

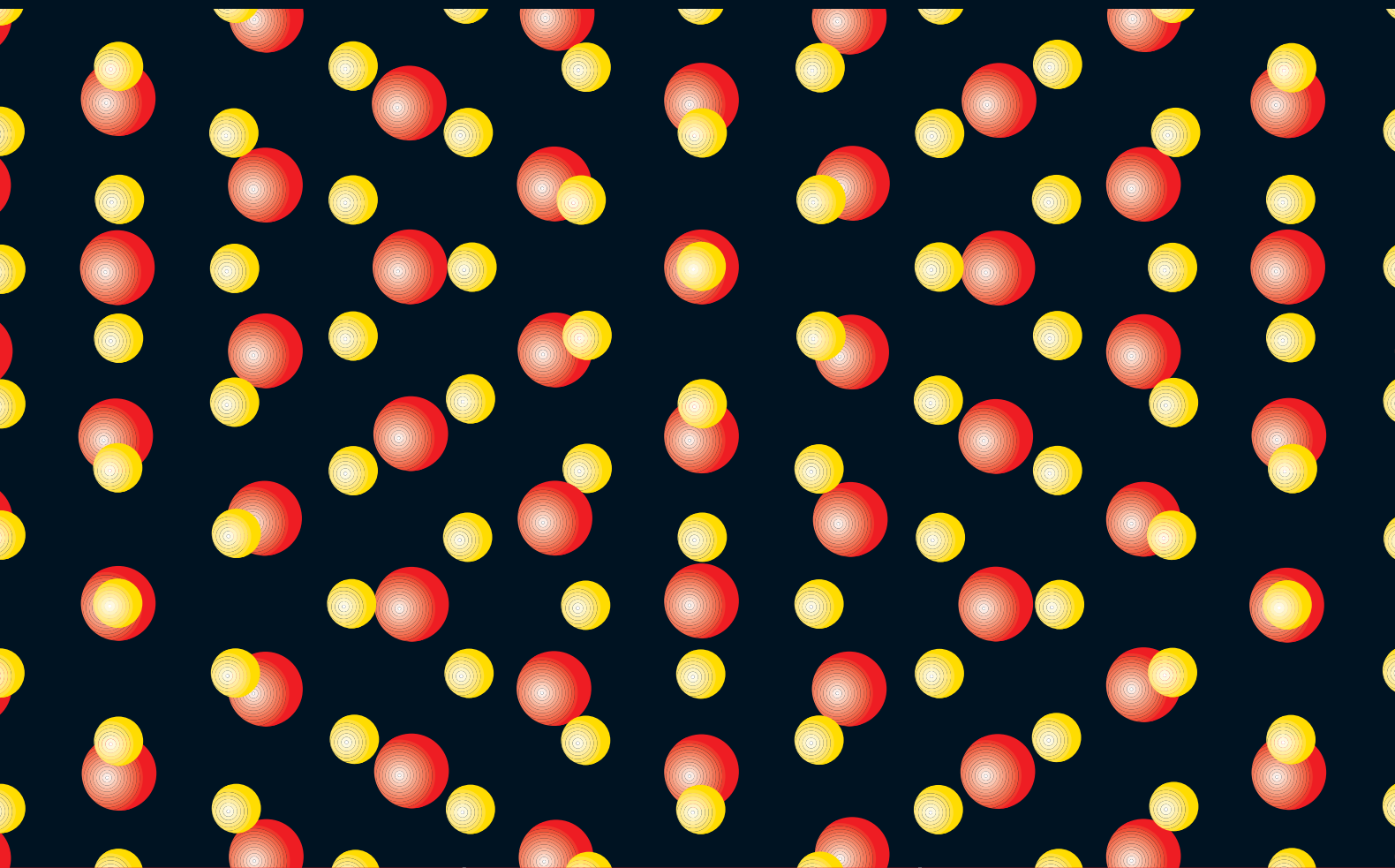
# COMPOUND SEMICONDUCTOR

April 2007 Volume 13 Number 3

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## EPITAXY

# GaN and germanium: are they perfect partners?



## SUPPLIERS GUIDE

**Substrate and  
epiwafer vendors:  
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### Founding father

The legacy of molecular  
beam epitaxy pioneer  
Klaus Ploog. **p19**

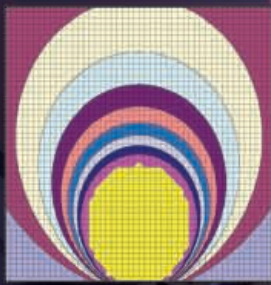
## INTERVIEW



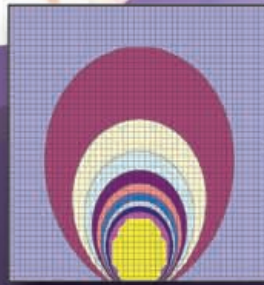
### Happy talk

TriQuint's Tim Dunn on  
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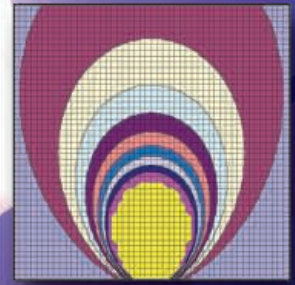
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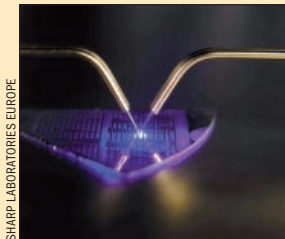
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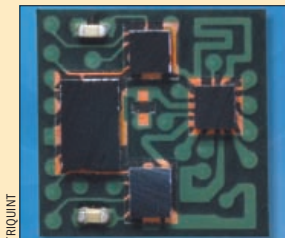
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**Pioneering diodes**  
SiC PIN diodes are becoming increasingly attractive, as radar systems shift to higher frequencies. **p25**

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**Main cover image:** Germanium and GaN have a 20% lattice mismatch, but scientists at the IMEC research center in Belgium have managed to grow high-quality material. See p14. Credit: Alison Tovey.



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US mailing information: *Compound Semiconductor* (ISSN 1096-598X) is published 11 times a year for \$165 by IOP Publishing, Dirac House, Temple Back, Bristol BS1 6BE, UK. Periodicals postage paid at Middlesex, NJ 08846. POSTMASTER: send address corrections to *Compound Semiconductor*, c/o PO Box 177, Middlesex, NJ 08846. US agent: Pronto Mailers Association Inc, 200 Wood Avenue, PO Box 177, Middlesex, NJ 08846.

# “Rebel” with a cause



We should shortly be hearing plenty about the new line-up of “Rebel” LEDs from Philips Lumileds. Set for warm-white, cool-white and RGB lighting applications, the launch is an important one for the company as it lines itself up against traditional competitors like Cree and Nichia.

Cree already has its high-efficiency XR-C chips in volume production, but these look like increasingly interesting times for all the incumbent makers of high-end white LEDs. This particular playing field could get a whole lot busier as some major new players try to take a chunk out of a market that has traditionally been the preserve of the “big five” chip makers and the top Taiwanese suppliers.

Panasonic and Showa Denko may not yet be part of the high-brightness LED fabric, but companies with credentials like theirs are not to be taken lightly. Panasonic is the name under which the somewhat less brand-friendly Matsushita Electric Industries increasingly masquerades. A manufacturer of everything from batteries to washing machines to electronic rice cookers, this is a company with massive financial clout (2006 sales: ¥8.9 trillion, or \$76 billion) and a long history in the semiconductor business to boot.

Now, Panasonic is looking to sink its teeth into white LEDs, claiming to be the first manufacturer to produce such products commercially on GaN substrates. Whatever the precise nature of its material system, the company is targeting high-end applications and claiming some impressive performance figures.

Showa Denko is no household name, but, like Panasonic, the chemicals company claims to be bringing the advantages of a new technology to white LEDs. Said to be faster than MOCVD, its physical vapor deposition process is a closely guarded secret. Crucially, it is compatible with large sapphire wafers, and therefore an important route towards cutting the key \$/lumen metric – necessary for solid-state lighting to take off in a big way.

It will, of course, take some time for these new entrants to make their mark. Indeed, Cree could exhaust the world’s supply of GaN substrates in less than a day’s production at one of its fabs. But for the “old guard” of the LED business, there are some new kids in town. Lumileds will be hoping that its Rebel can stand up to the test.

**Michael Hatcher** Editor

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## PHOTOVOLTAICS

## Funding for solar cells

Three projects involving multi-junction solar cells have been selected for funding via the US Department of Energy's (DOE's) \$168 million Solar America Initiative (SAI).

Raymond Orbach, the US Undersecretary of Energy, announced details of the funding round at chip manufacturer Spectrolab, which is involved in the three funded projects.

Boeing is heading a project focused on cell fabrication research that is set to receive \$5.9 million through the SAI in its first year, rising to total funding of \$13.3 million over three years if goals are met. Those funds will be augmented by an equivalent contribution from the members of the project team. Spectrolab is also involved in a potential \$14.8 million project headed up by Amonix that aims to develop a low-cost concentrator system for utility applications.

Spectrolab will also take part in a project led by solar panel maker Practical Instruments that is focused on rooftop residential applications of III-V photovoltaics.

The DOE says that the SAI funding will boost annual US manufacturing capacity of photovoltaic systems, to 2.85 GW by 2010.



EPIA/BP SOLAR

**In the money:** triple-junction photovoltaics.

## III-V LOGIC

## Glasgow team lands £4 million digital grant

The UK's Engineering and Physical Sciences Research Council (EPSRC) has approved a £4 million (\$7.7 million) grant to the University of Glasgow for the development of logic transistors based on compound semiconductors.

Headed by Iain Thayne, the three-year project will be hosted at the Scottish university's Nanoelectronics Research Centre. A collaboration between five teams at Glasgow, the project begins on May 1 with the aim of delivering prototype transistor technology that can be scaled up to volume production.

MBE, electron-beam lithography and reactive ion etching equipment are all available at Glasgow, while the project will also

## PHOTONICS

## Entrepreneur takes over control of Avanex fabs

Optical communications component and module vendor Avanex is to rid itself of the costly III-V semiconductor facilities in Nozay, France, that it acquired from Alcatel Optronics in 2003. Serial entrepreneur Alexandre Krivine and Avanex France boss Didier Sauvage are taking over control of the fabs.

On completion of the deal, which is expected by May 7, Avanex will also hand over €13.4 million (\$17.7 million) to ensure that the facilities have a viable future, and can continue to supply Avanex with key components, such as lasers.

Krivine and Sauvage have decided to call the new operation "3S Photonics". It will be 90% owned by Krivine's firm, Global Research Company, with Avanex retaining a 10% stake. Krivine has an engineering background, although his previous major investments have all involved software, telecoms and internet-related ventures.

Sauvage, meanwhile, has worked in the optoelectronic chip sector for over two decades, and during the technology bubble he headed up an Alcatel Optronics team that swelled to 400. In 2005, Sauvage became site leader in Nozay and instigated measures designed to cut the cost of the chip operation. He claims to have cut losses at the fab by a factor of six.

Krivine was initially brought in to advise Avanex on the options available to it in July 2006. After the failure of a planned merger later that year, Sauvage and Krivine decided that taking on the III-V fabs was an option. For Avanex, the switch should result in annual savings of up to \$16 million.

While Avanex will remain an important customer for 3S Photonics, Sauvage and Krivine plan to widen the scope of the business, and are aiming at applications in different areas of optical communications, as well as defense and medicine. Key examples include 980 nm pump lasers, and chips for the fast-growing fiber-to-the-home sector. Armed with both MBE and MOCVD capability for GaAs and InP applications under one roof, they will also offer foundry services.

They say that breaking even on an operating basis by the start of 2008 looks plausible, and are targeting annual revenue of €25–30 million to achieve this. Current like-for-like sales are €22–23 million.

Despite the start-up fund from Avanex, Krivine says that his venture into III-V semiconductors is not without its risks. He has arranged a €12 million debt facility with a Swiss bank, and is looking to raise further investment of some €5–6 million through the venture capital community.

make use of the University of Surrey's Ion Beam Centre, and specialist microscopy equipment at the Daresbury Laboratory.

Advances in CMOS transistor processing such as high-k dielectrics continue to push the performance of silicon transistors, but a fundamental technology roadblock still faces chip manufacturers. Although that roadblock may not be reached for another decade, research teams are already looking at the new technologies that could take over from traditional CMOS at that time.

The Glasgow team has been working with Freescale Semiconductor on the development of GaAs-based structures for digital applications. "In the coming three years, we plan to move to higher-mobility materials to further increase the drive current to meet the targets of the 22 nm technology generation," Thayne said. "The most obvious migration will be to look at

[GaAs-based] high-indium-concentration materials."

Thayne adds that despite the development of high-k dielectrics, there is still no consensus within the semiconductor industry about the best solution for transistors beyond the 22 nm generation. The Glasgow project is also investigating the use of germanium-on-insulator (GeOI) substrates: "As GaAs and germanium are lattice-matched, GeOI is a route to co-integrating III-V functionality on a silicon platform," Thayne said.

A critical aspect of the project is to develop silicon-like process flows in a III-V material environment, and Thayne's team will be working with high-k gate materials and metal oxides. He expects that coming up with a device-quality gallium-based oxide compatible with high-mobility materials will present one of the project's toughest challenges.

EWAFERS

# Kopin gets GaN production-qualified

Kopin, the epiwafer supplier that has a particularly close relationship with RFIC manufacturer Skyworks Solutions, says that its new GaN transistor technology is ready for volume production.

The Taunton, MA, firm, which is already in the process of a major production scale-up for MOCVD-grown GaAs and GaAsInN HBT epiwafers, has been working on GaN HEMT development since 2004. Its GaN HEMT epiwafers have now been qualified by what Kopin describes as “a leader in GaN-enabled base-station products”.

A number of manufacturers of III-V chips, including RF Micro Devices, Cree, Freescale, Fujitsu and Nitronex, have been developing GaN-based transistors for broadband wireless infrastructure applica-

tions in recent years.

RF Micro Devices has just announced its first commercial supply deal for GaN products with a military customer, while Fujitsu now plans to set up a separate business venture focused on power-amplifier products including GaN components for WiMAX.

Although Skyworks does manufacture some AlGaAs HBT-based products for infrastructure applications, it has yet to reveal any plans involving GaN semiconductors.

Like most developers in the sector, Kopin has focused on using SiC substrates as the base material for the GaN devices. However, the firm adds that it has also looked into other substrate options, including sapphire.

● Kopin reported a sequential drop in sales of HBT epiwafers in its most recent trad-

ing quarter, which ended on December 30, 2006. At \$9 million, epiwafer sales were down slightly from the previous quarter, which Kopin CEO John Fan attributed to “an inventory correction in the market”.

Fan remains confident about prospects for 2007, however: “We begin the new year with a strong tailwind of demand as our wireless-circuit partners shift to our newest generation of InGaP HBT structures for advanced wireless handsets.”

Aixtron has already delivered three of its latest generation of production MOCVD systems to Kopin’s Taunton, MA, facility for a manufacturing scale-up this year. For the full fiscal 2006 period, revenue from HBT products was \$43.9 million, up slightly on the 2005 figure of \$42.7 million.

GAN AMPLIFIERS

# Japanese alliance takes aim at mobile WiMAX

In collaboration with the Japanese communications firm KDDI, Fujitsu’s development team has produced a prototype 25 W transmitter amplifier that is based on GaN HEMT devices.

The technology giant is in the process of setting up a standalone business focused on power amplifiers (PAs) for broadband wireless networks, and the GaN-based amplifier is set to become part of this new company’s product portfolio.

The prototype transmitter is specifically designed for future deployment in mobile WiMAX network equipment.

Fujitsu and its subsidiary research wing Fujitsu Laboratories have been at the forefront of GaN HEMT and PA development

for many years, and have broken a series of performance records in the process.

With mobile WiMAX now receiving backing from at least some of the major players in the wireless-communications industry, Fujitsu senses that a market opportunity has finally arrived, and that it can now begin to take advantage of its substantial investment in GaN transistors.

Fujitsu has been putting the final touches to the latest WiMAX amplifiers since May 2006. The result is a prototype transmitter that operates at 2.5 GHz, and has a power efficiency of around 30% for orthogonal frequency division multiplexing (OFDM) 16QAM signals.

KDDI has been looking into how the GaN

HEMT amplifiers can result in smaller, more energy-efficient base-station equipment that also requires less maintenance than existing systems.

“The deployment of this new amplifier technology is expected to reduce the size and power requirements of outdoor base stations by roughly half compared with conventional amplifiers,” says Fujitsu. The increased efficiency means that less waste heat is dissipated, and that air-conditioning requirements are much reduced.

As well as the size reduction, using GaN also means that smaller back-up batteries are needed, which should dramatically reduce the cost of the base stations required for mobile WiMAX.

FINANCE

# \$100 m stock sell-off gives Anadigics options

Anadigics, the GaAs chip maker that has seen its share price rocket over the past year, has raised \$98.8 million through the sale of 8.6 million shares.

The company plans to use the money to fund some capital expenditure, as well as for general corporate purposes. Some of the cash may be spent at its 6 inch GaAs semiconductor fabrication facility in Warren, NJ, where the weekly capacity is currently 950 HBT wafer starts.

“We believe that we have the ability, with incremental capital expenditures, to increase the weekly production capacity to as much as 1500 six-inch wafers in response to market conditions,” revealed the company in its prospectus.

Although this should give it sufficient capacity until 2009, Anadigics added that it is already looking at how it would be able to generate additional manufacturing capacity if that limit is reached.

“We are actively exploring future sources of additional capacity through the construction or acquisition of manufacturing facilities in low-cost manufacturing countries such as China, as well as pursuing relationships with foundries in Taiwan,”

the prospectus explained.

While Anadigics has been able to make inroads at key cell-phone vendors such as Samsung, LG and Motorola, it also has an increasing focus on emerging broadband wireless applications such as WiMAX.

Although the future role of WiMAX in mobile connectivity is not yet clear, the protocol does have major backing from Intel, which also happens to be Anadigics’ number-one customer.

Anadigics has developed “BiFET” technology that it calls “InGaP-plus”, which combines HBT and FET functions on a single InGaP die. It believes that this new process will play a major part in future WiMAX products.



## SUBSTRATES

# Yield improvements spin quarterly profit for AXT

GaAs, InP and germanium substrate vendor AXT has capped its turnaround story with a net profit of \$3.4 million for the quarter that ended on December 31. CEO Phil Yin, who has masterminded the company's change in fortunes since taking over two years ago, described 2006 as "a great year".

With potential orders from top-tier GaAs manufacturer Skyworks Solutions in the pipeline, as well as a major ramp in demand for germanium expected from photovoltaics applications, 2007 looks likely to be an even better year for the company.

Yin highlighted recent process improvements such as longer GaAs ingot growth, faster crystal production, and more efficient slicing into GaAs wafers as the reasons for a sudden upturn in operating performance.

In the latest quarter, AXT swung to an operating profit of \$1.2 million on total sales of \$13.1 million. That marked a huge improvement on the equivalent quarter a year ago, when AXT posted an operating loss of \$3.4 million on sales of \$7.7 million.



**Skyworks Solutions**, which manufactures BiFET components at its Newbury Park, CA, facility, is in the process of qualifying substrate material from AXT.

Optimistic about the company's prospects for 2007, Yin says that AXT is enjoying stronger demand from top-tier customers in the GaAs IC business, and key chip manufacturer Skyworks is currently qualifying GaAs material from AXT for use in its new BiFET process, which combines an HBT and FET structure on the same chip die.

Although this means that less GaAs material is required to achieve equivalent functionality with designs based on two individual chips, Yin remains confident about overall wafer volumes, commenting, "This is not going to have a negative effect: [it means that] more phones will be sold."

If the BiFET qualification with Skyworks goes according to plan, it should mean initial shipments of around 500–1000 GaAs substrates per month. "This is a customer that went to zero," said Yin, referring to the wafer-quality problems AXT experienced some three years ago. "They have let us back in the door." AXT is also in talks with Skyworks' main rival, RF Micro Devices.

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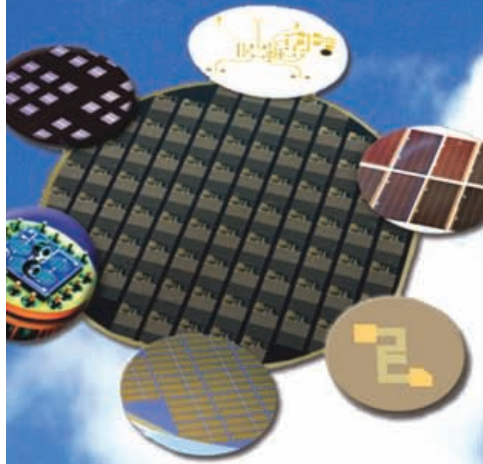
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### CHIP MANUFACTURING

# SDK plans to build 4 inch GaN fab

Japanese chemicals giant Showa Denko (SDK) has revealed plans to build a GaN LED fab based on 4 inch wafer production at its existing site in Chiba.

The company, which is already scaling up its monthly production of AlGaInP LEDs to 100 million units, says that it has developed an epiwafer fabrication process that is compatible with large sapphire substrates.

According to SDK, this deposition process is a hybrid of conventional MOCVD and its proprietary "plasma-assisted physical deposition", or PPD. The company also says that X-ray analysis of nitride crystals grown on sapphire using the new process shows a significant improvement in quality compared with those grown by MOCVD.

Although SDK won't reveal details, the firm did tell *Compound Semiconductor* that PPD is more akin to MBE than to MOCVD, and faster than both of these traditional methods. SDK has designed its own epitaxy equipment for the future chip production.

"Wafer warp is a big problem for a 4 inch process, but we have overcome these problems," SDK said. PPD has not only enabled SDK to go ahead with 4 inch wafer production; it has also enabled the company to develop the brightest blue LEDs on the market today. At a 20 mA drive current, these produce a 13 mW emission, which it

believes to be a record.

"SDK will start commercial shipment of these blue LEDs within this year," said the firm. Thanks to the 4 inch upgrade, SDK is expecting to increase its blue LED production from the current level of 30 million units per month to 100 million units per month by the end of 2007.

The production scale-up is another part of SDK's "Passion" project, under which the Japanese company is expanding its high-brightness LED business aggressively.

SDK sees large LCD backlighting and general illumination as two key markets that it can penetrate with its latest generation of emitters.

GaN LEDs are typically manufactured on 2 or 3 inch sapphire wafers, although many believe that a scale-up to 4 inch production will be necessary before large, extremely bright chips can be produced cheaply enough to seriously penetrate the market for general illumination, such as lighting in homes and offices.

However, scaling up sapphire-based production to 4 inch wafers has been a problem in the past because of the increased warp of the larger material, and because the local variations in temperature across the larger wafers created during the epitaxial process become more exaggerated.

### MERGERS AND ACQUISITIONS

## Cree goes global with expansion into China

Cree, the US maker of SiC- and GaN-based semiconductors, is set for a major expansion into China. The Durham, NC, firm is to acquire the high-brightness LED packager COTCO Luminant Device in a cash-and-stock deal valued at \$200 million.

Hong Kong-based COTCO sells packaged LEDs for applications such as large video screens, traffic signals and automotive lighting. It was founded 10 years ago and was already a customer of Cree's. In the most recent fiscal year, COTCO accounted for around \$25 million of Cree's chip revenue.

COTCO Luminant Device's parent company, COTCO Holdings, will receive \$70 million in cash and just over 7.6 million shares in Cree stock when the deal is completed. Up to \$125 million in additional payment may be made if the COTCO business hits certain financial targets over the next two fiscal years.

Cree says that the deal will add 15-20% to its annual sales, equivalent to between

\$55 million and \$70 million. Cree CEO Chuck Swoboda described the deal as the next step in the company's strategy to enable the "solid-state lighting revolution".

"We look forward to working together to expand our business in China and to transform Cree into a truly global company," Swoboda said. China is already a key market for high-brightness LEDs, and its government has been very keen to back solid-state technology because it can cut the energy cost of lighting so dramatically.

Once the deal is completed, Cree will also own the COTCO subsidiaries called COTCO International, COTCO Opto Technology, and COTCO Japan.

COTCO Holdings will consolidate its remaining Intelligent Module and Display business units under a new company called Light Engine Ltd, while because Cree will own the "COTCO" tradename, the name of the parent company will change to "United Luminous International (Holdings) Ltd".



## PRODUCT LAUNCH

# Panasonic develops white LEDs

Panasonic, the Japanese company better known for its consumer electronics, claims to have developed the first commercial white power LEDs to be manufactured on GaN substrates.

According to the Osaka-based company, InGaN-based LEDs grown on the native host material have an efficiency that is more than 50% higher than conventional LEDs fabricated on sapphire substrates.

Panasonic has issued few details about the exact nature of the material system and the deposition method that it uses, but if the company has indeed developed single-crystal GaN suitable for commercial LED production it would represent a significant breakthrough for the industry.

Makers of GaN-based transistors, LEDs and lasers have always known that a native substrate would make the ideal host material, but producing high-quality single-crystal GaN at a large-enough diameter and a low-enough price to support volume wafer manufacturing has proved impossible.

Panasonic's development is not restricted to the laboratory, either. It is set to begin sampling three different white LED products within weeks. The development was welcomed by Keith Evans, CEO of the GaN substrate maker Kyma Technologies: "We

are pleased to see that Panasonic has shown what we believe – that GaN substrates are needed and ultimately will be the preferred approach to making white LEDs."

According to Panasonic's own research, the power LEDs also have the highest output in the industry. Performance details quoted by the company say that the 460 nm-emitting blue chips produce a total radiative flux of 355 mW when driven at a forward current of 350 mA. This translates to an external quantum efficiency of 38%.

Those figures compare well with similar devices that have been developed by Philips Lumileds. In a paper published last year in *Applied Physics Letters*, Lumileds researchers showed that their new thin-film flip-chip InGaN LEDs also had an external quantum efficiency of 38%.

Emitting at the slightly shorter wavelength of 440–445 nm, the Lumileds LEDs also deliver around 350 mW of radiative flux when driven at 350 mA, increasing to nearly 900 mW at a drive current of 1 A. Panasonic's three products include a 3 W power device for lighting applications, a reflector design that is suited to camera flashes, and a point source for use in compact lighting fixtures. Samples of the products are available at ¥500 (\$4.30) per unit.



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### ... Seoul upgrades Acriche

Thanks to a new type of package, Seoul Semiconductor has improved the brightness of its Acriche single-emitter LEDs by 20%.

The Korean firm claims that the emitter, which can be run from a conventional AC electrical source, delivers 48 lm/W. It plans to increase this efficacy to 80 lm/W by the end of 2007.

### ... Osram touts kilolumen source

German LED manufacturer Osram Opto Semiconductors has developed a six-chip light source that delivers more than 1 klm. The output is brighter than a 50 W halogen lamp, suiting the LED to applications in general lighting. Volume production starts this summer.

### ... Philips buys TIR Systems

Lighting giant Philips, which already owns the high-end LED chip manufacturer Lumileds, is to increase its presence in solid-state lighting with a C\$75 million (\$64 million) cash

acquisition of Canada's TIR Systems. TIR developed the "Lexel" light source, which uses white LEDs for general-lighting applications.

### ... 4 inch sapphire from Sumitomo Metal

According to the Japanese news service *Nikkei.net*, Sumitomo Metal Fine Technology is planning to set itself up as a major supplier of large sapphire substrates suitable for producing white LEDs. The Osaka-based company has developed a fine-polishing technique that uses colloidal silica granules 100 nm in diameter to make the large wafers.

### ... Aonex and Kyma hook up

GaN substrate pioneer Kyma Technologies is working with the Caltech spin-out Aonex Technologies on the development of large-area wafers that feature a thin layer of sapphire on top of a polycrystalline AlN support. Aonex believes that these wafers can be scaled to a 4 inch diameter.



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BLUE LASERS

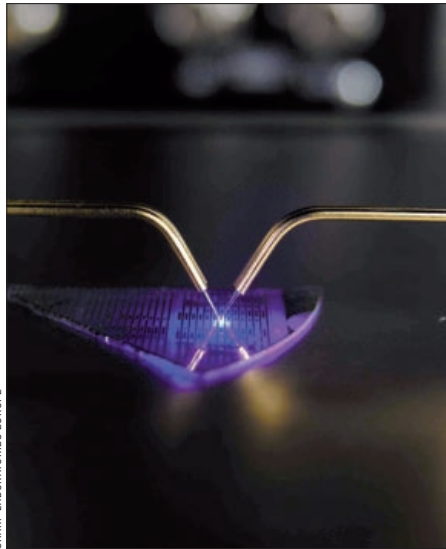
# Sharp prepares to enter the blue era as power laser nears mass production

Sharp Corporation, the Japanese company that pioneered the development of infrared and red-emitting semiconductor lasers for applications in optical data storage, is about to enter the blue era.

Volume production of high-power GaN-based lasers at Sharp will begin in May, following a short period of device sampling this month. The 406 nm laser that Sharp has developed produces 105 mW in continuous-wave mode and 210 mW in pulsed mode, with the company claiming that the latter figure represents the highest-power GaN laser on the market.

For consumers, that higher power will mean faster recording in dual-layer Blu-ray and high-definition DVD technology. At the 210 mW output rating, the laser will be suitable for 6x recording on either format.

The lasers will not come cheap, though – the quoted sample price is ¥50,000 (\$430). However, that price should drop once Sharp's overall production of blue-violet lasers is



Sharp's European research wing has steadily developed GaN-based lasers grown using MBE technology, producing the first such device in 2004.

scaled up to 250,000 units per month.

Sharp has a distinguished history in the development and manufacture of laser components for optical data storage applications. In 1982, it developed the first 780 nm devices for CD applications, and followed up this feat in 1998 with the first 635 nm, 30 mW red lasers.

The company typically uses MBE to manufacture these infrared and red lasers. Other companies such as Nichia and Sony have been faster to market with blue lasers based on MOCVD-produced GaN, but problems with their manufacturing has contributed to the delayed launch of important products such as Sony's PlayStation 3 videogames console.

Sharp says that the market for high-definition disc recorders is expected to "take off in earnest" this year, sparking a ramp in demand for the blue lasers. Its aim is to build production capacity that can respond rapidly to fluctuating market demand.



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### ...FTTH set for global boom

Worldwide fiber to the home (FTTH) shipments jumped 41% in the final quarter of 2006 and were up 58% over the year as a whole, according to a new report from analyst company Dittbener. The report says that a record 4.6 million optical network terminal (ONT) and optical line terminal (OLT) ports shipped in 2006.

III-V chips such as 1310 and 1490 nm distributed feedback (DFB) lasers and avalanche photodiodes are used in these ports. In the US, Verizon is expected to add 1 million FTTH subscribers in 2007.

### ...JDSU nabs Picolight

JDSU is to acquire Picolight, a manufacturer of optical pluggable transceivers based on 850 and 1310 nm VCSELs. JDSU will trade \$115 million-worth of its stock and pay up to \$10 million in cash in exchange for the company. The market for 10 Gigabit Ethernet optical components used by enterprise-focused network-equipment manufacturers,

which includes pluggable transceivers, is expected to grow from \$200 million in 2006 to more than \$650 million in 2010, according to analysts at LightCounting.

### ...German start-up attracts investment

Laser-system builder Rofin-Sinar has acquired an 80% share of m2k laser, a German start-up that has developed novel GaAs and GaSb high-power lasers. The start-up, which operates out of the Fraunhofer Institute of Applied Solid-State Physics in Freiburg, will continue to operate as a separate entity and to sell the chips to third parties.

### ...Bookham boosted by submarine deal

Fiber-optic system vendor Tyco Communications has chosen Bookham as the lead supplier of pump-laser modules for a new deployment of erbium-doped fiber amplifiers (EDFAs). Bookham's 980 nm pumps, manufactured at the US company's GaAs chip facility in Zurich, Switzerland, are able to emit more than 400 mW.

### ...Sofradir detectors to aid climate models

Sofradir, the maker of mercury cadmium telluride detectors, has won a €3.2 million (\$4.2 million) supply contract with NEC Toshiba Space. France-based Sofradir will deliver a custom bi-spectral long-wave infrared detector for a satellite observation project that is expected to improve the climate models used to predict environmental changes when launched in 2012.

### ...Infinera goes for \$150 million IPO

Infinera, the vertically integrated manufacturer of InP photonic circuits and digital network systems, has filed for an initial public offering (IPO) that could generate up to \$150 million. The company is currently running at a substantial loss, although sales are growing rapidly. Of the \$58.7 million annual revenue that it posted in 2006, \$44.3 million came in the final quarter. However, cumulative annual losses over the past three years exceeded \$200 million and the total accumulated deficit was \$313.1 million on 31 December, 2006.





## RF SEMICONDUCTORS

# Strong growth means TriQuint VP has good reason to be cheerful

Installed as vice-president of TriQuint's handset business unit in July 2006, Tim Dunn has already overseen a rapid upturn in the maker's wafer volumes and product sales. Dunn was understandably in a chirpy mood when he met **Michael Hatcher** at the 3GSM World Congress in Barcelona, Spain.



**Tim Dunn predicts** that TriQuint's transmit module shipments will top 100 million in 2007.

"2006 was an important year: TriQuint emerged as a strong player in mobile handsets." So says Tim Dunn, vice-president of the handset business unit of the Hillsboro, OR, company. And it is hard to argue with the bare figures. Thanks to design wins in nearly 100 new phones last year, TriQuint Semiconductor sold 43 million transmit modules – up from only 5 million the year before.

Dunn believes that this strong momentum will continue, and expects to ship 100 million transmit modules in 2007. "This forecast is based on existing design-ins for phones just hitting their stride," said the upbeat VP at the 3GSM World Congress held in Barcelona, Spain, in mid-February.

Key design wins in what have turned out to be some of the world's most popular GSM phones, such as Motorola's RAZR platform, are the major reason behind the upturn. Dunn admits that luck has played some part in this success, saying, "Fortunately, we got into some hot phones last year." Samsung, the world's third-biggest mobile phone maker after Nokia and Motorola, was TriQuint's top customer in

2006. The chip manufacturer has benefited from the relationship, as a wide range of Samsung's dual-band and quad-band phones became big sellers.

Measured specifically in terms of the global consumption of GaAs components, Dunn now estimates that TriQuint has a market share of around 13%. Additionally, he is hopeful of seeing that proportion grow as the wireless communications business enters the broadband era.

The 3GSM event, which switched from Cannes to Barcelona in 2006 because it became far too large for the original French location to accommodate, is where critical trends in this industry tend to emerge. Dunn identified two key drivers that are now shaping the handset business: the need for increased RF semiconductor content to support communication in multiple frequency bands; and the emergence of ultra-low-cost phones.

With up to 11 frequency bands now requiring support, plus the increasing need for WiFi-enabled handsets, and the emergence of wideband-CDMA and EDGE as dominant protocols, demands on RF components are tougher than ever. As a result, Dunn says that TriQuint is now less concerned about the challenge to GaAs from all-CMOS power amplifiers (PAs) than it has been for many years.

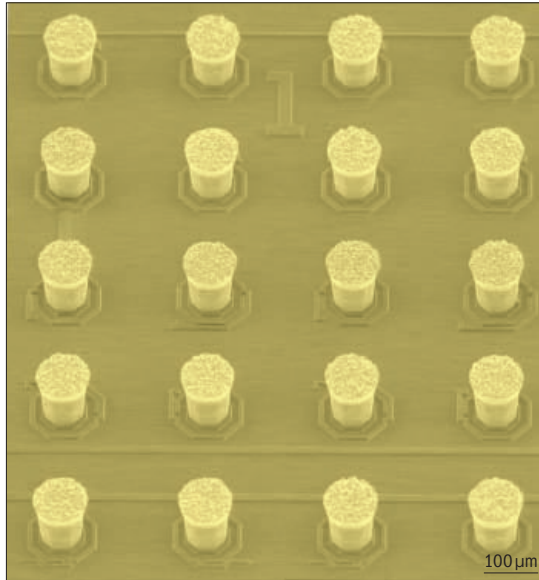
At the other end of the mobile handset business, phone makers are aiming to sell their products for just \$22 in developing countries. They need the front-end of the phone to represent no more than 5% of that sale price. Although this might suggest a route for all-CMOS PAs to get to market, Dunn believes that it will also become a profitable area for GaAs specialists.

## Shifting volumes

Its recent success in the handset business means that TriQuint has had to cope with a rapid increase in wafer volumes through its 6 inch GaAs fabrication facility in Oregon. "Wafer volumes have more than doubled over the past two years," Dunn said. "Revenue per wafer is also going up, because of the value that our modules add."

Coupled with a rebounding market for GaAs-based driver components that are used in optical communications – of which Dunn estimates that TriQuint has a 60% market share – and strong demand for front-end modules in broadband and WiFi applications, the company's GaAs fabs are under pressure to deliver more volume than ever before.

As a result, TriQuint is adding capacity in some innovative ways. While 6 inch manufacturing has expanded at the high-volume Oregon fab, the



**A key element of TriQuint's front-end modules** is the use of a flip-chip process instead of traditional wire-bonding for both GaAs and CMOS components. Although more design passes are required, it increases yields. This scanning electron microscope image shows the tiny copper pillars along the undersurface of individual die, which replace traditional wire bonds.

company's 4 inch GaAs fab in Richardson, TX, is also being upgraded to the larger format. However, this is not quite as simple a move as it first appears. That is because TriQuint's surface and bulk acoustic wave (SAW/BAW) filter factory in Orlando, FL, is approaching its capacity limit.

Though not based on GaAs, the BAW fabrication process also employs a 6 inch wafer platform, and this will be switched to Richardson, where a multi-functional manufacturing line is being established to help free up extra capacity.

Innovation of a different kind is at the heart of TriQuint's latest PA technology, which is the company's response to industry demands for better front-end components to support phones with very small transmitter and baseband systems.

This has led TriQuint to develop its so-called CuFlip assembly technology, which replaces a number of wire bonds with a flip-chip process. One of TriQuint's key products – the TQM7M4006 quad-band PA module – is made using this process. The module includes two InGaP PA chips, as well as a passive output matching die (also GaAs) and a CMOS controller component. All of these die are flip-chip mounted onto a laminate substrate.

This is a bit of a divergence from the usual approach, because GaAs die assembly has typically required wire-bond interconnects that are also used to fine-tune RF circuits. While flipping the die and attaching to laminate has obvious advantages in reducing the wire-bond count and leading to better product yields, the process does require more design passes at the outset of product development, as it is much less of a "black art" than the traditional approach. As a result, TriQuint has greatly increased its use of simulation tools at the design stage.

### Keeping options open

Another popular theme among the estimated 55,000 3GSM delegates was WiMAX, the emerging broadband wireless technology that some – though by no means all – see as a rival to third-generation cellular services. With the mobile industry divided from the very top over the merits of WiMAX, this is a tricky area for PA component manufacturers. Nobody will be keen to invest heavily in a technology that may become a white elephant. "The jury is still out," said Dunn of WiMAX's likely success, although he does believe that WiMAX applications will find a niche at the very least. For example, the broadband system could be deployed rapidly and layered over an existing network, perhaps temporarily for disaster relief, or where ultra-high demand on cellular bandwidth is expected, such as the 2008 Summer Olympics in Beijing, China.

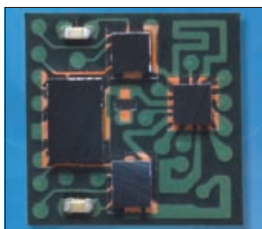
But the uncertainty within the industry over WiMAX is of no great concern to Dunn – for now, the volume business is in cellular transmit modules and PAs, and the former Intel man is confident that the progress made in 2006 will continue thanks to some new products and a new strategy for mobile communications – both of which were launched in Barcelona. Announcing this new handset strategy, Dunn highlighted the "customer-first", responsive approach that TriQuint is taking, rather than trying to second-guess which services and technologies will turn out to be the dominant ones of the future.

For some, says Dunn, the wireless future means high-speed handsets operating over wideband-CDMA-EDGE (or "WEDGE") networks. Others believe that the key trend will be basic communications services rolling out around the world. Others still regard widespread inclusion of short-range connectivity like Bluetooth and WiFi as the next logical step.

The TriQuint strategy is to meet any and all of these demands from a wide range of customers. New products launched for mobile handset applications are now grouped into a set of product "families", the names of which are physics-inspired, emphasizing the focus on the fundamental building blocks with which products such as mobile phones are built.

The "Hadron" family includes industry-standard PA modules; "Tritium" includes an integrated duplexer and filter for CDMA and wideband-CDMA applications; and the "Quantum" family consists of full transmit modules that combine a GaAs PHEMT switch, a low-pass filter and a control circuit with the PA function.

Curious though these product families may sound, it is the understanding of semiconductor device physics that underpins all these GaAs-based components. In case you were wondering, a hadron is defined as a subatomic particle that experiences the nuclear force. According to *Wikipedia* (your correspondent's grasp of particle physics is tenuous at the best of times), hadrons can disappear altogether under certain conditions. Thankfully, there appears to be no danger of that happening to the market for GaAs chips in mobile handsets for the foreseeable future.



**TriQuint inside:** TriQuint's TQM7M4006 transmit module features two highly integrated InGaP power amplifier die, a GaAs passive matching die and a CMOS controller – in a 5 mm x 5 mm package. All the components are flip-chip mounted to minimize thermal excursions.





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# Germanium — a surprise ba

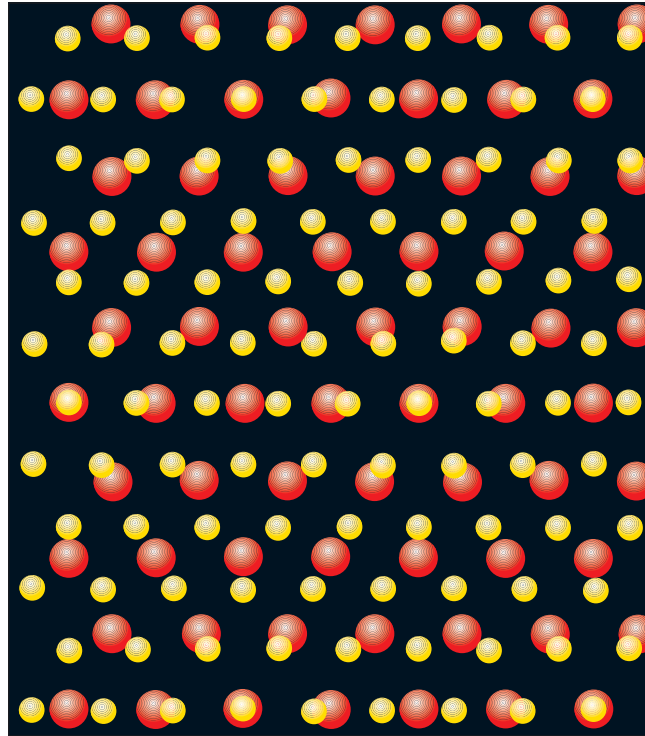
Germanium substrates are an unlikely candidate for nitride growth. However, a unique meshing ratio actually enables the fabrication of high-quality GaN directly on this platform, says IMEC's **Ruben Lieten**. The development could ultimately lead to more efficient and powerful HBTs.

The high cost and low availability of GaN substrates have driven nitride-chip manufacturers to use other platforms for growth, such as sapphire, SiC and silicon. These three alternatives have provided the basis for the production of countless devices, but in every case intermediate layers have had to be inserted into the structure to combat significant lattice and thermal mismatches (see table). Although the additional buffer layers are only an irritation for LED manufacturers, they are the show-stopper for the fabrication of heterostructure devices such as GaN HBTs that require contacts to be made directly to the substrate. This is because they prohibit the formation of a heterojunction between the upper, high-quality, GaN layer and the substrates.

This particular limitation has prompted our team at the Interuniversity Micro Electronics Center (IMEC) in Belgium to investigate alternatives that could ultimately be used for our development of an InGaN-based photo-electrolysis cell, which will use solar radiation to split water. This type of device would really benefit from a conductive substrate in contact with the active InGaN layer, because back contacting can be applied to the design.

Our pursuit of a new nitride platform has focused on germanium (111) material. A theoretical lattice mismatch of  $-20\%$  with GaN suggests that it would be very challenging to produce high-quality films. However, if we could overcome this obstacle, we could reap the rewards of germanium's otherwise excellent properties. These include a relatively low bandgap that will lead to more uniform heating in MBE growth chambers; a native oxide that is much easier to remove prior to growth than the oxide associated with silicon; and a very small thermal mismatch with GaN, which prevents the formation of large thermal-induced stresses during sample cooling after the growth stage.

It turned out that GaN can actually form high-quality films by direct growth on germanium, probably because there is a very favorable relationship between the sizes of the germanium and GaN lattices (see figure 1). The mesh ratio between the two hexagonal structures is close to 5:4, and the lattice mismatch between the two materials is just  $+0.4\%$ .



**Fig. 1.** A meshing ratio near 5:4 enables the formation of high-quality GaN fi

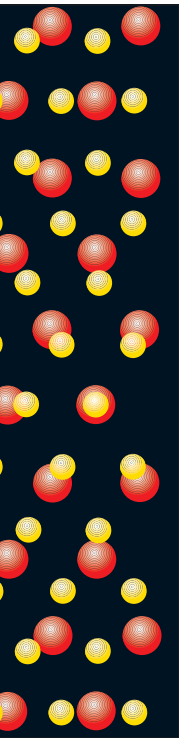
We produced our films by MBE using a Riber tool fitted with an Oxford Applied Research nitrogen plasma source (see figure 2). The common alternative technique, MOCVD, is not suited to this material system because high-quality GaN demands a reactor temperature of  $1000\text{--}1100\text{ }^{\circ}\text{C}$  and germanium melts at  $940\text{ }^{\circ}\text{C}$ . With MBE this is not an issue, because the epitaxy is carried out below  $800\text{ }^{\circ}\text{C}$ .

We have characterized our GaN-on-germanium epiwafers using various techniques. Reflection high-energy electron diffraction (RHEED) images taken in the reactor reveal an abrupt transition at the onset of growth, followed by the formation of a smooth surface. Post-growth X-ray diffraction measurements on a  $38\text{ nm}$ -thick film confirm that this material has a good crystal quality. X-ray rocking curve measurements on the same sample produced a peak from the GaN epilayer with a full-width half-maximum of  $371\text{ arcsec}$ , indicating that the crystal quality is comparable to that of GaN grown on sapphire and silicon. Additional " $\omega$ - $2\theta$ " scans on the same sample demonstrated that the GaN-germanium interface is also of high quality. Current-voltage measurements on our material also show rectifying behavior for n-type GaN on p-type germanium (see figure 3).

The bandgap difference between GaN and Ge could provide a large DC current gain.



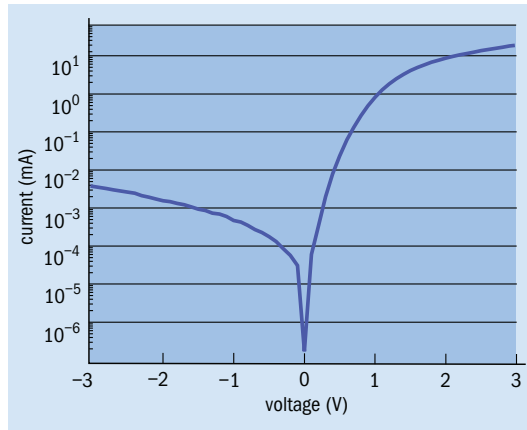
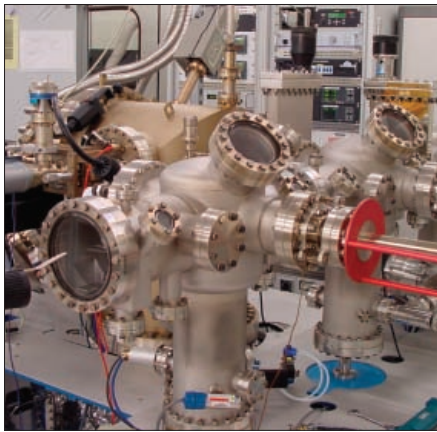
# Search for high-quality nitrides



on Ge substrates.

## Different substrates for nitride growth

Material	Lattice constant <i>a</i> (Å)	Lattice mismatch (%)	Thermal expansion coefficient (10 <sup>-6</sup> K <sup>-1</sup> )	Thermal mismatch (%)	Thermal conductivity (W/cmK)	Bandgap (eV)
GaN (reference)	3.19	0	5.6	0	1.30	3.39
sapphire	2.75	16.0	7.5	-34.0	0.33	8.00
6-H SiC	3.08	3.5	4.2	25.0	4.90	2.36
silicon (111)	3.84	-16.9	2.6	54.0	1.30	1.12
germanium (111)	4.00	-20.3	5.9	-5.5	0.58	0.66



**Fig. 2 (left).** IMEC's GaN-on-germanium epiwafers are grown using a Riber MBE reactor fitted with a nitrogen plasma source.

**Fig. 3 (right).** An n-type layer of GaN on p-type germanium shows rectifying behavior.

This series of studies shows that high-quality GaN films are grown directly on germanium (111) without the need for intermediate layers. When formed in this way, GaN has a small compressive stress as the thermal mismatch between these layers is only 5.5%. Because GaN can undergo “surface wetting” on germanium, and no chemical reaction occurs between gallium and germanium, the interface between the two materials is of high quality.

These results are very encouraging, but two issues still need to be addressed. The first is that the GaN layer always behaves as an n-type material, which is probably due to some germanium diffusion. The exact cause of the n-type doping is unknown, but it probably results from etching of defects in the germanium surface during the growth, which creates voids in the substrate. This is consistent with secondary ion mass spectrometry measurements, which show that any diffusion between the gallium and germanium atoms is limited. However, even a limited diffusion of germanium into GaN can create a considerable carrier concentration.

The other drawback of our current GaN-on-germanium samples is that they contain two phases that have a 4° twist with respect to one another, according to transmission electron microscopy images

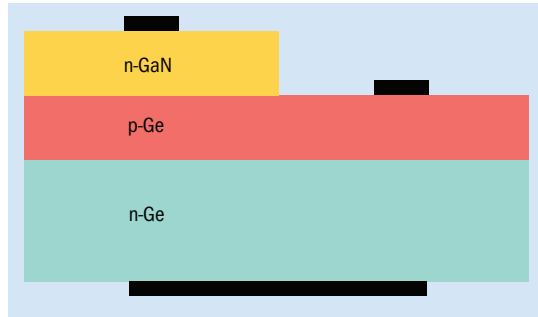
and X-ray diffraction curves. However, resolving this issue should only require a switch to off-axis germanium (111) substrates.

It could therefore be possible to make nitride-based structures on germanium substrates that can be used as the back contact in vertical devices. Junctions can be formed between n-type GaN and p-type germanium, or p-type GaN and n-type germanium, and used in devices such as HBTs, LEDs, heterojunction solar cells, and heterojunction diodes.

HBTs could be formed by growing n-doped GaN on p-type and n-type germanium (see figure 4, p16). This would create a device that would have a bandgap difference at the GaN–Ge heterojunction of 2.7 eV, far larger than that of Si/SiGe, InP/InGaAs, and AlGaAs/GaAs, which have bandgap differences of just 0.2, 0.7 and 0.3 eV respectively.

The enormous bandgap difference between GaN and germanium could provide a very large DC current gain, or be traded to invert the base and emitter doping concentrations. A higher base doping concentration would deliver two major benefits: a cut in base resistance, leading to lower power consumption and faster switching; and an increase in pinch-off voltage, which can also boost the switching speed through a shortening of the base width.

**Fig. 4.** The GaN and germanium materials system can be used to produce NPN HBTs consisting of an n-type GaN layer and a p-type germanium layer on an n-doped germanium substrate. P-type germanium is used for the base and n-type GaN for the emitter.



There are more ways in which the switching speeds and power consumptions can be improved. The large bandgap difference suppresses the emitter transit time, which increases switching speeds, while the very small bandgap of germanium cuts the operating voltage of the transistor's base-emitter junction and lowers its power consumption.

GaN-on-germanium HBTs should also benefit from good intrinsic characteristics. Electron mobility for germanium, a key parameter for NPN HBT performance, is  $3900 \text{ cm}^2/\text{Vs}$ , and the surface recombination speed in this material is lower than that of GaAs and InP. This means that GaN-on-germanium HBTs would not suffer from poor low-current gain and non-ideal base characteristics that can plague other forms of this device.



**About the author**  
**Ruben Lieten (lietenr@imec.be)** is a research assistant of the Research Foundation Flanders, and is associated with Vrije University, Brussels.

All of this sounds very promising. However, before we can unlock the great potential of this material combination, we must minimize the HBT's depletion recombination current by fabricating a heterojunction with very few defects. To do this we must improve our fabrication processes, as the one used today appears to create defects through unwanted etching into the germanium substrate.

The alignment of the conduction band edges of GaN and germanium is also under investigation. If they are not aligned, conduction band spikes occur at the interface that can restrict transistor gain (although this reduction is only small owing to the large differences in bandgap between the two materials). The band structure is also influenced by GaN's polarity on germanium, which is currently unknown and under investigation.

Although there are unresolved issues, the GaN-on-germanium material system shows great promise for the fabrication of very fast transistors operating with lower power consumptions than current offerings. At IMEC we will continue to refine this structure before developing an initial device. We will then assess whether this transistor merits further investigation.

**Further reading**

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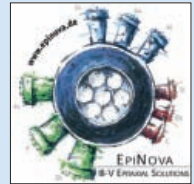


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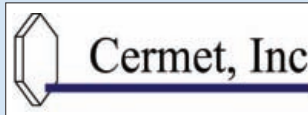
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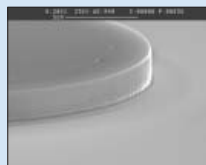
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# A life in research: the impact of Klaus Ploog, MBE pioneer

**Helmut Jung** looks back at the influential career of Klaus Ploog, whose achievements include the invention of the superlattice and the delta-doping technique that are used in today's HEMTs.

Most of us are looking forward to our retirement. It's an opportunity to leave behind the commute, the long hours and the worries about the success of our products, and devote time to the more relaxing things in life.

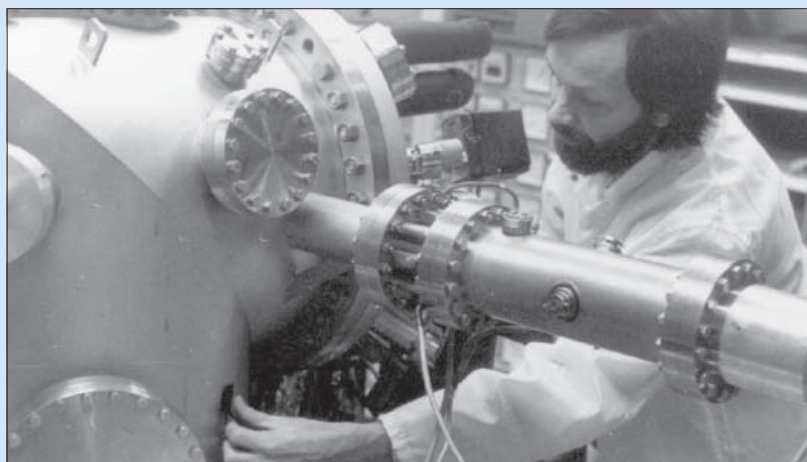
Academics, however, don't always share this view. Instead, some will continue to work because their research means so much to them. Nobel prize-winning solid-state physicist Sir Neville Mott, for example, carried on writing papers up until his death at 90. Similarly, the German MBE pioneer Klaus Ploog has managed to find a way to continue his research. Although the law of his homeland has forced him retire as director of the Paul-Drude Institute (PDI), Ploog has taken a visiting professorship at Tokyo Institute of Technology, Japan.

Ploog has been involved in MBE research throughout his career and is a legend within that community. Born in 1941 in Klein Kampen, Germany, he studied chemistry at the universities of Kiel and Munich. After graduating in 1967, he started work as a research scientist at Munich University, and gained a PhD with *summa cum laude* (the highest honour) three years later.

## Klaus Ploog's research at Stuttgart and the PDI has left a major impression on academia and industry.

He stayed at Munich as a lecturer for another year, then spent two years as a research associate at the Jülich Research Centre before moving to the Max Planck Institute for Solid-State Research in Stuttgart, where he started to assemble his MBE group. Research in the early 1970s was hampered by a lack of fully equipped commercial MBE tools, and epitaxial effusion cells had to be developed and fabricated in-house. "Often we had to overcome elementary problems," recalls Ploog's colleague Albrecht Fischer. "We had great problems getting

### Klaus Ploog: a lasting influence



Klaus Ploog's phenomenal career has been felt in industry and academia. He has been granted several patents, including that for the "selectively doped FET" (a structure that we know today as an HEMT), and published more than 1800 technical papers. The importance of these papers is shown by how often they have been referenced. His high number of citations puts him in second place on the all-time *ISI Web of Knowledge* "h-index", with a score of 71 (meaning 71 of his papers have been referenced more than 71 times).

His international awards include:

- 1983 Technology Transfer Award of the Federal Research Ministry, Germany;
- 1989 Award of the Italian Physical Association;
- 1998 Iberdrola Ciencia y Tecnología Award, Spain;

- 1990 Philip-Morris Research Award for pioneering work in MBE processes to produce atomically controlled semiconductor layer structures with specific electronic properties;
- 1999 Max Planck Research Award for promotion of internationally outstanding achievements;
- 2003 Welker Award for outstanding contributions on III-V semiconductors;
- 2007 Eugen and Ilse Seibold-DFG award for promotion of the German-Japanese relationship in science.

He has also been a visiting research professor at Stanford University, CA, and the Japanese institutions NTT Basic Research Laboratories, NTT Electrical Communication Laboratories, Mitsubishi Central Research Laboratories, Kyushu Institute of Technology, and Tokyo Institute of Technology.

boron nitride crucibles for evaporating aluminum."

Despite these difficulties, Ploog built up the expertise required to fabricate high-quality III-V epitaxial structures incorporating dopant atoms. He and his team could then grow semiconductor struc-

**Ploog fosters international relations**

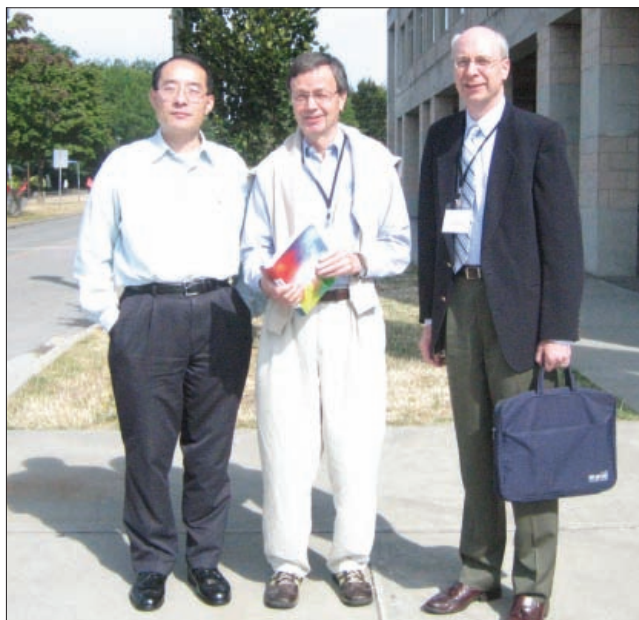
Ploog has held the post of visiting professor at several Japanese institutions, including Waseda University in Tokyo. The high esteem in which he is held in that country, as well as his popularity, is obvious in the way that Yoshiji Horikoshi, a member of Waseda University's board of directors, talks about him: "I first got to know Klaus Ploog in 1982, in Tokyo, during the second International MBE Conference, when

he presented an invited speech entitled 'Doping superlattices'.

"After the conference we went to the NTT Basic Research Laboratories in Musashino. At that time he and my boss Dr Okamoto discussed the idea of establishing a researcher exchange program between the two organizations. The program started the following year, and I was honoured to be the first visitor in November 1983. In Stuttgart, all of

my family enjoyed the excellent care of Prof. Ploog, his family and all the members of his laboratory.

"Ploog has also established efficient channels of communication and technical exchange between Germany and Asian countries, especially Japan. This relationship is so important to us that I asked him to become a visiting professor at Waseda University, [an offer] which he kindly accepted."



**Klaus Ploog** (center) enjoys the Vancouver sunshine with former PhD students Yong-Hang Zhang (left) and E Fred Schubert (right), who are now at Arizona State University and Rensselaer Polytechnic Institute in Troy, NY.



**Klaus Ploog** was director of the Paul Drude Institute from 1992 until his retirement in late 2006.

tures with atomic accuracy on GaAs, and then on AlGaAs; work that led to the fabrication of the first tailor-made doped-superlattice structures.

The high-quality samples produced by Ploog's team during this pioneering period were in high demand from academic groups studying quantum mechanical phenomena throughout the world. These researchers included Klaus von Klitzing, who explored his Nobel prize-winning discovery of the quantum Hall effect further with Ploog's material. "Today 'nano' is one of the most important words in modern research," says von Klitzing. "Klaus Ploog contributed enormously to nanoscience and nanoelectronics. When he pioneered the capabilities of MBE for new electronic devices, the word 'nanoscience' was not in use."

Von Klitzing believes that it is only through the epitaxial growth techniques pioneered by Ploog and others, along with the development of scanning-probe techniques, that today's scientists can

control materials with atomic precision and subsequently explore the nano-world.

Ploog's influence stretches beyond academia, however. Today's volume manufacturers of transistors are also indebted to his work. The delta-doped layers used in HEMTs, and other devices that confine doping atoms to an ultra-thin layer, were first developed by his group more than 20 years ago. "Delta doping has become the standard doping technique in numerous devices, due to the inherent advantages of delta-doped structures over uniformly doped ones," explains E Fred Schubert, a former PhD student of Ploog's who is now Wellfleet senior constellation professor, Future Chips, at Rensselaer Polytechnic Institute in Troy, NY. "Since its inception, delta doping has been used in billions of devices."

Ploog's other legacy to HEMT production, from around the same period, is the superlattice buffer. This improves the epitaxial quality of the entire tran-



**Klaus Ploog's** skills as a researcher were revealed during his time as a PhD student. He was awarded a doctorate *summa cum laude*.



## Commercial impact of Ploog's research

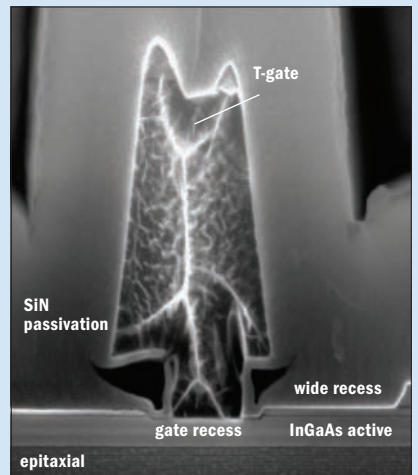
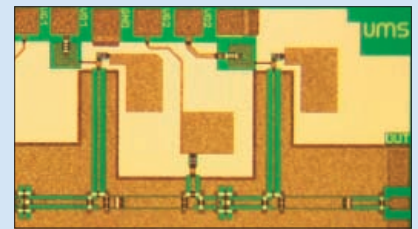
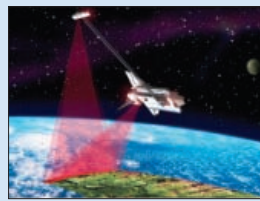
UMS, a European company with manufacturing sites in Ulm, Germany, and Orsay, France, produces a range of amplifiers that feature Klaus Ploog's delta-doping technique and superlattice buffer layer.

One of the company's PHEMT-based low-noise amplifiers operates at frequencies between 80 and 100 GHz and is used in passive and active radar-imaging systems. This  $2 \times 1$  mm two-stage chip offers low power consumption and is built using the company's proprietary short-gate-length single-recess technology.

The amplifier's gain, input and output loss characteristics are among the best ever reported for InGaAs/AlGaAs HEMTs, and compare favorably to InP-based and metamorphic technologies.

UMS also makes an amplifier for X-band applications that has a power output comparable to the highest value of its competitors. It features a double recess and double-side doped technology (see figure 1). The PHEMTs used in this device have two etching stop-layers each 1 nm thick, with abrupt interfaces, which provide reproducible recessing.

The amplifier produces an output power of almost 40 dBm (10 W) between 8 GHz and 11 GHz, and a power-added efficiency of 45–50% over that frequency range at 6 dB and 10 dB compression levels.



The PHEMT-based amplifiers produced by UMS are deployed in adaptive cruise-control radar systems in cars, mobile-phone base stations and communication satellites (above). **UMS' PHEMT chip** (top right) targets applications requiring low-noise amplification at 94 GHz. It produces a gain of up to 12.5 dB between 85–98 GHz. Output and input losses at the target frequency are below –20 dB.

**Fig. 1 (right).** SEM images reveal UMS' gate structure, featured in its InGaAs/AlGaAs high-power PHEMT structures.

istor, and is now standard in all HEMT epiwafers.

In 1991 Ploog left Stuttgart to take on the professorship of material science at Darmstadt University, Germany. He didn't stay long, though, and a year later became the director at the newly founded PDI for Solid-State Electronics in east Berlin, at the heart of the freshly reunited Germany. By 1993 he had the additional title of professor of material science at the Humboldt University physics department in Berlin, Germany.

### New directions

At the PDI, Ploog continued to push the capabilities of MBE technology, with research that headed in new directions, such as the growth of ferromagnetic semiconductor nanostructures for spintronics and lower-dimensional structures. Developments in all these areas could have major commercial implications in the future. For example, variants of the quantum-wire and quantum-dot structures are now starting to appear in commercial devices such as quantum-dot lasers, while spintronic devices are a hot research topic that could lead to the development of programmable magneto-logic devices.

Ploog has been an active and pioneering developer of wide-bandgap materials based on GaN. When the rest of the community was still focused on polar material, Ploog's team was investigating cubic nitrides and growth on new "non-polar" substrate orientations. His team was also the first to grow GaN by MBE along a non-polar crystal direction.

Non-polar GaN is now a very hot topic. Lasers and

LEDs produced using this growth direction promise to have higher efficiencies than their "polar" equivalents, owing to the removal of internal electric fields. There have even been reports this year from UCSB and Rohm of non-polar lasers. HEMTs could also benefit from the non-polar approach, as carriers in the device's channel can be fixed and adjusted by external doping species.

Ploog's research at Stuttgart and the PDI has left a major impression on academia and industry. It has also brought him friends, including many in Japan (see box, "Ploog fosters international relations"), where he has fostered relations between the Japanese and German III–V semiconductor communities. However, his greatest contribution is helping to establish MBE as a *de facto* tool for growing high-quality devices. The techniques that he established are now used to produce various III–V transistors at foundries throughout the world, including the one in Europe owned by United Monolithic Semiconductors (UMS), where the author of this article works.

### Further reading

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### About the author

**Helmut Jung (jung@ums-ultm.de)** has worked at UMS since its inception in 1996, and for the first five years he was in charge of PHEMT development and process control. He is now responsible for technology co-operations, and heavily involved in power PHEMT and GaN HEMT development. Before joining the company he worked for DaimlerChrysler, developing InP- and GaAs-based lasers, GaAs-based diodes, PHEMTs and MESFETs. Prior to this he was one of Klaus Ploog's PhD students, investigating laser sub-band transitions in single and multiple quantum wells. Jung thanks his colleagues J Grünepütt, H Blanck and Z Ouarch for their contributions to MMIC development.

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## EDGE-EMITTING LASERS

# Inner stripe boosts GaN laser output

Switching from a buried ridge-waveguide structure to an inner stripe design can increase the output power of single mode lasers to a record-breaking 1000 mW, says NEC. **Richard Stevenson** investigates the novel approach.

Blue-violet laser diodes are finally starting to have an impact on the life of the home-entertainment buff. Blu-ray and HD DVD players and recorders incorporating these devices are now in stores and, although prices aren't cheap, there is a growing selection of movie titles in both formats. Gamers are also benefiting, since the PlayStation3 console from Sony features a Blu-ray player.

Despite these recent successes, further improvements in 405 nm laser performance are needed for these edge-emitting devices to serve a broader range of applications. For example, if they are to offer faster writing and recording speeds, an increase in laser output power is required – in conjunction with a high-quality beam profile.

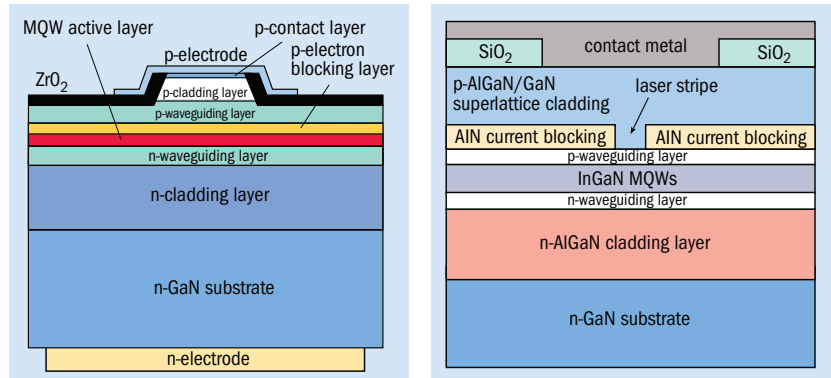
Unfortunately, it is very difficult to address these weaknesses with a conventional ridge-waveguide laser design (see figure 1 (a)) which can only maintain single mode emission at low output powers. Above an output power that is referred to as the “kink level”, emission switches to a higher order mode that is incompatible with the focusing optics used to read from, and write to, the disc.

Narrowing the waveguide is one way to overcome this problem. However, it is difficult to use dry etching to fabricate stripe widths of 1.4  $\mu\text{m}$  or less, which are needed for “kink-free” operation up to 200 mW. And even if a laser with such a narrow waveguide could be produced, it would suffer from a high operating voltage and temperature that would impair performance.

The drawbacks of dry etching have led researchers at NEC Corporation in Japan to develop an alternative design that features an “inner-stripe” and a regrown AlN optical-confinement and current-blocking layer. It's a structure that delivers three key advantages, says Masaki Ohya, assistant manager of the company's system devices research laboratories: a narrow waveguide with dimensions that can be precisely defined by crystal growth and photolithography; a low electrical resistance that stems from lateral current flow in the AlGaIn/GaN superlattice; and a relatively low operating temperature thanks to the width of the p-type cladding layer and contact metal.

## A wet etching approach

To produce these high-quality inner-stripe structures first requires growth of crack-free AlN on GaN. This is followed by formation of a damage-free stripe in the material and planar regrowth of the AlGaIn/GaN superlattice cladding. The NEC researchers have approached the task by using a very low growth temperature of 400  $^{\circ}\text{C}$ . This creates an amorphous, crack-free AlN film (confirmed by X-ray diffraction



**Fig. 1.** Conventional GaN blue-violet laser diodes use a ridge-waveguide structure to confine the light in the cavity, such as this buried ridge-waveguide design by Nichia (a). NEC's new structure (b) replaces the ridge with an “inner stripe”. The stripe is produced by growing the n-type cladding layer, the active region and the AlN current-blocking layer by MOCVD. A 1.0–1.4  $\mu\text{m}$  stripe is then defined by conventional photolithography and wet etching, before a second growth step adds the p-type superlattice cladding and magnesium-doped contact layer.

measurements), which can then be wet-etched with phosphoric acid to produce a high-quality stripe. “With dry etching you have no selectivity, and you don't get sharp interfaces,” explained Ohya. Ramping the reactor temperature for subsequent growth crystallizes the remaining AlN, allowing high-quality growth of the p-type structure.

Ohya and colleagues have made lasers with 650  $\mu\text{m}$ -long cavities, fabricated from material with a low-reflection-coated front facet and a high-reflection-coated rear facet. A typical 1.4  $\mu\text{m}$ -wide stripe produces a kink-free continuous wave (CW) output power of more than 200 mW over the 20–90  $^{\circ}\text{C}$  range, with a threshold current and voltage of 32 mA and 4.1 V at 25  $^{\circ}\text{C}$ .

Variants of this design with a 1.0  $\mu\text{m}$ -wide stripe produce more than 400 mW in CW mode over the same temperature range, while in pulsed mode, with a 50% duty cycle, this increases to more than 600 mW. When the duty cycle is cut to 0.03%, kink-free output surpasses 1000 mW at up to 70  $^{\circ}\text{C}$ . “To our knowledge, that's the highest single mode output power for blue-violet laser diodes,” said Ohya.

The researchers have also started to assess the reliability of their new design. When pulsed with a 50% duty cycle at 80  $^{\circ}\text{C}$  over the course of 1000 h, four 1.4  $\mu\text{m}$  cavity lasers required a 10% increase in operating current to maintain a 200 mW output. Transmission electron microscopy images reveal that these tests did not produce defects near the regrown interfaces, and suggest that this type of laser is a strong contender for deployment in tomorrow's high-density optical disc systems.

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# Global consortium pioneers high-frequency SiC PIN diodes

A partnership between Ukraine, Russia, Greece and the US has developed a series of SiC PIN diodes for microwave applications. The devices already deliver a better performance than incumbent silicon and GaAs equivalents, says team member **Nicolas Camara**, and more improvements are expected.

PIN diodes are widely used as phase-shifters, switches, attenuators, and limiters in RF, ultrahigh frequency and microwave systems. These devices – which serve in applications ranging from civilian and military radar to mobile-phone base-station transmitters and satellite communication units – are preferred to their electromechanical equivalents because they are cheaper, more reliable, last longer, and can operate at higher speeds. They are also more efficient, as they can operate at very high microwave power levels using a low direct-current (DC) bias. The frequency response of these PINs is also good, due to their relatively low off-state capacitance for a given on-resistance, while their higher blocking voltages give them the edge over MESFETs for applications requiring either high powers or high frequencies.

High-frequency versions of the device are currently made from GaAs and silicon. However, improvements in performance are promised by switching to SiC, which has superior intrinsic properties. This material could enable higher switching speeds and similar microwave-power-control capabilities, or provide greater power handling at equivalent switching speeds.

Switching to SiC PINs could also cut the number of devices required in a circuit. When silicon PINs are used, several diodes have to be combined to handle powers of more than a few kilowatts in pulsed mode, resulting in complex, narrow-band circuits that have the added disadvantage of needing a dedicated cooling system. With SiC, however, only one or two diodes would be needed to handle a few kilowatts of RF power, leading to a simpler, broadband circuit that is easier to cool.

Changes in radar technology are also increasing the attractiveness of SiC PINs. Frequency bands that were once set aside for radar are now used for wireless communication, which has forced radar systems to turn to higher frequencies. This means that diodes need to have smaller capacitances and smaller physical sizes to significantly increase their thermal resistance.

The power-handling requirements for today's diodes are also more stringent, because higher pow-



US DEPARTMENT OF DEFENSE

**SiC PIN diodes** have the potential to exceed the performance of GaAs and silicon equivalents used in high-performance radar systems, such as those deployed by the US military.

ers are needed to pinpoint increasingly sophisticated planes operating in stealth mode, which reflect as little energy as possible.

When used in this application, silicon's low breakdown voltage limits the output from the diode and its low thermal conductivity hampers heat dissipation. SiC PINs, in comparison, excel in both of these areas. They can also operate at higher temperatures than both silicon and GaAs devices, which are typically limited to environments below 175°C. This enables SiC PINs to be placed in other harsh environments, such as those found next to engines and airplane turbines.

**Fabricating 4H-SiC PINs**

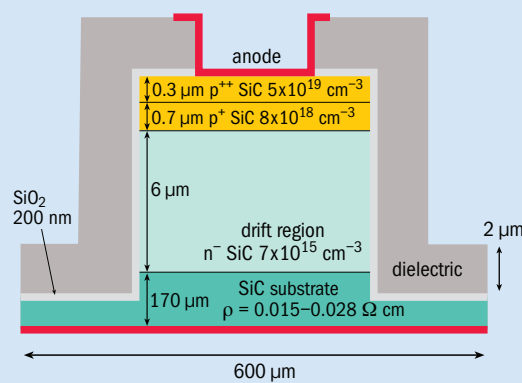
Our SiC PIN structures are produced on commercial low-resistivity n-type substrates. To reduce the diode's series resistance, an epitaxial p-type layer is used in preference to an implanted layer, and 200  $\mu\text{m}$  of the substrate is systematically removed by boron carbide lapping. High-pressure plasma etching in an  $\text{SF}_6$  environment then forms "deep-tilt" smooth mesa structures up to the substrate.

To improve the device's breakdown voltage, we grow 200 nm of  $\text{SiO}_2$  in a wet environment, followed by a layer of tetra-ethyl-ortho-silicate and/or a special high-temperature polyimide coating.

A critical step in the fabrication process of the PIN is the creation of the ohmic contact, which must have as small a series resistance as possible. We have developed a proprietary process for this contact (see US patent 6,599,644), which enables the fabrication of state-of-the-art contacts that produce excellent

stability under high thermal stresses, and have a resistance of  $10^{-5} \Omega \text{cm}^2$  at 200  $^\circ\text{C}$  and less than  $3 \times 10^{-5} \Omega \text{cm}^2$  at room temperature. The nickel-based cathode has a contact resistance that is below  $10^{-5} \Omega \text{cm}^2$  and does not influence the total series resistance.

A 5  $\mu\text{m}$ -thick layer of gold is added to the device, by electroplating, on the top of the emitter and on the back of the diode. This ensures good adhesion of the structure to the package under microwave stress conditions, and improves the heat-dissipation characteristics of the advice.



GaN, like SiC, has several characteristics that make it a potential candidate for high-power microwave PIN diodes, but it is actually inappropriate for several reasons. Unlike SiC, it is not suited to the fabrication of vertical transport devices that offer excellent stability at high power levels. Heavy p-doping is also difficult, which makes contact resistance much higher, and it is impossible to grow thermal oxides that lead to high-quality passivation at the device's edge. Lastly, the restricted availability of GaN substrates means that fabrication has to be carried out on a foreign platform, such as sapphire, which results in poor heat dissipation and higher device resistance.

**PINs versus MESFETs**

For these reasons research and commercial efforts using wide bandgap materials are focused on SiC. In the main, PIN diodes are being developed for low-frequency switching requirements and SiC MESFETs for high-frequency microwave applications. This is not surprising because the market for low-frequency SiC PIN diodes is orders of magnitude larger than that for its higher-frequency counterparts. In addition, the current tendency in all forms of compound semiconductor technology is to replace microwave diodes with MMICs, which explains the popularity of SiC-related micro-

wave component research programs dedicated to MESFETs.

However, SiC microwave PIN diodes do have the potential to deliver high performance as they do not suffer from the traditional problems of a high number of defects and forward-bias degradation that plague SiC devices used for power electronics. Having fewer defects is a direct consequence of the smaller device dimensions, which are needed to reduce capacitance and boost performance at high frequencies. These chips are smaller in all dimensions, and thicknesses of the active layer can be reduced to below 6  $\mu\text{m}$  for applications requiring power handling of 5 kW or more.

To speed up SiC PIN development, the Foundation for Research and Technology–Hellas (FORTH) formed a consortium five years ago with Svetlana Electronpribor and Ioffe Institute from Russia and ORION from Ukraine. This team has been supervised by George Haddad from the University of Michigan, who has been a leading developer of silicon and GaAs-based diodes for the last 40 years.

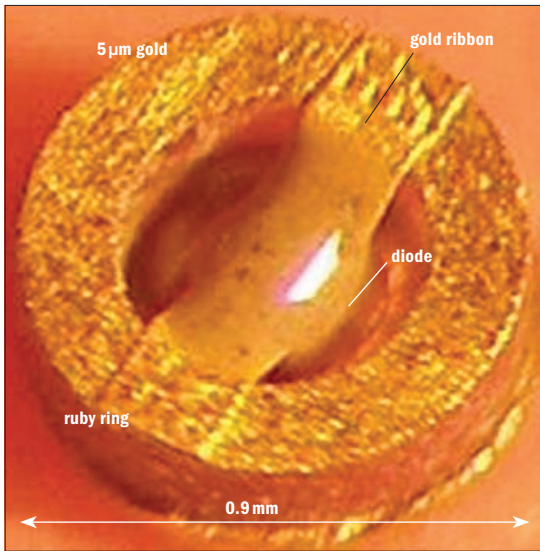
Our consortium has built SiC PIN diodes on 4H substrates that can operate in the X-band (8–12 GHz) and tested them in broadband switches. These devices were fabricated after the epitaxial structure and device geometry had been optimized, and they make the best use of available material and existing process technology.

The 4H-SiC diodes were fabricated from CVD-grown, commercially available epiwafers and material grown by the sublimation method at the Ioffe Institute (see box "Fabricating 4H-SiC PINs", and figure 1 for a description of the diode's packaging). The CVD-grown diodes produced excellent DC characteristics and fast switching. The drift layer resistance at a 100 mA forward current is  $1.6 \times 10^{-4} \Omega \text{cm}^2$ , indicating that the base layer is effectively conductivity modulated and a switching speed of less than 10 ns is possible. Capacitance at a punch-through voltage of  $-100 \text{ V}$  was well below 0.5 pF for mesa structures with a diameter of up to 150  $\mu\text{m}$ , which shows that this structure has the potential to operate at high frequencies.

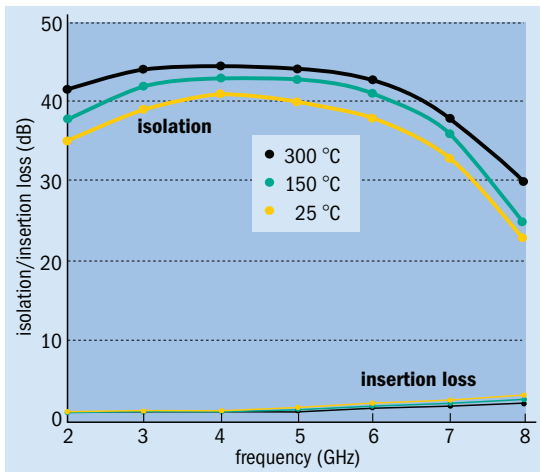
We have evaluated the performance of our packaged 80–150  $\mu\text{m}$  diameter devices in special tunable waveguide single-pole-single-throw (SPST) switches suitable for power X-band applications (see figure 2). The key attributes for this type of switch are high speed, good power handling, and high and low transmission of the input signal in the "on" and "off" states, respectively. In the "on" state a perfect switch would produce an output signal that is identical to the input, giving it an insertion loss of 0 dB, and in its "off" state no signal would be transmitted, giving it an infinite value for isolation.

Over a narrow band between 8.5 and 10.5 GHz, our SPST switches produced an isolation of 19–25 dB and insertion loss of less than 2 dB. This loss is similar to that for commercial silicon RF switches operating at several gigahertz, which have an isola-





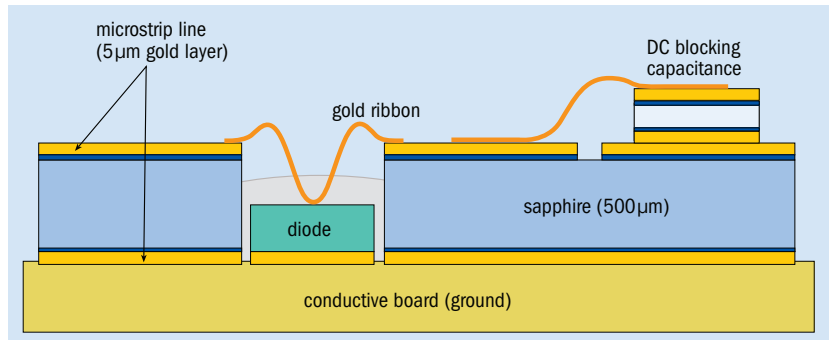
**Fig. 1.** The wafer was diced into 600 μm × 600 μm chips that each contained a single diode. These chips were then soldered by diffuse welding and thermal compression to form packages with a 5 μm-thick upper gold layer that can sustain mechanical strength up to 700 °C. A special high-temperature polyimide was added to the package that enabled the SiC PIN diode to deliver a leakage current of less than 10 μA at temperatures up to 600 °C.



**Fig. 3.** Switches based on SiC PINs operate at much higher temperatures than those based on silicon and GaAs.

tion figure that usually exceeds 30 dB. The stability of our switches' electrical characteristics is excellent, according to extensive high-thermal-stress tests that were conducted over long periods.

We have also carried out high-power tests at 9.5 GHz on 100 μm diameter diodes to determine the power-handling capabilities. These tests involved using 1 μs pulses, an on-off time ratio of 1000, and drive currents of 100 mA for the “on” state and voltages of 100 V for the “off” state. In the “off” configuration the switches produced a very stable isolation of 22.5 dB at microwave powers of 2 kW, and in the “on” state the devices delivered an insertion loss below 1 dB for powers up to 1.8 kW. The relatively low isolation is due to a differential resistance of



**Fig. 2.** The single-pole-double-throw (SPDT) switches shunt the RF signal to ground through a PIN diode that has its resistance controlled by a positive DC signal. These prototypes are high-temperature-resistant microwave hybrid integrated circuits (HICs) with Al/Au microstrip lines formed on a 500 μm sapphire dielectric. The diode's top contact is connected to the microwave IC board with 60 μm-thick gold ribbons, and its back is soldered to the Ni/Au modulator board (ground) by thermally assisted compression. A high-temperature-resistant dielectric compound is then added to the PIN that protects it from air ionization at high voltages. The capacitances of the SPDT switches that protect the signal from the DC voltage were designed to extend the operation temperature to more than 300 °C. The inductance was made of a single gold wire, and typical SMA connectors were soldered to the microstrip by thermally assisted compression.

more than 1 Ω for the 100 mA drive current used.

We have improved the isolation and broadband operation of our switches by building two types of modulator featuring multiple diodes. Our three-diode modulator is a compact and convenient design for portable communication systems, while our version containing two diodes is suitable for high-temperature operation. The three-diode package produces 30 dB isolation, an insertion loss below 2 dB and switching in less than 30 ns in the 1–6 GHz band. Its two-diode counterpart produced a transmission loss of just 1–2.5 dB and isolation of 33–45 dB between 2–7 GHz at temperatures up to 300 °C (see figure 3). The peak value for the isolation actually increases with temperature, proving for the first time the suitability of SiC PINs operating at high temperature for high-frequency applications. We are continuing to investigate the behavior of these PIN circuits under high-power CW and pulsed-signal operation.

The results of our SiC PIN development program demonstrate that these devices offer higher operating temperatures and comparable power-handling characteristics to their commercial silicon and GaAs equivalents. However, this work is still in its infancy, and we believe that the great potential of SiC indicates that there is still plenty of room for improving devices.

One target is a reduction of resistance in the “on” state to improve the isolation, which can be achieved by additional thinning of the substrate. However, we will also be trying to develop a full 4H-SiC modulator that will feature a switching diode and a driving circuit made from the same material. We will begin by developing separate circuits for the switch and its driver, before we unite them with a MMIC approach that will produce an integrated module suitable for harsh environments.



**About the author**  
**Nicolas Camara (nicolas.camara@cnm.es)** is a researcher at the Foundation for Research and Technology–Hellas, Greece. He thanks NATO and INTAS (the international association for the promotion of co-operation with scientists from the new independent states of the former Soviet Union) for funding the work of the consortium.



## METALLIC SUBSTRATES

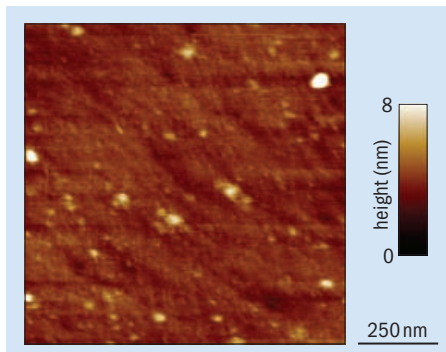
# TiC platform produces high-quality GaN

The Naval Research Laboratory (NRL) in Washington DC has produced a series of GaN films on metallic titanium carbide (TiC) substrates that could lead to the fabrication of vertical devices operating at high powers and temperatures.

Vertical devices, such as lasers, LEDs and Schottky diodes, have the potential to deliver a higher performance than lateral ones, according to Jaime Freitas from NRL, because the current's direction is parallel to the dislocation lines. The metallic substrate can also boost device performance by preventing current crowding at the interface, reducing substrate contact resistance, and improving thermal management.

Pieces of TiC (100) and (111) substrates measuring 5 mm × 5 mm formed the platform for producing GaN films by MOCVD that have a 4% lattice mismatch with the underlying substrate. The substrates were heated under hydrogen at 1350 °C for 3 min, before a nucleation layer was grown at 450 °C and the rest of the film at 1000 °C.

Although growth on TiC (100) produced



**AFM images** reveal that the GaN-on-TiC (111) films have a surface roughness of 0.55 nm. These were taken after the wafers were used for other experiments that reduced the surface quality. If the samples had been measured straight after growth, they would have shown a lower value for roughness.

a polycrystalline material, epitaxy on TiC (111) created a 3.3 μm-thick film with a good surface. Atomic force microscopy (AFM) measurements show that this layer has a surface roughness of 0.55 nm (see figure), while

scanning electron microscopy images reveal that the surface has a good morphology. The only nanopipes seen in this film are reproductions of those at the substrate surface.

The phonon spectra obtained by Raman spectroscopy on the GaN-on-TiC (111) samples confirmed the material's good crystalline quality, and indicated that the GaN layer is under a small tensile stress of 0.3 GPa.

The researchers have also measured the current-voltage (I-V) properties of this film, which exhibits a combination of Schottky and Ohmic characteristics. This suggests that the structure may be adequate for fabricating vertical devices, but elaborate experiments using metal contacts are needed to obtain a quantitative analysis. Freitas says that the measurements with metal contacts are in progress, and that the team hopes to produce some "simple" device structures at some point.

**Journal reference**

J Freitas et al. 2007 *Appl. Phys. Lett.* **90** 091910.

## GaN OPTOELECTRONICS

## Strained M-plane film boosts detector selectivity

A GaN ultraviolet photodetector with a detection bandwidth of just 6 nm has been built by scientists from the Tata Institute of Fundamental Research (TIFR), India, the Polytechnic University of Madrid, Spain, and the Paul Drude Institute for Solid-State Electronics, Germany.

The detector delivers a five-fold improvement in bandwidth over its nearest rival, which features a passive absorbing layer with a higher bandgap. "In addition, our detector's configuration is polarization sensitive," explained Sandip Ghosh from TIFR, "which further reduces the influence of scat-

tered background radiation."

The team's detector could be used for real-time studies of hazardous airborne biological and chemical agents using a laser-induced-fluorescence detection technique. Rapid identification of a range of these chemical species requires simultaneous detection at several specific wavelengths, and consequently a set of photodetectors with very narrow spectral bands.

The narrow-band photodetectors were fabricated by growing 0.4 μm-thick [110] orientated M-plane GaN films on γ-LiAlO<sub>2</sub> (100) substrates by RF plasma-assisted

MBE. These films were used to fabricate polarization filters and planar Schottky barrier photodetectors with a 200 μm-diameter active region. Orthogonal alignment of the c-axis of the photodetector and filter produces a system with a peak responsivity of 360 nm and a bandwidth of 6 nm.

The team is now attempting to push the detection band to shorter wavelengths with AlGaIn alloys.

**Journal reference**

S Ghosh et al. 2007 *Appl. Phys. Lett.* **90** 091110.

## INTERBAND CASCADE LASER

## 4 μm laser can operate at higher temperatures

Engineers at the Naval Research Laboratory (NRL) in Washington DC have increased the operating temperature of interband cascade lasers emitting at wavelengths of 4 μm or longer by more than 100 °C. The researchers' 4.05 μm laser can produce continuous-wave (CW) emission up to 269 K, and could

be used for various applications, including chemical and biochemical sensing.

"The applications of interest to us are infrared (IR) countermeasures against heat-seeking missiles, IR projection, and IR scene simulation," revealed Igor Vurgafman from NRL. He believes that interband lasers are a better prospect for 3–4 μm laser emission than quantum-cascade lasers (QCLs), which have already produced room-temperature emission at 3.8 μm. He says that QCLs operating in this range suffer high strain, which leads to problems with electron leakage.

NRL's 4 mm-long laser was fabricated by MBE on an n-type GaSb (100) substrate, and mounted epitaxial-side-up on a copper heat sink. The device produced a maximum CW output power of 130 mW at 78 K, 58 mW at 200 K, and 9 mW at 260 K, and has a threshold current density of 660 A/cm<sup>2</sup> at 260 K.

The laser is still to be optimized, and improvements to the design should lead to CW-mode operation at room temperature.

**Journal reference**

W W Bewley et al. 2007 *Electron. Lett.* **43** 283.



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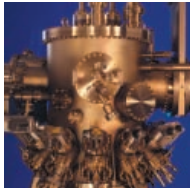
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