN HEMTs with ultra-thin ALD $Al_2O_3$ passivation, say the researchers.

Future work targets optimum material growth conditions and improved breakdown voltage for high-power, high-frequency conditions.

## Device technology

In the 'Device Technology' session, Hitachi Cable reported how it has boosted the output of high-power GaAs MESFETs by 20% by not only using a high-quality channel but also optimizing the epitaxial buffer layer. Key factors were found to be a reduced impurity level in the epilayer–substrate interface, smooth electron flow near the buffer layer, and low leakage current at the buffer layer. An appropriate buffer structure had Al concentration of 0.20–0.40 (with higher Al concentration effective for improving leakage current due to raising the heterojunction barrier), while multiple heterojunctions (with a periodic stacked GaAs/AlGaAs layer) were more effective than a single AlGaAs buffer layer.

Recent progress in MOCVD epi growth and device fabrication techniques have enabled several demonstrations of GaN/InGaN npn heterojunction bipolar transistors (HBTs) that used a single-pass epi growth scheme, showing that good dc performance can be realized for III-N HBTs without additional re-growth. To further develop a viable III-N HBT technology for RF power amplification (preferred to III-N HFETs for linear power amplifiers because of the higher power density, linear current gain and uniform device turn-on characteristics), high collector current density ($J_C$), low collector offset voltage ($V_{offset}$) and low knee voltage ($V_{knee}$) are desired.

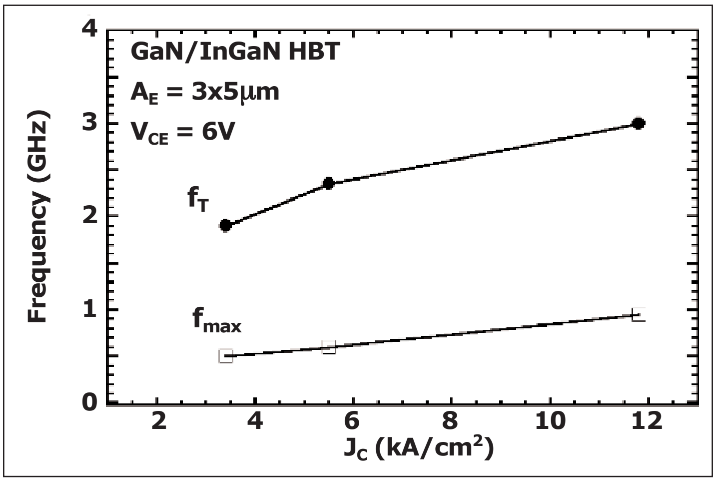

**Figure 3. The $f_T$ and $f_{max}$ at different $J_C$ of a 3x5μm$^2$ GaN/InGaN HBT fabricated by GeorgiaTech.**

To this end, researchers led by Russ Dupuis and Shyh-Chiang Shen at the Georgia Institute of Technology reported GaN/$In_{0.03}Ga_{0.97}N$ npn HBTs grown by MOCVD on sapphire substrates having a $J_C$ >20kA/cm$^2$ with a low $V_{offset}$ of 0.22V and a $V_{knee}$ of 2.1V. Also, the breakdown voltage ($BV_{CEO}$) was a high 110V with low off-state leakage, and the maximal small-signal differential current gain ($h_{fe}$) was 38. In addition, the cut-off frequency ($f_T$), measured at $J_C$ = 11.8kA/cm$^2$, is reckoned to be the first over 3.0GHz for a GaN/InGaN HBT.

However, $f_{max}$ is a much lower 950MHz, suggesting that the large base resistance ($R_B$) of 22kΩ is still a challenge to achieve higher power gain.

Presenter Yun Zhang comments that better $f_T$ and $f_{max}$ performance can be expected for III-N HBTs grown on substrates with better thermal conductivity and lower defect density, with perhaps $f_T$ >5GHz achievable on semi-insulating silicon carbide or gallium nitride. Indeed, already an $f_T$ of 5.3GHz and an $f_{max}$ of 1.3GHz have been achieved.

## Interactive Forum

In the 'Interactive Forum', researchers from University of Notre Dame, IntelliEPI of Richardson, TX and IBM T.J. Watson Research Center, Yorktown Heights, NY reported for the first time a self-aligned and potentially manufacturable vertical tunneling field-effect transistor (VTFET) process using an $In_{0.53}Ga_{0.47}As$/InAs/InP pocket vertical heterojunction.

Tunnel field-effect transistors (TFETs) are being investigated for low-power applications due to their potential for very low subthreshold swing and low off-state leakage. Most efforts have focused on Si-and Ge-based TFETs but — due to high tunneling barrier and effective mass — these exhibited a low on-current ($I_{on}$). In contrast, III-Vs — with small effective mass and broken band lineup — promise high $I_{on}$ and $I_{on}/I_{off}$ ratios.

Pocket vertical TFETs are adopted because the gate electric field can augment the internal tunnel junction electrical field, controling more effectively the band overlap for minimal subthreshold swing. At 300K, the VTFETs showed an $I_{on}/I_{off} = 10^4$ and $I_{on} = 3–4.8\mu A/\mu m$ with a subthreshold swing (SS) of 220mV/dec using 8nm-thick atomic-layer-deposited $Al_2O_3$ gate oxide.

Previous results by other researchers have yielded 20µA/µm ($V_{GS}$ = 2V) and an SS >150mV/dec for $In_{0.53}Ga_{0.47}As$ TFETs using 10nm $Al_2O_3$ gate oxide, and an improved $I_{on}$ of 50µA/µm ($V_{GS}$ = 2V) and an SS of 86mV/dec were achieved by using 5nm ALD-deposited $HfO_2$ gate oxide and $In_{0.7}Ga_{0.3}As$ tunnel junctions.

The researchers note that their results are largely limited by the unoptimized ohmic contacts, interface density of states under the gate, and traps in the tunneling junction.

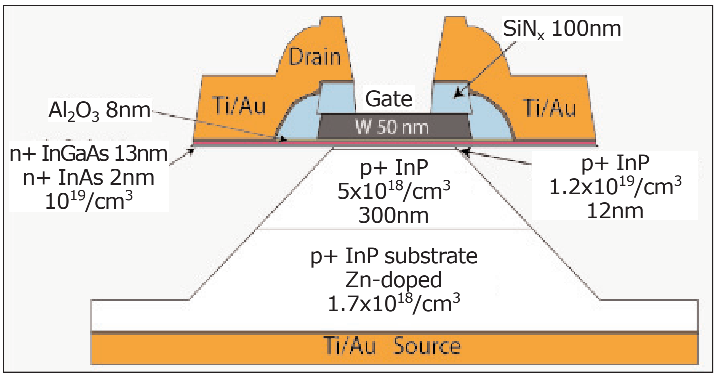

**Figure 4. Cross section of vertical $In_{0.53}Ga_{0.47}As/InAs/InP$ TFET fabricated using a gate-first self-aligning process.**

## Fab Management & Technology Transfer

In the 'Fab Management & Technology Transfer' session, Cobham Sensor Systems described the relocation of its GaAs MMIC wafer fab in Roanoke, VI (at the former ITT site) to a more modern 50,000ft$^2$ facility in nearby Blacksburg (starting in early February 2010 and completing last October).

Another presentation described the transfer of Freescale Semiconductor's 12V GaAs pHEMT to Taiwanese 6" GaAs foundry WIN Semiconductors (in four stages: transfer mask; epitaxial substrate; front-side process; back-side process), after Freescale closed its GaAs fab at the end of 2008 and exited GaAs wafer processing.

## Mobile phone markets

In the 'Business Analysis' session, Quinn Bolton of Needham and Company noted that the handset market is bifurcating into two markets: broadband-data-driven smartphones for developed markets; and low-cost multi-SIM mobiles for emerging markets. Indeed, only a third of handsets are currently 3G enabled, but by 2014 3G multi-mode, multi-band phones will represent about 59% of mobile device shipments. The firm forecasts that cellular handset unit shipments will grow at a CAGR of 11% between 2009 and 2014. Also, there will be at least 35% unit growth in data modems, although this "might be conservative", says Bolton, given recent growth in the market for tablets. So, total mobile device unit shipments are forecast to grow at a CAGR of 13% from 1.4 billion in 2009 to 2.29 billion in 2014.

## China LED manufacturing

Morris Young, CEO of substrate maker AXT Inc of Fremont, CA, USA, gave an overview of China's 'Fast Growing Role in the Future of Compound Semiconductor Technology and Manufacturing'. He detailed how MOCVD reactor installations at Chinese LED chip makers grew 152% in 2010 to an estimated 327 and are forecast to grow 133% in 2011 to 764. The number of systems currently in use exceeds 250, but the number of installations over 2010–2015 is expected to exceed 2000.

Among the 41 enterprises in China that mass produce and sell LEDs, 28 have MOCVD equipment. Between January 2009 and December 2010 alone, 45 new LED chip-related projects in China attracted total investment of RMB112.9bn, Young says. In particular, more than 10 firms in China have developed and plan to offer chips for LED backlighting of TVs.

Young noted that China is the leading producer of virgin germanium and gallium, and that in recent years, due to the rapid global growth in all compound semiconductor sectors, their consumption has risen significantly, as have the prices per kg. In particular, 99.99%-pure gallium rose from under $650 to almost $1000 in the 6 months from December 2010 to May 2011, while 99.99%-pure germanium rose from $880 to $1650 over 12 months, according to Metal Pages.

Young says that the Chinese Government's incentive policy (which includes subsidies of about $1.5m per MOCVD reactor) is playing an important role in compound semiconductor industry development, but that a strong capital market and entrepreneur spirit are also fueling the boom in LED market growth in China.

However, he cautioned that the Chinese government's MOCVD subsidies had stopped already, and expressed the belief that "a crash is going to come". ■

● Next year's CS MANTECH 2012 will take place on 23–26 April in Boston, MA, USA.

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## He Bong Kim Award

Opening ceremonies saw the presentation of the 'He Bong Kim Award' (named after MANTECH's founding chairman) in recognition of the best papers from last year's conference. The winner was 'Benchmarking of Thermal Boundary Resistance of GaN-SiC: Interfaces for AlGaN/GaN HEMTs— US, European and Japanese Suppliers' by Martin Kuball, Nicole Killat, Athikom Manoi and James W. Pomeroy of the UK's University of Bristol.