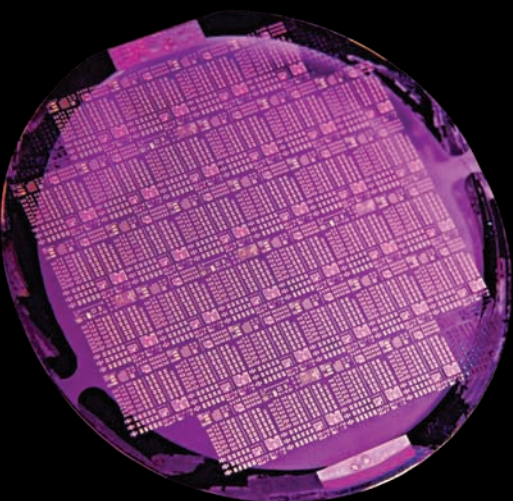
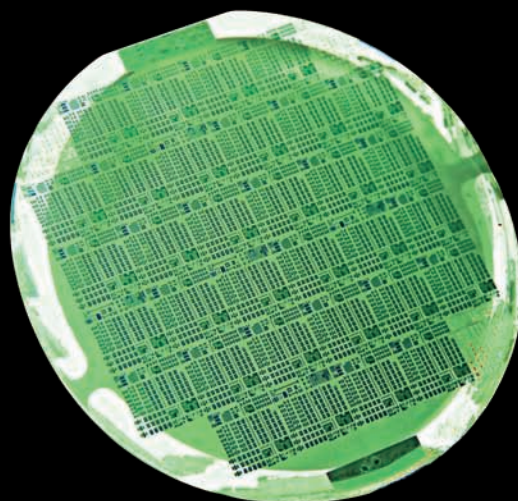
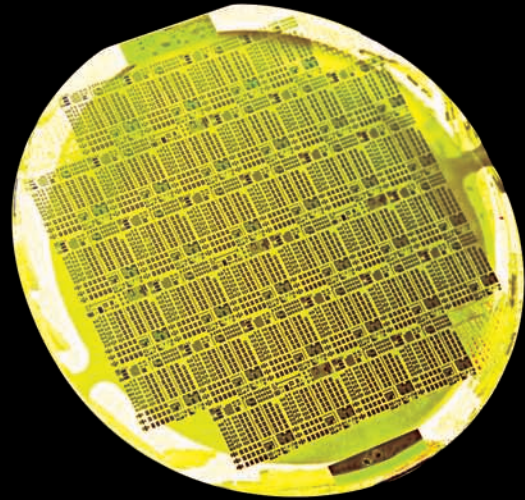
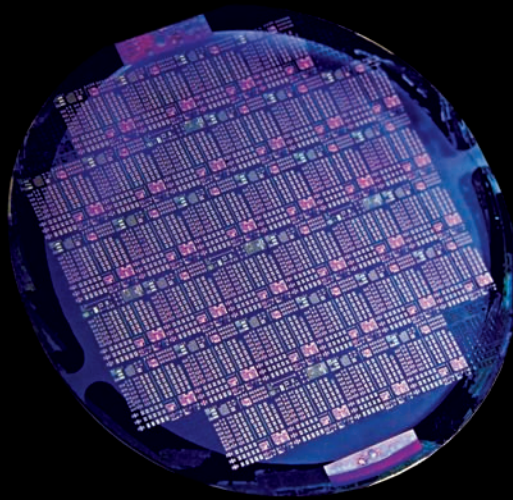
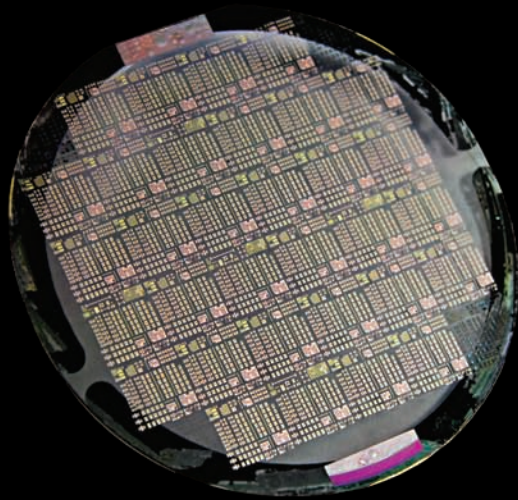


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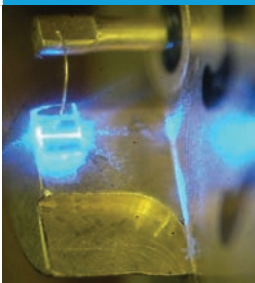


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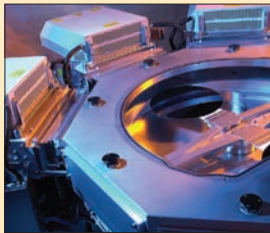
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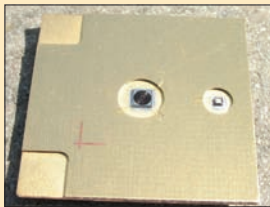


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**Main cover image:** With two new GaN foundry services now available, the technology is beginning to come of age. Shown here is a GaN-on-SiC device wafer from TriQuint. See pp 5 and 19. Credit: TriQuint/Louise Unwin.

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US mailing information: *Compound Semiconductor* (ISSN 1096-598X) is published 11 times a year for \$174 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.

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## Moore of the same?



When IBM's Bernie Meyerson stands up to talk, the semiconductor world takes notice. "Like a prophet descending from a holy mountain" was one description of Meyerson's appearance to address the assembled throng at the Semicon West trade show in San Francisco last month.

Meyerson's main point was clear: that scaling, the traditional method by which silicon chip makers have kept pace with Moore's law, will not work for much longer. You can't scale atoms. With gate dielectrics at only five atoms thick, the end of the scaling era is nigh.

This was a point reiterated by Klaus Rinnen from highly regarded market research specialist Gartner Dataquest. Rinnen told the Semicon West Market Symposium to prepare for major changes in the semiconductor industry landscape, saying: "The silicon end game is within sight." Rinnen believes that control over the industry will now slip away from device manufacturers and that service providers will begin to exert the key influence on chip usage and the lifetime of manufacturing equipment.

**"Scaling will not work for much longer".**

Could that be good for compound semiconductors? Perhaps, although not necessarily in the traditional sense. Rinnen expects that some highly disruptive technologies will emerge to meet the needs of fad- and fashion-driven applications of electronics. That will provide many opportunities for companies with novel types of devices using materials other than silicon.

At the moment, thin-film photovoltaics is at the top of Gartner's semiconductor hype cycle – and compound semiconductor makers are trying to seize an opportunity there. But with an increasingly open playing field developing into what Rinnen expects to be "an alien landscape for end markets" in 10 years from now, the companies currently involved in the traditional compounds niche could diversify and succeed in an industry less dominated by the traditional silicon players.

Other technologies on Gartner's radar include GaN-based ICs, carbon nanotube circuits, multigate transistors, printed semiconductors and organic LEDs. Whether or not any of these technologies will make it through to what Gartner calls the "plateau of productivity", we don't yet know. But the opportunities are clearly there.

An uncertain future is something that isn't lost on Applied Materials – the kingpin of semiconductor equipment. Its slogan at Semicon West? "Create change". A changing semiconductor industry could be good for compounds.

**Michael Hatcher** *Editor*

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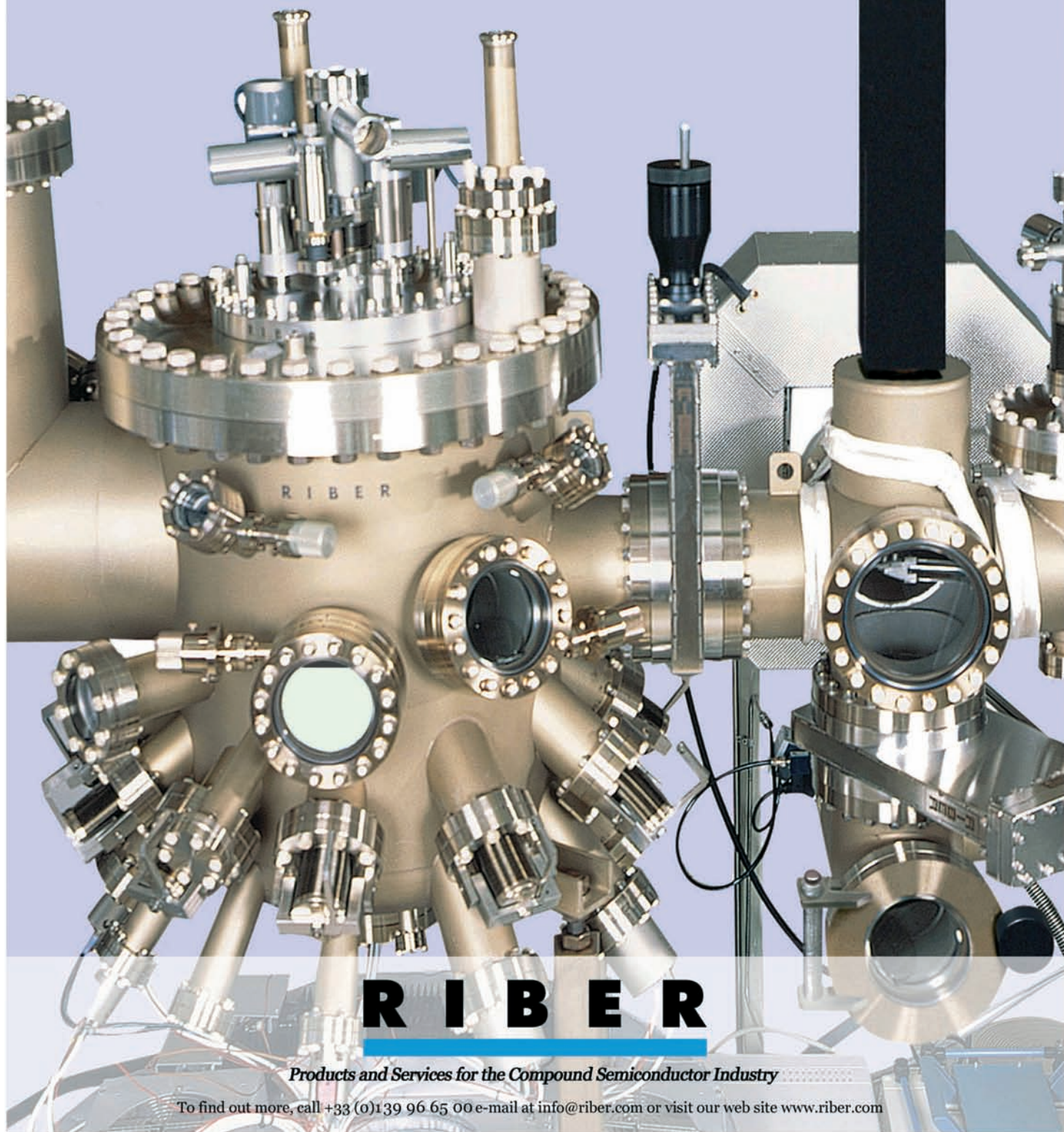
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## RF ELECTRONICS

# Strong demand fires up GaN foundries

By Andy Extnance in Atlanta

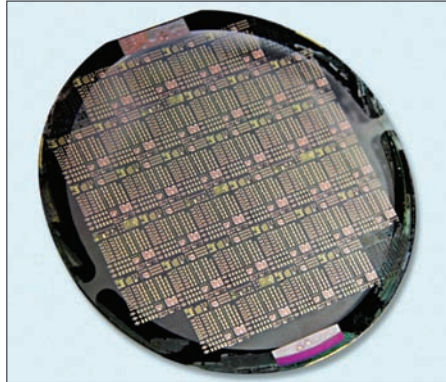
Cree and TriQuint have rolled out competing GaN foundry services amid interest in the high-power RF technology at the 2008 International Microwave Symposium.

In each case, military applications are providing a strong driving force in developing GaN devices, attracted by characteristics such as high power density and high-temperature operation.

Both companies are still involved in DARPA's Wide Bandgap Semiconductor Technology Initiative, with TriQuint in particular indicating to *Compound Semiconductor* that its GaN efforts are being supported by the recent award of the third phase of funding within this program.

TriQuint and Cree also contributed to the event's swarm of GaN power-amplifier product releases, which ironically are now encouraging other companies to design their own devices.

"Buying off the shelf tends to attract people into design," said John Palmour, executive vice-president for advanced devices at Cree. "Thanks to that there will be plenty of mili-



TriQuint will be formally expanding its existing foundry service to include GaN wafers like this one. It aims to have started the production in September.

tary and some R&D use of the foundry."

TriQuint's foundry will initially encompass the frequency range from DC to 18 GHz, which Cree is also intending to support.

The two foundries are also producing devices from GaN epitafers grown on SiC substrates and looking to move from 3 to 4 inch wafers. TriQuint is working with its

epiwafer supplier IQE, while Cree will be looking to exploit its position as the industry's dominant supplier of SiC substrates.

However, before any squabbles can break out between these two companies over which was the first commercial GaN foundry, a third player may wish to have a say. German firm United Monolithic Semiconductors (UMS) has been working on developing GaN devices in a European collaboration since 2006 and is also looking at a move to 4 inch wafers.

NXP Semiconductors adds a high-volume angle, expecting the collaboration to deliver commercial 100 W GaN devices for wideband-CDMA base stations in 2009. Mark Murphy, NXP's spokesperson for the project, says that the collaboration is currently achieving the company's reliability targets for this product line compared with its existing silicon LDMOS products.

Specific processes used by the collaboration are out of bounds to other customers, but UMS still offers GaN foundry services elsewhere to help to enhance the technology's overall commercial viability.

## III-V SOLAR

## Engineering issues will ruin CPV firms, warns analyst

By 2012 annual expenditure on installations using III-V solar cells will hit \$1.2 billion, but not all of this sector's emerging companies will survive to enjoy the benefits.

Market-research company Lux Research predicts that 2009 will mark the beginning of troubled times for some concentrating photovoltaic (CPV) system manufacturers.

"Within the next few years the funded business plans of many CPV companies will have come to fruition," said Lux senior analyst Michael LoCascio. "Many of these will not deliver on promises."

LoCascio says that as well as needing direct sunlight, the expensive GaAs-based cells used in CPV systems are commonly kept from operating at peak efficiency by engineering issues surrounding maintenance, cooling and wind resistance.

"CPV must be pointed towards the sun

with accuracy greater than one degree," he pointed out, "so even a modest wind gust can greatly reduce power output."

LoCascio predicts that when solar begins to reach cost parity with other power sources in 2012, III-V-based installations will gain nearly 2% of the overall system market. However, he shares the opinion of many within the industry that CPV could eventually overturn more established solar technologies in certain situations.

"I'm rather positive that CPV can be a disruptive technology in certain geographic areas, but not in its present form," LoCascio commented. "However, the more established CPV players employ top-notch engineering talent and are working diligently on the big issues. If they crack the code and drop prices, they may see a big win."

On the basis of interviews conducted in

the course of his research, LoCascio says that currently between 20 and 50% of CPV system costs are spent on semiconductor cells. He thinks that getting that figure down as quickly as possible is crucial for the future success of the CPV sector.

● One CPV player looking likely to crack LoCascio's code is SolFocus, which plans to install systems capable of producing up to 100 MW of grid-connected power in 2010. If it is reached, this figure would represent a huge expansion on the expected 2008 deployment of 1 MW, while SolFocus is confident that it will install 20 MW during 2009.

With improvements to its optical design and the efficiency of the III-V cells, SolFocus says that the conversion efficiency of its panels should rise from 18 to 25% in the next year, with overall system efficiency pegged at 2% less than the figure for panels.

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PROCESSING EQUIPMENT

# Aviza claims GaAs supply chain is overstretched

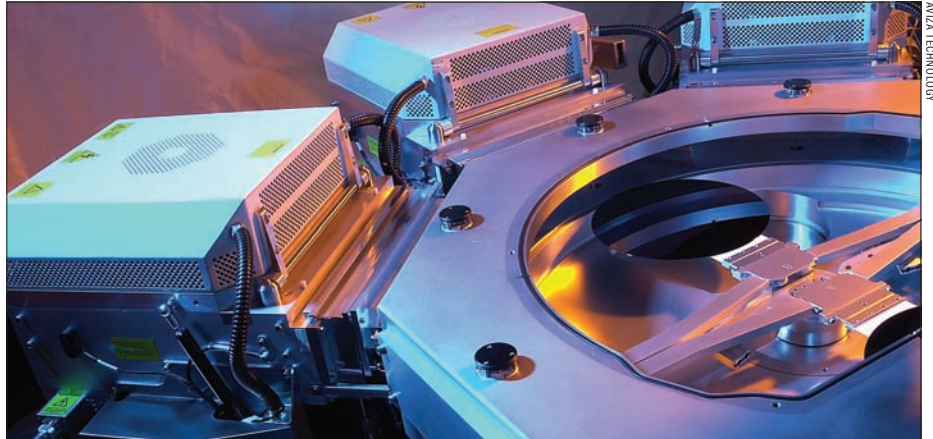
Wafer-processing equipment maker Aviza Technology has received its largest ever order from a GaAs manufacturer, supplying tools to Taiwan foundry WIN Semiconductor, and says that the deal reflects under-provision of capacity elsewhere.

“We have received multiple system orders in the past from WIN and other III-V customers, but not of this magnitude,” said Kevin Crofton, the senior vice-president of Aviza’s product business units.

“We believe that WIN’s investment is an indicator of an overall increase in demand for III-V devices used in the telecommunications arena. This is a leading indicator that the supply chain is insufficient at this point to meet demand.”

The order for etch, PVD and CVD processing equipment, which will be used to make chips for mobile communication, wireless and broadband market applications, totals \$15–20 million. This will enable WIN’s expansion to provide spare capacity when the tools are delivered before the end of the year. However, the Scottsdale, CA, tool manufacturer couldn’t say exactly how many systems the order comprised.

The Taiwanese foundry has turned to Aviza in a bid to address the industry’s capacity shortfall, applying high-volume



WIN Semiconductor has ordered several Delta and Sigma CVD tools and Omega etch systems from Aviza.

processes developed for silicon that Aviza’s tools bring to the compound niche.

“The application of silicon-style manufacturing techniques to the unique demands of III-V production drives down costs and maximizes yield,” Crofton said.

One example of this is Aviza’s Omega etch system, which simplifies processes by allowing users to perform front- and back-side etches using the same hardware.

Metallization techniques developed for silicon have also been transferred to compound

semiconductor production. The company’s Sigma PVD system was designed to maximize metal coverage in deposition for back-side vias, and boasts higher throughput than lift-off processes for compound devices.

These systems also boast an electrostatic chuck that can uniquely clamp a wafer directly through an insulating carrier wafer. This cuts down on processing costs compared with other systems that need to add a conducting material layer to the carrier prior to clamping, Crofton points out.

CABLE TV

## RFMD casts GaN in starring cable TV role

RF Micro Devices (RFMD) is claiming the first GaN-based cable-TV products, as it seeks to produce amplifier modules with the best efficiency, noise level and power output for this market.

“We’re a huge player in cable TV currently,” explained Jeff Shealy, who was CEO of RF Nitro, the company that RFMD bought in 2001 to obtain its GaN technology. “It’s very important for us to remain on the top in performance.”

The Greensboro, NC, company is pairing its GaN HEMTs with GaAs PHEMTs in hybrid power doubler-amplifier modules, targeted at use in cable TV infrastructure. Each module features two GaAs PHEMT and two GaN HEMT die.

These modules have already won places in reference designs that will see them used by original equipment manufacturers, RFMD says. The doubler amplifier mod-

ules are available immediately in volume and the company expects to begin shipping purchased modules this year, with initial orders already “in hand”.

RFMD’s GaN HEMTs exploit the higher power density of the semiconductor material to deliver highly efficient performance at the power levels used in cable TV.

Initial deployments should begin in the fourth quarter of the year, thanks to a design win with a cutting-edge CATV systems company based in Europe, while RFMD is also targeting US cable giants like Motorola and Cisco Systems.

The chip company claims that the modules deliver industry-leading carrier-to-intermodulation noise levels as low as 63 dB and provide gain of more than 20 dB. The amplifiers can also be driven at higher powers – with final power output increased by 2–3 dBmV over competing devices – meaning that fewer amplifiers are needed in overall systems.

The GaN HEMTs in these modules are made using the same process as RFMD’s recently announced high-power GaN

HEMTs targeted at radar applications.

Because of the importance of GaN in military applications, Shealy is now vice-president of Aerospace & Defense at the company. However, GaN devices are being deployed across RFMD’s multimarket product group. The different groups can exploit economic GaN device production by piggy-backing off the company’s high-volume GaAs power amplifier manufacturing.

“Our manufacturing is a tremendous advantage to us,” Shealy told *Compound Semiconductor*. “We use a high-performance SiC platform, so we pay a little more in variable costs for the technology but our fixed costs enable us to manufacture this technology in a very low-cost fashion.”

Although the cost of GaN devices remains high, the new hybrid amplifier is a relatively large component. The additional cost can be better absorbed within the total bill of materials than for smaller, discrete devices.

The GaN HEMTs are produced on 3 inch SiC substrates, using the same line that is used to manufacture GaAs devices on 4 inch wafers in RFMD’s high-volume fab.



## MOBILE HANDSETS

# Economic nerves hit PA makers

Shares in Anadigics and RF Micro Devices (RFMD) plummeted by more than 10% after analysts trimmed estimates of both companies' future sales.

On July 14, Jay Srivasta of Roth Capital Partners and Mike Burton of ThinkPanmure both said that Anadigics will be hit by what Srivasta summarizes as "weak macro-economic conditions".

Srivasta pointed out that for Anadigics: "Recent reports suggest that sales at its two largest handset customers – Samsung and LG – may be slowing. Samsung appears to have begun the process of reducing its inventory levels."

Srivasta still agrees with Anadigics' revenue estimate of \$77–79 million for the second quarter of 2008. However, he thinks that Anadigics will disappoint by delivering sales of \$82 million in the following three months, compared with other analysts expecting \$83 million on average.

Meanwhile, Burton lowered his estimates of the revenue that RFMD will earn in the year to March 2009, from \$1.04 billion to \$973.5 million.

This is partly based on a continuation of the troubles that RFMD has experienced in the Chinese market. However, Burton

again points to the "less-than-seasonal" sales that handset component makers are facing at the moment.

Despite these issues, both analysts are still rating these stocks as a "Buy".

Shares in TriQuint Semiconductor also suffered a 10% hit after the company lowered its revenue expectations for the second quarter of the year. For the three months up to June 30, TriQuint had said previously that it would post revenue of between \$130 million and \$135 million.

However, citing delays in the manufacturing ramp-up of some new products and what it described as "shipment timing issues", this figure has now been downgraded to just \$120 million.

But, the Hillsboro, OR, company appeared to dispel any worries that these lower sales were the result of a slowing global economy or of slack demand for its RF products.

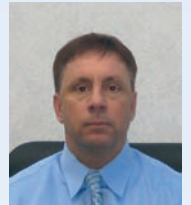
Bookings remain very strong, it said, citing a book-to-bill ratio of 1.3 in the second quarter. As a result, TriQuint's management expects the company to show a return to form in the third quarter of the year, which it is currently about halfway through, and post revenue of between \$150 million and \$160 million.

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#### ...Showa Denko adds SiC reactor

The Japanese conglomerate Showa Denko will extend its SiC epiwafer manufacturing capacity, having ordered a SiC multiwafer Hot-Wall Planetary Reactor system from Aixtron. Better known to *Compound Semiconductor* readers for its LED manufacturing, Showa Denko says that it will be announcing its future SiC manufacturing plans in the upcoming months.

#### ...PA design-win frenzy

TriQuint and RFMD's GaAs handset front-end modules have won both companies places in several new handset designs. TriQuint says that its TQM7M5012 PA module has been picked up by 15 customers for use in 3G handsets. Similarly, RFMD's Polaris front-end modules will be found in "six new feature-rich multimedia handsets", although the company is beginning a phasing-out process for Polaris that will take place through 2011.

#### ...IQE wins \$20m GaAs PHEMT deal

IQE's Bethlehem, PA, business unit has secured a sole-supplier contract for \$20 million of GaAs PHEMT epiwafers from a "major US wireless component manufacturer." The deal is a contract extension for the company's MBE-grown wafers, deliverable over two years. IQE says that, including this deal, its order book for the next year has now swollen to \$20 million. As a consequence, the company expects to record above-expectation revenues for the first half of 2008.

#### ...Micromem ships first GaAs Hall sensors

Field trials have begun on packaged sensors, as the Canadian design company Micromem continues to forge ahead with its unusual GaAs applications. BAE Systems has also come on board as a partner in developing these sensors, in addition to its existing co-development role on magnetic RAM, which uses the sensors.

SOLID-STATE LIGHTING

# DOE aims for standards clarification

LED-based lighting manufacturers now have an authoritative basis to use when comparing rival products, thanks to a core framework of testing guidelines that will soon be completed by the US Department of Energy (DOE) – despite the proposal of a different scheme by the Environmental Protection Agency (EPA).

The first three US specifications, which cover definitions and testing for products in areas including light output and chromaticity, will soon be joined by a longevity testing standard.

LED chip and lighting fixture maker Cree is contributing to the work, and the company's director of new business development, Mark McClear, says that the standards are already having an impact on its chip-making operations.

"Every one of these standards has ripple effects – both backward into the manufacturing of the LEDs and forward into the consumer experience," said McClear. "The object of standards is to align all of those interests, so that everybody has a good experience. These four get us to a point where we can offer credible luminaires in the marketplace."

The American National Standards Insti-

tute published the C78.377-2008 specification for chromaticity ranges of solid-state lighting (SSL) products earlier this year. It also approved an addendum to its RP-16-05 nomenclature standard that defines the levels of complexity of SSL products on May 8.

"Cree has switched its LED bins to support the chromaticity standard," McClear said. "If luminaires in the market are going to be tested to this standard it doesn't make sense to sell LEDs that are outside of it."

Meanwhile, the LM-79 standard from the Illuminating Engineering Society of North America (IESNA) – published in May – regulates methods for testing SSL's light output, efficiency and chromaticity. IESNA is also responsible for the pending LM-80 standard, which will cover testing for depreciation in the lumen light output of packaged LEDs. That data can then be converted into a luminaire lifetime by use of an approved model, meaning the manufacturer of the packaged LED chip bears significant responsibility.

"We've got thousands on test and they're in all different types of environment," explained McClear. "We've got rows and rows of environmental chambers and they all had to be modified so that we can be testing to the LM-80 standard."

Attempts to use these standards as the basis for the Energy Star program are proving more controversial. This program is synonymous with energy-efficient home appliances, which will allow luminaires to be labelled with the Energy Star logo if they meet its performance criteria.

Although Energy Star is a collaboration between the DOE and the EPA, the two sides want different definitions for the Energy Star for SSL. Jim Brodrick, who leads the DOE SSL program, said: "DOE has worked very diligently with industry to chart a technically rigorous and market-appropriate path that would lead to a strong SSL market. EPA, in essence, has bypassed this type of process by rushing out criteria that lack the technical requirements that would prevent the qualification of dim, bluish light products that we know will 'turn off' consumers."

On his way to meet the DOE about this very dispute, McClear explained: "EPA and DOE part company over the use of LM-79. The EPA has got a different method."

"There definitely has to be a harmonization between the DOE and the EPA programs – and they will be harmonized," predicted McClear.

SEMICON WEST

## Silicon show switches on to LEDs

This year's Semicon West trade show was notable for the high-profile presence of many in the US photovoltaics community, but LEDs also made an impression at the event, held in San Francisco's Moscone Center in mid-July.

For the first time in its history, the silicon-focused show also featured a conference session on high-brightness LEDs and solid-state lighting.

Strategies Unlimited's Bob Steele, who opened the proceedings with a market overview, observed that the LED community was now in the equivalent position of the silicon microelectronics industry in the mid-1980s. In a well-attended session, Steele joined LED proponents Bob Walker from Sierra Ventures, Alexei Erchak from Luminus Devices and Gerry Negley from Cree Lighting Solutions in detailing the rapid progress made in LED technology recently, while Fred Welsh from the US

Department of Energy revealed that the US Congress would likely provide a substantial increase in central funding of LED-based research and development for 2009.

"Total funding could reach perhaps \$30 million," Welsh said, although he added that this decision had not yet been finalized, as of July 16.

Welsh, Steele and Walker were all at pains to stress that although good solid-state lighting products were now emerging for general lighting applications, the worrying number of low-quality LED-based lamps on the market could have a negative impact by overplaying claims of high efficiency and disappointing customers.

● Also at Semicon West was a new "tabletop" MOCVD reactor from the Texas firm Nano-Master. The company's first such tool was shipped to the University of Arkansas recently to produce AlGaIn and InGaIn structures.



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...Asia boom for Aixtron

LED manufacturers in Asia are behind a renewed surge in sales of MOCVD reactors at Aixtron. In mid-July the German company received an order for two AIX 2600G3 tools from China-based Changelight, while Taiwan's Formosa ordered four new CRIUS systems. EpiLEDs Technologies also ordered four CRIUS reactors and the Taiwanese epifoundry Visual Photonics Epitaxy has placed a major new order for "multiple" tools.

...Nichia sparks new Seoul battle

Seoul Semiconductor has responded to a new claim over LED intellectual property from Nichia by vowing to take action on its Japanese rival. The Korean company was bumped into action after Nichia filed a suit in Germany against Seoul's high-profile "Acriche" white LEDs, which are already being used in streetlights in Europe.



**Australian LED technology start-up**  
**BluGlass** says that it is now ready to market its disruptive method for manufacturing light-emitting semiconductors based on GaN. The Sydney firm's new headquarters, which were opened in mid-July by former Midnight Oil front man and now Australia's environment minister Peter Garrett, features the remote-plasma CVD machine developed in collaboration with Irish equipment firm EMF. The technique reduces material consumption and allows low-temperature GaN deposition on ZnO-buffered speciality glass, and is aimed at low-cost LED production.

**PRECURSOR MATERIALS**

**Delivery system yields efficient vapor control**

Rohm and Haas is trying to woo customers with an upgraded VaporStation, which offers an unprecedented level of control over vapor concentrations entering multiple MOCVD reactors.

The electronics materials division of the Philadelphia, PA, company has replaced standard metalorganic bubblers in its systems with inverted mini-bubblers from Matheson Tri-Gas. These bubblers, plus improved control software and panel layout, have been introduced successfully in the company's last three VaporStation installations, and the system is now set to be used in all future deployments.

"The VaporStation central delivery system supplies a constant concentration vapor of a precursor compound in hydrogen carrier gas to a multitude of MOCVD reactors," said Egbert Woelk, Rohm and Haas' director of marketing for metalorganics. The inverted design acts as both a bubbler and evaporator that produces the metalorganic

vapor mixture, usually using trimethylgallium, immediately prior to use.

"We also introduced baffles to streamline the flow and intermix carrier gas and liquid more thoroughly," Woelk said. "This improves the delivery at the fringe of the performance envelope."

Since VaporStation debuted in 2004 Rohm and Haas has championed the cause for delivery of metalorganic reagents using systems that are more efficient than traditional bubblers. Rival precursor materials specialist SAFC Hitech has also recently moved to scale up its method of gas delivery, with what Woelk believes to be a system that imitates the Rohm and Haas approach.

"Rohm and Haas has been on the forefront of an industry-changing approach and the industry is realizing that new approaches are necessary to reduce the cost of production," Woelk said. "The VaporStation central delivery system is an answer to this need and we anticipate that the adoption of this approach will grow steadily."

Up to 10 MOCVD reactors can be connected to the VaporStation central delivery system, which Rohm and Haas leases to its customers to connect into their fabs.

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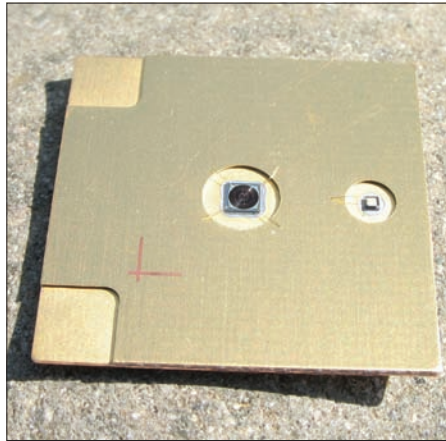
# Europeans near III-V solar cell record

German researchers have developed 37.6% efficient triple-junction photovoltaic cells for use in highly concentrated sunlight, which they say match state-of-the-art cells under these conditions. The Fraunhofer Institute for Solar Energy Systems (ISE) team also says that these cells are the most efficient produced in Europe.

Whereas the 40.7% record set by US company Spectrolab used lenses that concentrate sunlight 240 times, Fraunhofer ISE's cells perform best at a concentration ratio of 1700. This should reduce the cost of concentrator photovoltaic (CPV) modules because the higher concentration optical systems can focus light onto a smaller total area of compound semiconductor cells.

"The cell still runs at higher than 1700 suns," said Andreas Bett, project leader for the ISE team. "We couldn't measure any higher because our set-up doesn't work at higher concentrations."

The cells are now being transferred to ISE's production partner Azur Space, where they will be in commercial production "within months". Bett anticipates a smooth handover because ISE used the same type



This cell, which is destined for manufacture at Azur Space, is specifically optimized to target the highest-concentration photovoltaic systems.

of Aixtron system to develop the cells that Azur Space will use to manufacture them.

"We are looking at not only our highest efficiency but also a reproducible, very stable process," he explained to *Compound Semiconductor*. "That's really good because the yield will be very, very high – I'm

expecting it to be higher than 95%."

Central to ISE's record were the thin tunnel diodes positioned between its device's GaInP top cell and GaInAs middle cell, and also between the middle cell and the germanium bottom cell. Extensive computational modeling allowed the overall epistructure to accommodate 30 nm thick diodes featuring AlGaAs layers that are carbon-doped at levels of up to  $10^{20} \text{ cm}^{-3}$ .

"This is especially challenging for metamorphic triple-junction solar cells," explained Frank Dimroth, head of ISE's III-V epitaxy and solar cells group. "Carbon-doped AlGaAs is usually not well lattice matched to the GaInAs material used as the second junction in this high-efficiency solar cell."

However, ISE's modeling has helped it to produce a device that includes highly carbon-doped AlGaAs in a better lattice-matched, higher-quality crystal structure.

To highlight their effectiveness further, these latest cells have already been included in a CPV module that operates at 28.5% efficiency. Bett says that cell efficiencies can near 45% in the future, and that this will help module efficiencies to approach 35%.

PHOTONIC INTEGRATION

## Infinera gets whacked despite Deutsche deal

Shares in InP-based photonic integrated circuit (PIC) manufacturer Infinera fell 30% in mid-June, despite the company securing a deal with a major telecom carrier.

In perhaps its highest-profile design win to date, Deutsche Telekom has chosen an Infinera system with which to upgrade to its pan-European network. But investors took fright when the company, which runs an InP wafer fab in California, significantly cut financial expectations for fiscal 2008.

Previously, Infinera management had indicated that 2008 revenue would be 25% greater than the 2007 figure, which was just in excess of \$309 million.

That meteoric rate of growth would have translated to 2008 sales of approximately \$385 million. However, with subdued sales to North American customers now expected in the third quarter of the year, which ends in September, annual growth will be pegged back to just 10%, which will equate to 2008 sales of only around \$340 million.

CEO Jagdeep Singh says that, despite the lower forecast, he believes that Infinera has lost neither existing customers nor market share in the fiber-optic networking sector.

Referring to the Deutsche Telekom deal, Singh said: "Today's win and ongoing engagements with other leading carriers worldwide give us continued confidence in the strength of the long-term strategy and growth outlook for Infinera."

Since it is with one of the world's biggest carriers, the Deutsche Telekom deal represents a significant breakthrough for Infinera's digital optical network architecture, which relies on large InP semiconductor chips each featuring dozens of tiny optoelectronic components.

The specific system chosen by the German carrier for its backbone includes up to 160 dense WDM channels operating in the C-band, which provides an optical reach of 2500 km and supports future capacity upgrades to 8Tbit/s.

● Infinera CEO Jagdeep Singh has scooped Ernst & Young's Entrepreneur of the Year award for 2008. "When we started, the experts told us it couldn't be done," said Singh of the company's PIC technology.



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#### ...Opnext buys StrataLight for \$172 m

Seeing California-based StrataLight as a way to expand its offering in the up-and-coming 40 Gbit/s optical communications market, Opnext has made a takeover bid consisting of 26.55 million common shares plus \$30 million cash. The New Jersey-based laser diode maker will add StrataLight's 40 Gbit/s optical transport subsystem-level products to its own 40 Gbit/s optical modules for short-reach telecoms and datacoms applications.

#### ...Emcore gets \$29m solar boost

Supply agreements with a rooftop system maker and a more conventional plant-scale firm have swollen Emcore's photovoltaic cell backlog further. Production for the orders has commenced and shipments are scheduled until June 2010. This comes after Menova Energy, which had previously reported using Emcore cells, gained a \$5.9 million deal to deploy a demonstration system on the roof of a Wal-Mart store in Canada.

## BLUE LASERS

# Targeting defects improves InGaN blue lasers

One of the most extensive analyses of blue diode laser degradation has found that improved control of crystal quality is the key to making the devices more reliable.

These InGaN-based chips have found widespread application in Blu-ray disc players and Sony's PlayStation3 console, even though until now it has not been completely clear how operating conditions affect laser diode performance over time.

However, researchers at the University of Padova in Italy studying a set of lasers manufactured by Matsushita Electric Industries (otherwise known as Panasonic) have found that the degradation process in these lasers is activated electrothermally, not by optical or straightforward heating mechanisms.

Matteo Meneghini from the Padova laboratory said: "The most important driving force for the degradation of [blue] laser diodes is driving current...the dependence is almost linear."

Ascribing this degradation path to an increase in non-radiative recombination in the active layer of the InGaN chips with time, the Padova team says that further optimization of epitaxial growth conditions could improve laser reliability.

The lasers provided by Matsushita Electric for the tests were based on a triple-quantum-well design, grown homoepitaxially by MOCVD on a GaN base and all sourced from a single wafer.

Owing to their advanced design, they showed very low threading dislocation densities in the region of  $10^6 \text{ cm}^{-2}$ . "For this reason, these diodes do not suffer from early and catastrophic degradation," Meneghini said. "[They] are only affected by a slow increase in the threshold current during operation. Degradation has been found to be mostly due to the important current flow crossing the active layer (up to  $7\text{--}8 \text{ kA/cm}^2$ )."

However, when the lasers were stored at  $180^\circ\text{C}$ , without any electrical bias, there was only a marginal effect on their reliability – even after spending 100 hours at the elevated temperature.

Similarly, Meneghini and colleagues found that the applied optical field did not influence degradation characteristics.

Knowing that it is specifically electro-thermal stress that causes laser diodes to fail over time, the team is investigating defects present in the semiconductor material to find ways to improve device lifetimes.

They believe that the findings will be applicable to other manufacturers of InGaN diodes

because the epitaxial structure is the most important factor in device degradation.

"The dislocation density must be reduced to guarantee long lifetime," said the team. "Homoepitaxial growth represents one of the

best strategies to preserve sample quality."

"Optimizing the growth conditions used for the active layer can lead to a reduced defect concentration, with corresponding improvement of device reliability."

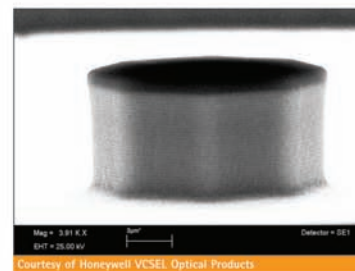


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ANADIGICS

# Broadband wireless excites Anadigics

As vice-president of Anadigics' wireless business, **Ali Khatibzadeh** has played a key role in refocusing the company on 3G cellphone and wireless networking technologies. With that strategy now paying off, he talks to **Andy Exance** about Anadigics' plans for GaN, femtocells, WiMAX and LTE at the MTT-S meeting in Atlanta, Georgia.



ANADIGICS

## Why have you come to IMS 2008?

We're looking at developments in power amplifier technology, for both mobile devices and infrastructure. Femtocell is an area that we're looking into. Also we are monitoring some technologies that are being developed. GaN is one area that we're observing, although we are looking at different technologies and have not made a commitment to it.

## What is your view of femtocell technology?

It's an exciting market. We believe operators are committed to investing in femtocells as a way of extending their capacity and enabling more subscribers.

It's more than just a booster in the house. It enables the operator to offload the signal from the tower into the wired optical network, so operators have the wire as well as the wireless connection. When you're at home you can use your mobile device, but you go into the wired connection. You look at the operators: at any time, how many of your subscribers are at home using their cellphones? If you can offload those to a landline, how much more capacity can you gain? That's really the math, and it lets you get better data-rate connections in the home.

I would say that volumes and replacement rates will not be as high as the handset market – it's like a router business. It's somewhat of a consumer market, but it also has some of the characteristics that we see in infrastructure. It is a performance-driven, less price-sensitive market. The femtocell market is at an early stage, so it's a good time to enter.

## What are the technical differences between handset and femtocell power amplifiers?

What we see is that femtocells require higher performance. A femtocell box at any time has to be

able to handle multiple signals and multiple users at home, so these amplifiers tend to be more optimized for performance, linearity and other requirements, not just for power consumption and battery operating time. So we see in the femtocell market, for example, that supply voltages could be higher than battery-operated mobile products.

The need for high-performance components makes femtocells well suited to our technology differentiation in power amplifiers. We believe that we can leverage that and play well in this market. We are developing products and talking to specific customers and partners. We also talk to the operators, so we have a good understanding of the "ecosystem" in the femtocell market. We will be announcing products for this market in the second half of this year.

## How readily can Anadigics' existing technology serve these applications?

We believe that our differentiated InGaP-plus technology can do a very good job for femtocells. If you look at traditional wireless infrastructure products, InGaP technology can serve up to the driver amplifiers. In the output stages, that's where the technology falls short. That's where you'll see a lot of interest in GaN and other high-voltage technologies. We're not currently playing in that market, but as time goes on we'll reassess our strategy.

In the femtocell application you don't need high power. In femtocells you stop at the 1 W power level. With our InGaP-plus, which integrates HBT and PHEMT on the same die, we were the first company to introduce this kind of technology in high-volume production. Something like more than 90% of the products that we ship today are based on that technology. All of our competitors are still talking about developing or introducing it. We are well into maturity. Currently we are introducing a new version of this technology that will allow us to integrate more functionality. We can integrate literally all of the front-end components, with the exception of some of the filters that are SAW or BAW technology. Especially for some applications like WiFi, we believe that we have the most integrated solution.

## How does the conflict between WiMAX and Long Term Evolution (LTE) affect Anadigics?

Obviously we've been following the development of WiMAX. That's been a business plan to extend the hotspot concept into a mobile network that has a range equivalent to cellular networks, but also high data rates in a similar manner to WiFi. From the established operators the view is that 3G, HSPA and EV-DO networks already offer high data rates and mobility combined. However, they don't offer the data rates that WiMAX is promising. In their view they can expand the 3G networks to LTE and be able

## Ali Khatibzadeh: the CV

### 2000 – present:

Anadigics' senior vice-president and general manager, Wireless Business Unit.

**1998–2000:** director of technology for Ericsson's American Standards Business Unit.

**1987–1988:** various management positions in Texas Instruments' Wireless Communications Business Unit.

**1982–1987:** North Carolina State University, BS, MS, PhD in electrical engineering and physics.

to offer similar data rates to WiMAX, yet maintain the mobility and all of the other services that consumers are used to. So it's really a competition between the established cellular operators, who will hold out for LTE, and the newcomers to the market that are bringing in WiMAX.

Our strategy to handle this is very simple. We want to be anywhere there is broadband data connectivity, whether it be wireless or wireline; WiMAX or LTE; cable or fiber. Our strategy is: wherever we see broadband data connectivity we want to be in the RF front-end components. We are well positioned in the WiMAX as well as in the 3G and 4G standards.

When you look at it, the spectra are like real estate – they will be developed. Whether WiMAX or another standard wins in the end, we will have the products for both markets. We believe that there will be healthy competition between the two. So it's not an either/or scenario for us. Its different real estate, different spectra and services will be deployed regardless of which standard we want to be in.

#### **How do you decide which new technologies you are going to develop?**

One technology cannot cover all of our market. You cannot cover cable amplifiers and fiber amplifiers as well as handset mobile power amplifiers.

We've been able to cover this whole market with our InGaP-plus technology combined with our more traditional MESFET technology that we use for higher voltages, for example in producing very linear line amplifiers (for cable TV). But that does put more burden on our current technology and that's one of the reasons why we've come to IMS, to look at new technologies and how they could play in this market.

In the cellular and WiFi space – my side of the business – we see technology being driven along two vectors. First, there's a multiband, multimode integration push. If you look in any 3G handset today, you'll more than likely see two or three power amplifiers inside. With the new spectrum that's released in the US – 700MHz – the plan is to have LTE developed in that spectrum. We have to address the many different bands used around the world, and we also see a strong push to integrate more functionality into the front end. That's an area of focus for our technology. How can we integrate more of these functions into the same package, the same die.

The other vector is performance. We still see a continued push on performance improvement. If you look at WiMAX products, for example, today the first-generation WiMAX products are designed for embedded applications or data-card applications for mobile systems operating with a battery. We believe they'll still be pushed to improve the performance in terms of power consumption. That will be true of LTE – any technology that uses OFDM modulation requires high-performance power amplifiers, so we have to continue building up performances.

#### **What is the next big market for Anadigics?**

Embedded module applications for notebook computers. Today more than 98% of notebook computers produced have embedded WiFi modules. We

supply most of them through Intel but, if you look at the attach rate for cellular modems in notebook computers it's around 2–3%, which is very low. We believe that that number will go up. Qualcomm has announced the Gobi module, which is a multimode, multistandard module. We work very closely with Qualcomm. We always appear on all of their reference designs and we're frequently primary source.

In the past the cellular modem used to be specific to a standard – you'd buy one that works for Verizon, or you'd buy one that works for Vodafone. Now with a Gobi module it's multimode and multistandard, so it can operate more flexibly.

Today if you buy a notebook computer, you have WiFi, you have Bluetooth and you have infrared. We think in the future there will also be a 3G high-speed modem and possibly WiMAX, or WiMAX/WiFi with a dual mode. They'll have these technologies built into them so that the consumer will be able to choose what service they want to sign on to and the operators will compete for their business.

As the costs of these 3G high-speed modules come down and they become more multistandard we believe that the attach rate could exceed 30%, making it an important new market for us.

#### **How are the current economic conditions affecting Anadigics' business?**

You look at Anadigics' business today and it's very global. In the wireless space, in my segment, maybe 85% of our business is Asia. The Asian economy hasn't had anything like a similar situation to the US economy in terms of signs of the slowdown, and that's reflected in our business. That's where design and manufacture are being done and that's where we're winning the business and supplying the product.

We see continued strong demand for wireless products. There has been a recent resurgence of investment for cable infrastructure and we see that reflected in our business. Fiber-to-the-home is another area that is starting to grow for us.

Our strategy is that if you look at the handset market, the forecast is that it will grow by around 15% this year. Anadigics is focused on the 3G space within that, after we exited the 2G market a couple of years ago. That space is growing. When you read the reports, even though low-end handset sales are slow, there is still a lot of demand for smartphones and more feature-rich phones that we're in. Our Asian customers are seeing a lot of 3G phones sold in Europe, Asia and Japan. Also, although they keep delaying, 3G will happen in China.

We're also seeing an interesting trend for 3G phones in shops. If you look at 2008 compared with last year, many of these smartphones are now priced at sub-\$200. A lot are \$100 or less. Of course, these are subsidized prices, but last year most of these smartphones were being sold for \$300–\$500. The iPhone is a good example, it's now being sold for \$200. You see PDAs, Palms for \$99. That's accelerating the adoption by consumers. I think that the services are also catching up with the features on these phones. In my house we used to have five cellphones: now we have three smartphones and two cellphones!

**“Today more than 98% of notebook computers produced have embedded WiFi modules. We supply most of them through Intel.”**

# Researchers target imaging s

IPRM 2008 focused on two major themes: InP HEMTs for millimeter-wave imaging systems; and faster lasers, modulators and drivers to address increasingly bottlenecked internet traffic. **Richard Stevenson** reports.

The nitride community is devoting a great deal of effort to improving LED efficacies because this could spur the growth of solid-state lighting. Similarly, SiC researchers are unified by their goal – more efficient power devices that can ultimately cut carbon footprints. But if you attend an InP meeting, you'll fail to pick up on a common mantra.

The reason behind this is not down to any weakness of InP but is actually a result of its strength. That's because InP is an incredibly versatile material, and its inherent properties have positioned it as the key material for telecom-wavelength lasers, modulators and detectors, and the best III-V for making high-speed transistors for imaging systems.

Both of these themes came out in force at the 20th international conference on Indium Phosphide and Related Materials (IPRM), which was hosted in beautiful Versailles, on the outskirts of Paris.

InP-based HEMTs have been grabbing the headlines since the International Electron Devices Meeting (IEDM) in Washington last December, due to the claim for the first terahertz transistor by Richard Lai's group at Northrop Grumman Space Technology. These HEMTs provided the building blocks for the first low-noise amplifier (LNA) operating at 340 GHz. An amplifier operating at this high frequency improves the spatial resolution of millimeter-wave imaging systems and can tighten airport security by identifying concealed weapons.

Although nobody eclipsed Northrop Grumman's terahertz claim at the IPRM meeting, it is clear that many other players are catching up fast. IAF Fraunhofer in Germany, for example, has now scaled its process down to 35 nm gate lengths. Arnulf Leuther revealed that this has increased its HEMT's  $f_{\max}$  to more than 700 GHz. This device's  $f_T$  is 515 GHz and it produces a maximum transconductance of 2500 mS/mm. The drain current peaks at 1600 mA/mm and is half of this value when at maximum transconductance.

The IAF group's HEMT is very similar in design to Northrop Grumman's, although the transistor is grown on a GaAs substrate and features a metamorphic InGaAlAs buffer. This raises the question of why the IAF transistor has not hit the terahertz regime. This was discussed when the floor was opened for questions, but neither Leuther nor Lai could provide



The 20th IPRM meeting was held in the Palais des Congrès de Versailles, Fr

any definitive reasons for the speed difference. However, it was noted that the cross-sectional area of the gate plays a key role in determining  $f_{\max}$ .

Leuther went on to describe the performance of a 0.15 mm<sup>2</sup> single-stage LNA with a 2 × 10 μm metamorphic HEMT that has a 35 nm gate length. A gain of 2.5 dB was produced at 320 GHz – the upper frequency limit for this measurement – and hit 7 dB at 270 GHz. The transistor actually delivers 9 dB of gain at 270 GHz, according to the researchers, with losses occurring due to passive circuit elements.

Fujitsu's Masaru Sato gave an invited talk in the same session and described efforts to address real-time imaging at 94 GHz. He identified two essential requirements: arrays of detectors rather than single receivers; and LNAs that deliver 30 dB of gain with a noise figure of less than 5.5 dB. The Japanese company has targeted these LNA specifications with an InP HEMT technology featuring 130 nm T-shaped gates on 100 μm thick InP substrates. These deliver 1500 mS/mm with an  $f_T$  of 220 GHz.

Sato told the audience that high-gain amplifiers can be plagued by instability, due to feedback that travels through the substrate. To combat this, Fujitsu researchers simulated the performances of devices employing thin-film microstrip lines and inverted microstrip lines in conjunction with a flip-chip geometry. Calculations revealed that the former design was unsuitable because feedback at



The 20th international conference on Indium Phosphide and Related Materials (IPRM) was held in Versailles, France, on 25–29 May. Some 258 delegates enjoyed 20 technical sessions and a conference dinner in Abbaye des Vaux de Carnay.



# Systems and optical networks



R. STEVENSON

e. This is just a stone's throw from the Chateau de Versailles – a magnificent building in equally stunning grounds, which was constructed by French royalty in the 17th century.

70–120 GHz could hit  $-20$  dB. However, the latter design could suppress feedback to less than  $-40$  dB. The team then used the superior design in a seven-stage  $2.5\text{ mm} \times 1.2\text{ mm}$  LNA chip that provided more than 35 dB of linear gain between 90 and 110 GHz. Noise was just 4–4.5 dB.

Sato's team went on to build a passive millimeter-wave imager with this LNA, by incorporating a detector MMIC, a linearly tapered slot antenna and a 20 cm diameter polyethylene lens. This system has captured several images, including one of a person behind 10 mm thick plywood.

Although Northrop Grumman representatives didn't announce any advances on the results presented at IEDM, they did disclose more details about their record-breaking transistors. When *Compound Semiconductor* interviewed Lai earlier this year, he was coy regarding the details of the high-mobility InAs channel that helped to boost transistor speed. But at IPRM, Lai's colleague, Michael Lange, revealed that the channel comprised an InAs film sandwiched between  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  layers. The team investigated what effect the thickness of the bottom InGaAs cladding layer had on HEMT performance and found that a thicker layer can produce a higher  $f_{\text{max}}$ .

IPRM 2008 also focused on devices for optical networks, with technical sessions devoted to lasers, integrated devices, modulators and detectors.

Ute Troppenz from the Heinrich Hertz Institute

(HHI) in Berlin, Germany, kicked off the laser session with an invited talk on 40 Gbit/s directly modulated passive feedback lasers operating at  $1.55\text{ }\mu\text{m}$ . She explained that these operate in a "self-pulsation" regime that allows fast and flexible locking to an external optical data stream.

The HHI edge emitter comprises a distributed feedback (DFB) laser and a passive section, and it is fabricated with the same processing steps that are used to make a conventional laser. The  $250\text{ }\mu\text{m}$  long DFB section features a ridge waveguide and an InGaAsP multiple quantum well active region. An identical length is used for the passive section. This doubles the size of the laser but has minimal impact on the technological demands, according to the researchers.

Trials at 40 Gbit/s revealed that HHI's laser is capable of successful transmission over 2 km fiber links. This makes it a promising device for cutting costs in very short networks, such as Ethernet, thanks to the elimination of separate modulators.

Another directly modulated laser design –  $1.55\text{ }\mu\text{m}$  buried heterostructure lasers – was the subject of a presentation from Ian Lealman from the Center for Integrated Photonics (CIP), Ipswich, UK. Iron has traditionally been used as a dopant in these devices, but this tends to interdiffuse with zinc during MOCVD growth. CIP has been hoping to overcome this problem by developing a rubidium alternative,



R. STEVENSON

**Researchers mingle over lunch** on the steps of the Palais des Congrès de Versailles.

through a program involving SAFC Hitech and the University of Surrey.

This UK-based partnership is not the first to turn to rubidium-based precursors, but previous efforts have been restricted by low-volatility sources, which make it difficult to incorporate rubidium in the epilayers. This team has enjoyed success by switching from linear molecules to a ring-shaped cyclic organometallic, which has opened the door to atmospheric pressure MOCVD growth.

Lasers that are 0.35 mm long have been produced with the new precursors, which feature nine InGaAsP quantum wells. Testing revealed similar threshold and slope efficiencies to iron-doped alternatives. Initial reliability tests are encouraging and show no degradation in threshold current or light output after 5700 hours of operation at 85 °C.

Hirosha Yasaka from NTT Photonics Laboratory, Japan, gave an invited talk on the development of a superior waveguide structure for high-speed Mach-Zehnder (MZ) modulators. Improvements were driven by a switch from a PIN structure to a NIN design. Removal of the p-doped layer reduces absorption losses and increases operating speeds.

The modulators were grown on semi-insulating InP substrates and each featured a 0.2 μm thick InGaAlAs/InAlAs multiple quantum well core layer sandwiched by 50 nm thick undoped InGaAsP layers. InP n-type layers clad this structure, and wafer processing produced 40 Gbit/s modulators on 4.5 × 0.8 mm chips that cover 1530–1565 nm. “We’ve confirmed error-free modulation for all wavelengths,” remarked Yasaka.

He and his co-workers have also developed chips capable of 80 Gbit/s modulation, which employ differential quadrature phase-shift keying (DQPSK). This method is currently enjoying a great deal of popularity thanks to its high spectral efficiency and robustness to dispersion.

Modulators for DQPSK require two MZ modu-

lators, which act as phase modulators, alongside an optical “ $\pi/2$ ” phase shifter and an optical combiner. NTT’s engineers have built a 7.5 × 1.3 mm chip incorporating all of these elements, which features an NPIN structure with a thin p-doped layer. This additional layer takes on the role of the semi-insulating layer in a NIN structure and should enable monolithic integration with semiconductor active devices, such as laser diodes and photodetectors.

Testing the MZ modulator revealed a minimum fiber-to-fiber loss of 13 dB, which includes a 3.5 dB/facet loss associated with optical coupling between the chip and lensed fiber. Extinction ratios exceed 18 dB and a clear opening in the eye diagrams reveals successful transmission at 80 Gbit/s.

The lasers and modulators session included a talk by Anne Rouvié from the Alcatel-Thales III-V lab on the effects of carbon doping in AlInAs avalanche photodiodes (APDs). Rouvié says that these detectors are candidates for deployment in optical telecommunication networks thanks to a signal-to-noise ratio that beats PIN diodes by more than 10 dB.

MOCVD-grown APDs frequently use zinc dopants for the growth of the thin (50 nm), highly doped charge layer. Zinc is not ideal, however, because it diffuses into the surrounding material, so Rouvié and co-workers have developed a carbon-doping process for the growth of this critical layer.

Measurements on the carbon-doped APDs reveal that they are superior to zinc-doped devices. Dark current at a multiplication factor of 10 is just 17 nA – nearly three orders of magnitude less than the zinc-doped ones – while the gain-bandwidth product is 140 GHz and responsivity at 1.55 μm is 0.9 A/W.

Integrating different types of device into a larger InP chip was the theme of Ben Yoo’s invited talk. His group at the University of California, Davis, is following a similar path to that of Infinera, with the goal of reducing the need for a large number of discrete components. Yoo believes that cost savings can come through this approach, thanks to a reduction in overall material costs. However, tough challenges are also faced, in terms of yield, reliability, isolation, and the management of high-power densities, heat dissipation and cross-talk.

Yoo’s team has produced a variety of large InP chips that employ optical code division multiple access, a technology for local area networks that is more than 20 years old but is unsuitable for discrete components, he says. These chips include a 16.8 × 11.4 mm design operating at 1.55 μm, which features mode-locked lasers, arrayed waveguide gratings, MZ modulators, and amplitude and phase modulators. They can operate over 128 channels that are spaced by 10 GHz.

The interesting talks at IPRM 2008 are testament to the fact that InP research is alive and kicking. Diversity may mean that this community is not united by a common goal, but they will continue to extol the virtues of this material at the next meeting, to be held in spring 2009 at Newport Beach, CA. ●



## GERMANIUM

# Umicore magnifies substrate dimensions

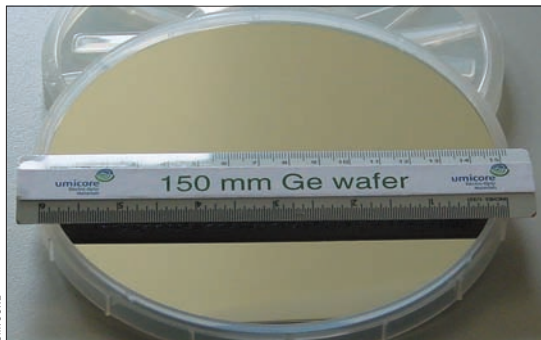
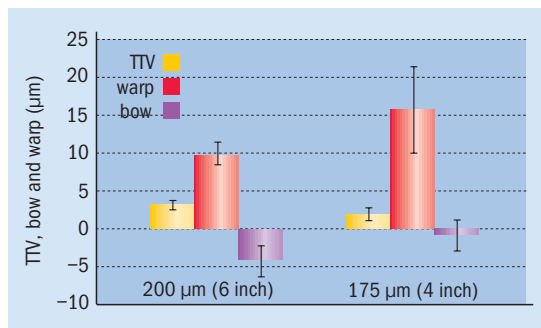
Low-resistivity 150 mm germanium substrates with uniform thicknesses offer a great platform for lowering the cost of triple-junction solar cells for deployment in terrestrial applications, according to a team of researchers from **Umicore**.



UMICORE

## Umicore produces dislocation-free

monocrystalline germanium ingots (above) with diameters of up to 150 mm, by pulling a rotating seed crystal from a bath of molten, purified germanium. **Fig. 1.** (top right) Measurements of total thickness variation (TTV), bow and warp are used to evaluate the performance of Umicore's 200- $\mu\text{m}$  thick 150 mm substrates. 100 mm substrates that are included for comparison are 175- $\mu\text{m}$  thick. Umicore's epi-ready substrates (bottom right) have a surface that corresponds to a (100) plane off-orientated by 6° to the nearest (111) plane.



UMICORE

Triple-junction solar cells for terrestrial concentrator systems are attracting an unprecedented level of interest. Trials in Spain are evaluating the performance of these assemblies for power generation to electrical grids, while cell manufacturers are seeking options to lower the technology's cost per kilowatt-hour.

Germanium substrates form the basis of all triple-junction cells, which feature individual germanium, GaAs and GaInP subcells connected in series. The standard diameter for these substrates is 100 mm, but a switch to 150 mm equivalents would enable cell manufacturers to cut the processing cost per die, as this can more than double the number of devices extracted from each wafer.

At Umicore Electro-Optic Materials, which is based in Olen, Belgium, we have started to respond to rising market demand through the development and sampling of 150 mm germanium substrates that are tailored to the needs of triple-junction solar cell manufacturers. These substrates, which we plan to launch in early 2009, are thin, have a low resistivity and feature epi-ready surfaces for the growth of high-quality epitaxial films by MOCVD.

Low resistivity is essential to limit the solar cell's series resistance in the high-current regime that occurs in concentrator photovoltaics, and thin substrates are needed to improve heat dissipation. Thin-

ner substrates have the additional advantage that less material is needed, but this must be balanced against the substrate's strength and its adherence to well defined geometrical specifications.

We grow our dislocation-free monocrystalline germanium ingots by the Czochralski technique. A rotating seed crystal is pulled from a bath of molten, purified germanium, leading to the growth of material with a diameter of up to 300 mm.

Adding a gallium dopant into the melt provides the p-type resistivity required for making terrestrial cells. Good control of this process leads to 150 mm diameter ingots with a resistivity of  $10 \pm 4 \text{ m}\Omega \text{ cm}$  over the entire ingot. Variations of the within-wafer resistivity, expressed as a radial dispersion, are less than 10%.

The 150 mm substrates that we produce from our monocrystalline germanium are formed by first rounding and aligning the ingot. After wire sawing, the substrates undergo edge and surface grinding, chemical etching, polishing and epicleaning to form a platform that's 200  $\mu\text{m}$  thick.

The resulting substrates are slightly thicker than our 100 mm germanium, which is 140–180  $\mu\text{m}$  thick. However, the penalty of using thicker material is offset by improvements in manufacturing efficiencies when processing larger ingots.

We characterize the thickness and geometry with a tool that maps the capacitance over the entire surface and converts this into a thickness profile. 150 mm substrates, with a center thickness of 200  $\mu\text{m}$ , show comparable total thickness variation, bow and warp to 100 mm substrates with a thickness of 175  $\mu\text{m}$  (figure 1). The additional thickness strengthens the substrate and gives it a wafer fracture force of 60 N.

Our 150 mm substrates have a surface that corresponds to a (100) plane off-orientated by 6° to the nearest (111) plane. This geometry, which has been confirmed by X-ray diffraction, aids the growth of epilayers that are free from anti-phase domains.

These substrates are polished on one side to create a surface with a very low defect density, according to laser light scattering measurements. The roughness on the epi-ready side is very similar to that of our 100 mm germanium, which ensures its suitability for high-quality MOCVD epitaxy.

We are now focusing on improving our 150 mm manufacturing process throughput, which will cut production costs. We are also looking at surface contamination levels, in terms of defects and metals, and the impact that they could have on cell performance. We believe that we are also well placed for any demand for even larger diameters, such as 200 or 300 mm germanium substrates.

## Symposia

## Meeting Activities

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### ELECTRONICS, PHOTONICS, AND MAGNETISM

- A: Performance and Reliability of Semiconductor Devices
- B: Transparent Conductors and Semiconductors for Optoelectronics
- C: Theory and Applications of Ferroelectric and Multiferroic Materials
- D: Rare-Earth Doping of Advanced Materials for Photonic Applications
- E: Materials and Technologies for 3-D Integration
- F: Low-Cost Solution-Based Deposition of Inorganic Films for Electronic/Photonic Devices
- G: Organic and Hybrid Materials for Large-Area Functional Systems
- H: Physics and Technology of Organic Semiconductor Devices
- I: Reliability and Properties of Electronic Devices on Flexible Substrates
- J: Material Science for Quantum Information Processing Technologies
- K: Magnetic Nanostructures by Design
- L: New Materials with High Spin Polarization and Their Applications

### ENERGY AND THE ENVIRONMENT

- M: Energy Harvesting—Molecules and Materials
- N: Next-Generation and Nano-Architected Photovoltaics
- O: Structure/Property Relationships in Fluoride-Derivative Compounds
- P: Photovoltaic Materials and Manufacturing Issues
- Q: Scientific Basis for Nuclear Waste Management XXXII
- R: Materials for Future Fusion and Fission Technologies
- S: Solid-State Ionics
- T: Mobile Energy
- U: Advanced Intermetallic-Based Alloys for Extreme Environment and Energy Applications

### ENGINEERED MATERIALS AND MODELING

- V: Materials, Devices, and Characterization for Smart Systems
- W: Computational Materials Design via Multiscale Modeling
- Y: Biomineral Interfaces—From Experiment to Theory
- Z: Mechanics of Biological and Biomedical Materials
- AA: Materials for Optical Sensors in Biomedical Applications
- BB: Polymer-Based Smart Materials—Process, Properties, and Application
- CC: Design, Fabrication, and Self Assembly of "Patchy" and Anisometric Particles
- DD: Materials in Tissue Engineering

### NANOSCIENCE

- EE: Nano- and Microscale Materials—Mechanical Properties and Behavior under Extreme Environments
- FF: Nanofunctional Materials, Structures, and Devices for Biomedical Applications
- GG: Microelectromechanical Systems—Materials and Devices II
- HH: Advances in Material Design for Regenerative Medicine, Drug Delivery, and Targeting/Imaging
- II: Bio-inspired Transduction, Fundamentals, and Applications
- JJ: Nanotubes, Nanowires, Nanobelts, and Nanocoils—Promise, Expectations, and Status
- KK: Transport Properties in Polymer Nanocomposites
- LL: Nanowires—Synthesis, Properties, Assembly, and Application
- MM: Applications of Group IV Semiconductor Nanostructures
- NN: *In-situ* Studies across Spatial and Temporal Scales for Nanoscience and Technology
- OO: Grazing-Incidence Small-Angle X-Ray Scattering
- PP: Solid-State Chemistry of Inorganic Materials VII
- QQ: Synthesis and Processing of Organic and Polymeric Functional Materials for a Sustainable Energy Economy
- RR: Artificially Induced Grain Alignment in Thin Films
- SS: Selecting and Qualifying New Materials for Use in Regulated Industries
- TT: Local Structure and Dynamics in Amorphous Systems

### GENERAL INTEREST

- X: Frontiers of Materials Research

### Symposium Tutorial Program

Available only to meeting attendees, the symposium tutorials will concentrate on new, rapidly breaking areas of research.

### Exhibit

A major exhibit encompassing the full spectrum of equipment, instrumentation, products, software, publications, and services is scheduled for December 2-4 in the Hynes Convention Center. Convenient to the technical session rooms and scheduled to complement the program, the MRS Fall Exhibit offers everything you need all under one roof.

### Publications Desk

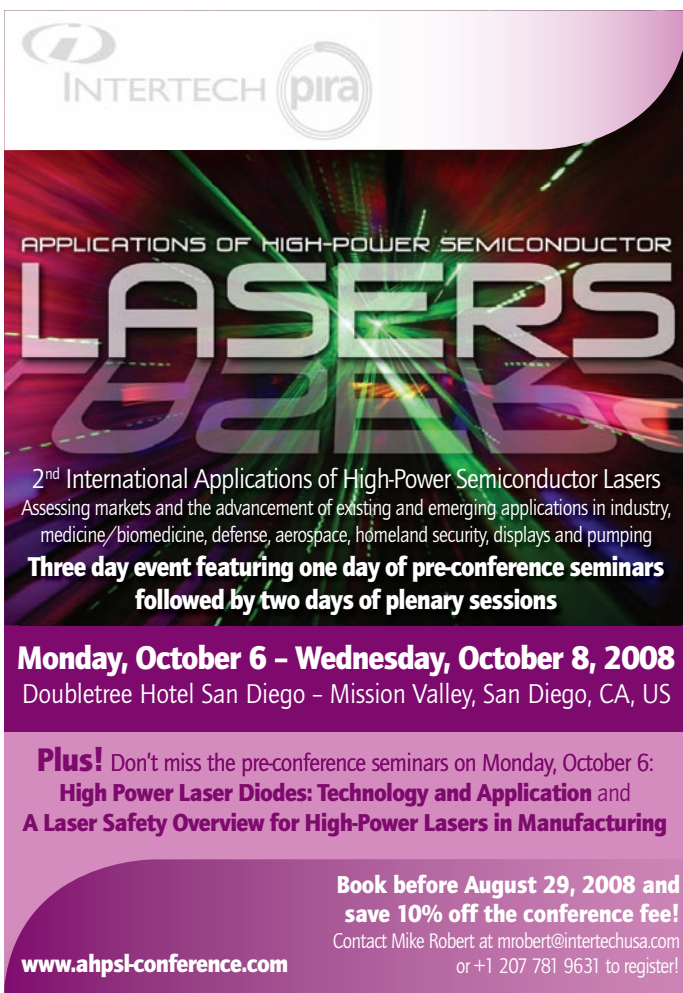
A full display of over 950 books will be available at the MRS Publications Desk. Symposium Proceedings from the 2007 MRS Fall Meeting and 2008 MRS Spring Meeting will be featured.

### Student Opportunities

Graduate students planning to attend the 2008 MRS Fall Meeting are encouraged to apply for a Symposium Assistant position and/or a Graduate Student Award. Applications will be accessible on the MRS Web site by June 1.

### Career Center

A Career Center for MRS members and meeting attendees will be open Tuesday through Thursday.



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# GaN players aim for defense market

US military interests seem to be setting the GaN market in motion, but will this provide sufficient rewards for companies getting into the sector? **Andy Extance** speaks to some of the key figures and tries to extract some sense from the facts that are slipping out from between the official secrets.

Amid the heat of Atlanta's Georgia World Congress Center, GaN RF electronics emerged as one of the hottest topics at this year's MTT-S International Microwave Symposium. In fact, while wondering if the heated GaN discussions could actually cause a fire, one delegate questioning the safety of the venue commented: "If it catches light, you'll never get all of these people out."

While commercial GaN applications, such as amplifiers for cable TV and wireless communications base stations, are just getting going, it's the military whose interests are particularly inflamed by the wide-bandgap semiconductor. With the GaN RF products offering particularly high performance, it seemed at the conference that defense companies will pay a premium to secure the benefits of this up-and-coming technology.

Their interest can only have been spurred on even more by company announcements of GaN transistor portfolios boasting record performance at the symposium (see "MTT-S IMS 2008 GaN records", p20). Among these, RF Micro Devices (RFMD) particularly caught the delegates' eyes with its 400 W S-band radar power amplifier. As well as an impressive power output, which RFMD claims is unmatched by any US companies in the GaN area, the device's bandwidth is another standout feature. RFMD's amplifier spanned twice the range of a competing 300 MHz bandwidth module and the company says that it can push this to 1 GHz in the 2.5–3.5 GHz domain.

The Japanese firm Eudyna, which dominates the high-power RF GaN market, was not impressed by RFMD's 400 W module. It demonstrated a 500 W amplifier operating at 1.5 GHz at the 2006 MTT-S show, and Warren Gould, Eudyna's senior director of business development, felt that this reflected the company's overall hold in the area. "They're all trying to get into our customers and it's tough," he said. "We've got higher breakdown voltages, better performance and we're already in production."

While RFMD agrees that Eudyna was there first, it is hoping to reap the benefit from domestic interest fueling the powerful US military market. "Our customers tell us that the only other people that they can get these parts from are the Japanese and there are problems sourcing those into the US," said Jeff Shealy, vice-president and general manager of

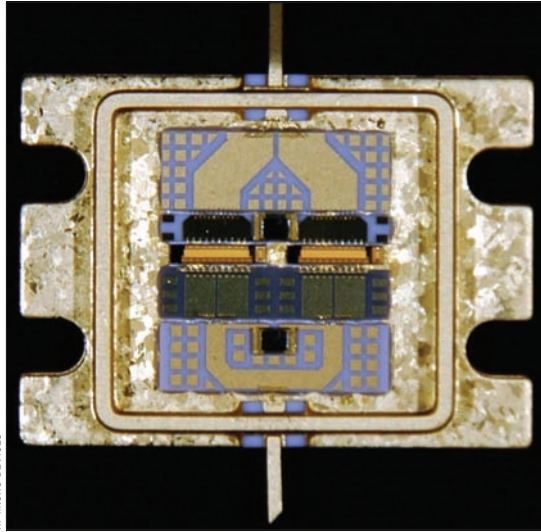


**Solid-state digital airport surveillance radar**, like this one from Northrop Grumman, is one example of the S-band radar applications being targeted by RFMD's 400 W GaN power amplifier.

RFMD's Aerospace and Defense Business Unit. "We're in discussions with every major defense manufacturer in the US as well as multiple companies abroad interested in our amplifier technology."

Shealy pointed out that, although GaN devices may still need to be linked together for kilowatt output radar, combining higher-power modules ultimately produces lower loss than would be incurred by lower-power solid-state devices. This in turn finally makes solid-state RF electronics a feasible replacement for microwave tubes at high powers. "The customers are very interested in replacing very heavy, bulky tube technology with a solid-state rack-mounted unit," Shealy explained.

However, despite the boon of highly reliable government-sponsored orders, the shroud of secrecy surrounding the defense market means that it is very hard to determine what dollar value the interest in the area is likely to turn into. Shealy admits limited visibility into the total military RF GaN market size, but at least he knows that the market is attractive to RFMD. "The volumes in the



**RFMD's 400 W GaN HEMT** delivers 10.5 dB of power gain, and is more reliable and compact than current travelling wave tubes that are used in S-band radar, says the company.

radar market are very small, but the selling prices are very good," he commented.

Despite being almost entirely prevented from talking about its business by the defense cloak, RFMD's North Carolina neighbor Nitronex paints a similar picture of a vibrant GaN business. "We can't make enough devices," admitted Ray Crampton, the company's marketing director. "It's insanely busy."

Nitronex's latest, higher-power GaN devices are RF transistors that cover the frequency range from DC to 2.7 GHz, with power outputs of up to 200 W. These powers are partly limited by their silicon substrates, which have a lower thermal conductivity than the SiC substrates that are used by most other companies. This makes it much more challenging to reach the full performance potential of GaN, and Nitronex has worked hard on its device designs to improve heat flows. However, the payback comes in the form of cheaper devices and the potential to use larger wafers. Nitronex is already working on 4 inch GaN-on-silicon wafers whereas the SiC substrate community still uses 3 inch diameter wafers or even smaller (table 1).

Crampton explains that many of Nitronex's devices, including its latest ones, are being sought out specifically for use in unnamed narrowband 2.5 GHz applications. Although Crampton could not be drawn on what these applications might be, he did concede that in 2008 and 2009 the vast majority (he feels that about two-thirds is a good estimate) of Nitronex's business would be with defense companies. Perhaps the firm's importance to the defense industry is best reflected by how it is addressing its current capacity constraints – with the support of military funds that are being pumped into the company specifically to finance work on enhancing its yields.

The success of Nitronex's business is doubly obscured, by its military work and by the fact that it

**MTT-S IMS 2008 GaN records**

- Panasonic:** highest gain (22 dB) at 26 GHz.
- Toshiba:** highest power (50 W) in the Ku band (12–18 GHz).
- RF Micro Devices:** highest bandwidth (>600 MHz) at power levels of more than 400 W.
- Cree:** highest drain efficiency (55% for a 90 W device across the 500 MHz to 2.5 GHz range).

**Table 1. GaN wafer diameters**

Company	Diameter	Substrate
Nitronex	4 inch	silicon
UMS	3 inch*	SiC
TriQuint	3 inch*	SiC
Cree	3 inch*	SiC
RFMD	3 inch	SiC
Eudyna	3 inch	SiC
Toshiba	2 inch	SiC

\*the company told Compound Semiconductor that upgrades to 4 inch wafers are in progress.

isn't publicly listed and therefore its accounts are less readily available. However, Crampton says that although the company is not quite profitable, it's getting ever closer to recording its first net income.

Although US GaN firms are clearly reaping the benefit of international military politics, other compound semiconductor companies also stand to gain. On the one hand, where the sale of RF components to certain countries is restricted, bespoke design houses and foundries are stepping in to provide the desired functions. On the other, countries with their own defense interests at heart are just as likely to spot the GaN opportunity as the US is.

This is very much the case at NXP, the Dutch semiconductor company pushing the commercial side of Europe's GaN efforts. It is collaborating with the United Monolithic Semiconductors foundry, in which the defense giant EADS owns a 50% stake, and Germany's Fraunhofer Institute of Applied Solid-State Physics.

As the commercial partner, NXP is setting itself some very clear goals, including the release of 100 W GaN transistors for WCDMA base stations in 2009. Perhaps thanks to this, the company seems to have one of the clearest perspectives on the overall potential of the GaN market, including the opaque military angle. It says that ultimately there is enough business for just three RF GaN foundries worldwide. It predicts that these will be distributed evenly between Asia, the US and Europe – another clear sign that national interests will have a strong role to play in the destiny of the GaN industry. ●

**Further reading**

- A Maekawa *et al.* 2006 *IMS Digest* 722.
- K Krishnamurthy *et al.* 2008 *IMS Digest* 303.

**"We can't make enough devices. It's insanely busy."**

**Ray Crampton**  
Marketing director,  
Nitronex

# Antimonides chase terahertz target

In just 10 years the InP/GaAsSb DHBT has evolved from a lab curiosity to research devices inching to terahertz cut-off frequencies, and a commercial product, says ETH Zürich's **Colombo Bolognesi**.

A key moment in my career occurred at the 1996 Lester Eastman Conference on High Performance Devices. As I sat through a talk on chirp-superlattice graded-collector InP/GaInAs DHBTs, it dawned on me that a GaAsSb base and an InP collector might dramatically ease the realization of InP DHBTs.

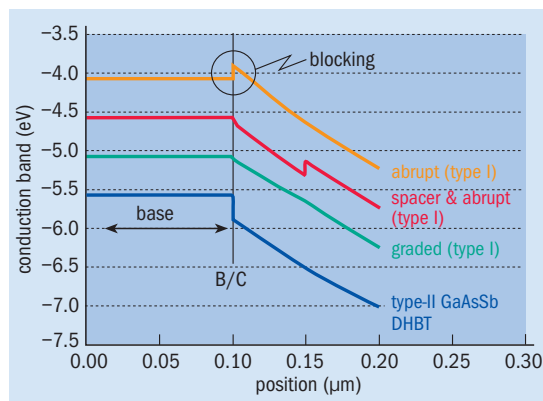
According to this new idea, you would inject "ballistic" electrons into an InP collector from a GaAsSb base, thanks to the position of GaAsSb's conduction band relative to InP (figure 1). Eliminating the need for compositional grading at the base-collector junction would simplify epitaxial growth and permit the use of selective etching techniques for chip processing, while doing away with ternary alloys would also boost thermal conductivity and ultimately make the devices more suitable for use in high thermal-dissipation circuits.

The GaAsSb-based design benefits that resulted included simplified fabrication and a better thermal management, and the HBT eventually showed higher breakdown voltages (figure 2). The injection of electrons across an abrupt junction into the InP collector was also expected to give the electrons a velocity kick as they entered the InP collector, thereby increasing their average velocity and ultimately reducing the transistor collector delay time.

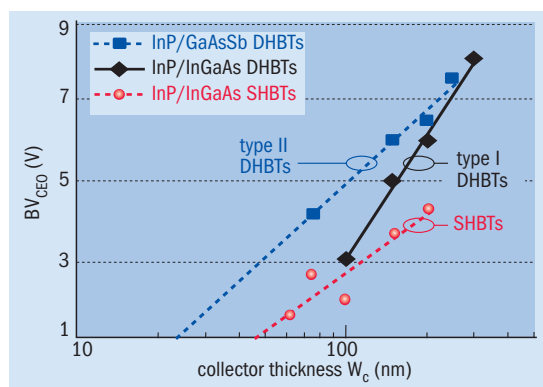
Our initial work on GaAsSb DHBTs was done in collaboration with Simon Watkins, a colleague specializing in MOCVD epitaxial growth at Simon Fraser University, British Columbia. With the support of John Sitch from Nortel, we secured a four-year grant totaling \$350,000 from the National Sciences and Engineering Research Council of Canada (NSERC), and initially we targeted 160 GHz transistors for potential laser drivers in 40 Gbit/s communication systems.

Before our proposal could be submitted, we were scooped by papers from Bellcore and Rockwell (Bhat *et al.*, McDermott *et al.*). In both cases, initial results were inferior to state-of-the-art GaInAs-based transistors, and both companies quickly abandoned work on GaAsSb-based devices.

The Bellcore/Rockwell results played on our minds: we were facing some high-risk research. In the end, we decided that we really wanted to attempt the development of antimonide-based DHBTs. Winning funding was a long shot, but we were successful, and work started in earnest in 1997. Back then, very little was known about GaAsSb-InP heterojunctions, so we began by growing this heterostruc-



**Fig. 1.** (top) Many type-I InP HBT designs suffer from a conduction-band profile that hampers the injection of electrons from the InGaAs base into the InP collector. Transistors with either an abrupt junction or a spacer followed by an abrupt junction form a barrier to electron transport. This can be eliminated with graded profiles, which include chirp superlattice designs. However, it's possible to do even better by turning to type-II GaAsSb DHBTs that can ballistically inject electrons from a GaAsSb base into an InP collector. **Fig. 2.** (bottom) Type-II DHBTs provide higher breakdown voltages than InP/GaInAs DHBTs and InP/GaInAs SHBTs, at the same collector thickness.

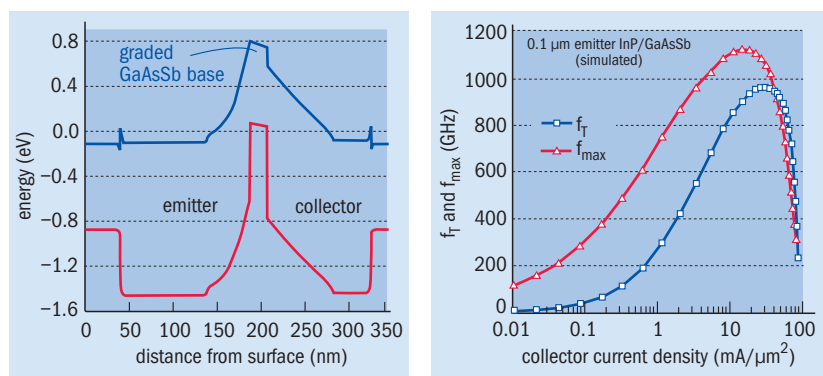


ture and measuring its band alignment (Hu *et al.*).

Later that year we were approached by Nick Moll, a senior member of the technical staff at Agilent (then Hewlett-Packard) Research Laboratories, who also had an interest in InP/GaAsSb DHBTs. A separate collaboration was then set up with Moll and Agilent to develop the technology.

Our collaborations with Nortel and Agilent were very fruitful and, because neither had InP/GaInAs HBT products, both were receptive to new ideas. The companies initially kept all options open through the simultaneous investigation of GaInAs and GaAsSb DHBTs. Eventually, both opted for the commercial development of GaAsSb DHBTs.

Nortel's efforts were grounded when Bookham acquired its III-V group in the wake of the telecom bubble, but Agilent was successful, and became the first and only organization in the US to commercialize InP/GaAsSb DHBTs. Agilent still doesn't reveal much about its InP/GaAsSb DHBT plans and products, presumably for strategic and competitive



**Fig. 3.** (left) Bolognesi's group is now developing graded-base InP/GaAsSb DHBTs that have an  $f_T$  of more than 600 GHz. **Fig. 4.** (right) Hydrodynamic simulations of InP/GaAsSb DHBT with a 100 nm wide emitter and 300 nm wide collector mesa reveal the potential of this device for terahertz operation. All doping levels and contact resistances used demonstrate realistic values.

reasons, but it is interesting to note that the Santa Rosa, CA, fab where InP/GaAsSb DHBTs are now manufactured is one of the few semiconductor assets retained by the company.

### Transitions to industry

In 1998 the characteristics of our first transistor with ballistically injected collector electrons appeared in print (Matine *et al.*) and two years later we followed it up with the first report of a bipolar transistor with an  $f_T$  and  $f_{max}$  in excess of 300 GHz (Dvorak *et al.*). Such performances represented a milestone for any material system, and our measurements were independently verified by Tom MacElwee at Nortel. These NSERC-funded results set a record for bandwidth per invested dollar.

Nortel left the game, but a basic process without passivation and interconnects was transferred to Agilent's Research Laboratories in Palo Alto and adapted for production at the company's Santa Rosa location. Martin Dvorak, my first PhD student at SFU, went on to join Agilent's Santa Rosa facility to develop InP/GaAsSb DHBTs there. By 2004 these devices had become commercial products, also thanks to Moll's tireless advocacy. Moll played a key role in establishing a manufacturable GaAsSb device process meeting Agilent's cost, yield, performance and reliability requirements.

Today, few companies are making money selling commercial InP DHBTs. However, we are pleased to see that, whether researchers are pursuing GaAsSb, GaInAs or SiGe technologies, bipolars or FETs, there is a fair chance that they are characterizing their high-frequency devices using one of Agilent's high-speed instruments with InP/GaAsSb DHBTs inside.

### What matters: $f_T$ or $f_{max}$ ?

Our group continues to develop GaAsSb-based DHBTs, although we relocated to ETH Zürich in 2006. We're continuing to develop faster transistors and one of our goals is a terahertz device. Claims for high speeds can be made in terms of  $f_T$  or  $f_{max}$ , and it is important to consider these terms and their

### Understanding $f_T$ and $f_{max}$

$f_T$  (the current gain cut-off frequency) and  $f_{max}$  (the maximum oscillation frequency) are the two common small-signal transistor figures of merit.  $f_T$  is defined with a short-circuited load and is determined by the transistor's carrier transit and signal-delay times. This means that it represents the device's operating speed. Circuits such as emitter-followers can achieve a bandwidth approaching the transistor  $f_T$  (which characterizes the gain-bandwidth product of some amplifiers). This indicates that this figure of merit can be a good indication of the performance of certain circuits.

Transistors can also deliver power gain at frequencies exceeding  $f_T$ .

This is because "transistor action" can produce an output impedance that exceeds input impedance (ideally, transistors should behave as perfect controlled current sources that push a current that is independent of the collector voltage). Losses can be compensated for when the transistor exhibits a power gain that is slightly larger than unity, and an unloaded transistor can oscillate up to frequencies approaching its  $f_{max}$ .

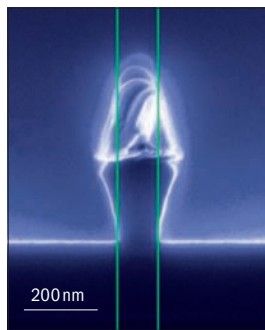
In microwave systems the name of the game is power amplification and generation. This means that  $f_{max}$  is the key figure of merit for power amplifiers and oscillators because it represents the power gain-bandwidth product of a transistor.

meanings (see "Understanding  $f_T$  and  $f_{max}$ ").

Once the origins of current and power gain in transistors are understood, particularly that the power gain depends on the termination of input and load impedances, it makes sense to refer to a terahertz transistor as a device with an  $f_T$  of 1 THz, because such a transistor will feature a sufficiently fast electron transport to maintain a current gain of at least unity at that frequency. Such a terahertz transistor may or may not show power gain at 1 THz, depending on input/output matching impedances and/or on whether the device has been "unilateralized" (i.e. on circuit conditions external to the transistor).

Measuring the speed of transistors with cut-off frequencies exceeding 500 GHz requires care. The  $f_T$  is determined through extrapolation over wide frequency ranges and calibration subtleties can produce erroneous conclusions. To make matters worse, unilateral power gain does not necessarily roll off at the  $-20$  dB/dec rate that is used in such extrapolations. This means that the implementation of amplifiers or oscillators is the true test for those primarily interested in  $f_{max}$ .

It's also not very simple to relate the transistor figures of merit  $f_T$  and  $f_{max}$  to digital IC performance. For starters, digital operation is no longer "small-signal", the condition that is assumed for the definitions of these two figures of merit. Furthermore, switching transistors face neither short-



**Sub-100 nm emitter mesas** for graded-base InP/GaAsSb DHBTs are produced by dry/wet etching.



circuited nor impedance-matched loads.

Some people in this field follow a rule of thumb that states that digital circuits require  $f_T$  and  $f_{max}$  values that are three to four times as great as the intended bit rate. Consequently, 40 Gbit/s circuits would need to use transistors with an  $f_T$  and  $f_{max}$  of at least 160 GHz. However, glaring counter-examples to this rule-of-thumb can be found in the literature, with data rates approaching the  $f_T$  and  $f_{max}$  cut-off frequencies. Increasingly, workers are finding that the raw  $f_T$  and  $f_{max}$  cut-off frequencies are weakly correlated to achievable data rates in digital ICs, and efforts are being made to define alternative, more pertinent transistor figures of merit.

Progress was made on this front through detailed numerical simulation by investigating the impact of transistor physical parameters and figures of merit on the maximum achievable data rates in digital circuits (Ruiz-Palmero *et al.*). These simulations did not rely on device circuit models but rather employed a fully calibrated physical hydrodynamic (HD) simulation of all of the transistors making up the emitter-coupled logic and current-mode logic test circuits. Unlike drift and diffusion models, the electron's energy in high electric fields is accounted for in HD simulations. The Ruiz-Palmero study avoids the approximations that are involved in SPICE-like circuit simulations based on compact models and/or in the development of analytical gate-delay expressions from equivalent circuit models.

These simulations show little correlation between  $f_T$ ,  $f_{max}$  and the minimal gate delay. Instead they suggest that adequately scaled InP/GaAsSb DHBTs with an  $f_T$  of 1 THz and an  $f_{max}$  of just 600 GHz could deliver data rates of up to 300 Gbit/s. In these simulations, type-I and -II transistors were both optimized to maximize data rates, and  $f_T$  and  $f_{max}$  cut-off frequencies were merely treated as side products of the optimization procedure.

The important point is that the results dismiss the notion that high-speed digital ICs demand a transistor with an  $f_{max}$  of greater than  $f_T$ . These simulations showed that whereas both type-I InP/GaInAs DHBTs and type-II InP/GaAsSb DHBTs could be used to implement 200 Gbit/s digital ICs, only the InP/GaAsSb DHBTs could be sufficiently scaled for higher data rates of at least 300 Gbit/s (Ruiz-Palmero *et al.*), thanks to the favorable breakdown voltages and thermal properties of full InP collectors.

### Terahertz quest

At last December's International Electron Devices Meeting in Washington, DC, we unveiled the results of our new graded-base devices (figure 3). These transistors had a conservatively estimated  $f_T$  of 600 GHz at room temperature and a breakdown voltage ( $BV_{CEO}$ ) of 4.2 V, which equates to a  $f_T \times BV_{CEO}$  figure of merit of more than 2.53 THz-V. Cooling to cryogenic temperatures improved all three characteristics. Measurements on a chuck held at 5 K produced an  $f_T$  of 705 GHz, a 4.4 V breakdown voltage

### Efforts at IPRM

Bolognesi was pleased to see the large number of GaAsSb-related papers at May's Indium Phosphide and Related Materials Conference, which was held close to the Château de Versailles, on the outskirts of Paris (see p14 for an overview of this meeting). Labs in Europe and Asia are showing a growing interest in this material. More than two-fifths of the HBT-related papers from this conference involved GaAsSb or its derivatives.

One paper that caught his eye particularly was



OLIVIER OSTINELLI

the first side-by-side comparison of type-I GaInAs and type-II DHBTs fabricated with the same process. This effort, which involved the French companies Alcatel-Thales and Picogiga, revealed that type-II DHBTs showed higher DC gains,

$f_T$  and  $f_{max}$  than type-I equivalents that have a similar breakdown voltage and a graded GaInAs base (Nodjiadjim *et al.*). This result is very important because practical applications often specify minimum transistor breakdown voltages.

and an increase in the product of  $f_T$  and  $BV_{CEO}$  to more than 3.10 THz-V. In comparison, SiGe HBTs with a 500 GHz  $f_T$  at cryogenic temperatures feature a much lower  $f_T \times BV_{CEO}$  product of <0.69 THz-V due to poor breakdown voltages.

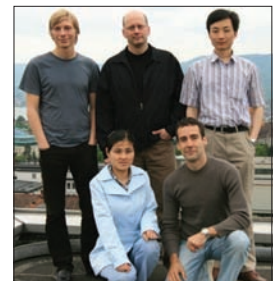
These figures indicate that it is realistic to talk about terahertz InP/GaAsSb DHBTs with a breakdown voltage of more than 2 V.

Our team now believes that all of the separate elements required to reach the terahertz bandwidth milestone are in place: the devices can be scaled to sub-100 nm sizes while still displaying useful gain; the emitter mesa etching can be done consistently; and sufficiently low contact resistances can be realized. Simulated characteristics of a transistor with a 100 nm emitter mesa and a 300 nm collector mesa computed with a full HD simulation also suggest that it is realistic to believe that  $f_T$  and  $f_{max}$  values can simultaneously near 1 THz (figure 3).

Success in this terahertz quest will ultimately depend on a group's ability to combine all of the key elements simultaneously. In a university environment with shared multiuser/purpose laboratories and fluctuating group personnel, this may be tantamount to standing a pin on its sharp end, but that does not mean that we shouldn't try.

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### About the author

**Colombo Bolognesi** (back row, center) is a PhD graduate from UCSB. He worked as a BiCMOS process integration engineer at Nortel before joining Simon Fraser University in 1995. In 2006 he relocated his group to ETH Zürich in Switzerland, where he is chair of terahertz electronics. His group also investigates HEMTs in the InP/GaInAs and AlGaIn/GaN material systems. The current ETH HBT team consists of **Rickard Löbblom** (top left), **Honggang Liu** (top right), **Yuping Zeng** (bottom left) and **Olivier Ostinelli** (bottom right).

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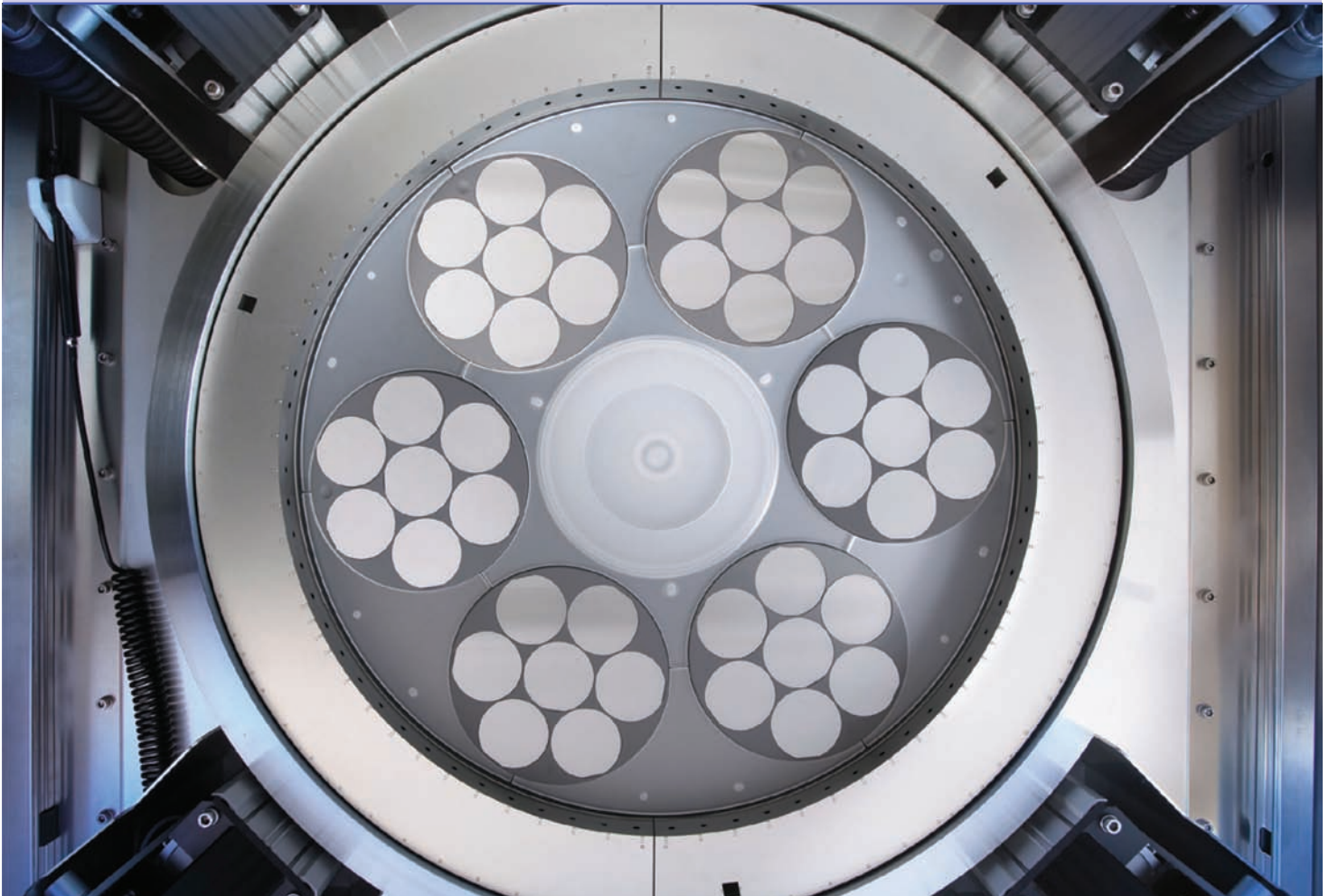
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# Japan pushes the GaN envelope

Japanese companies are continually pushing the boundaries of GaN electronics. Recent industrial efforts have led to the fastest transistors, diodes that can withstand blocking voltages of more than 10 kV and single-chip high-frequency amplifiers producing record gain. **Richard Stevenson** reports.

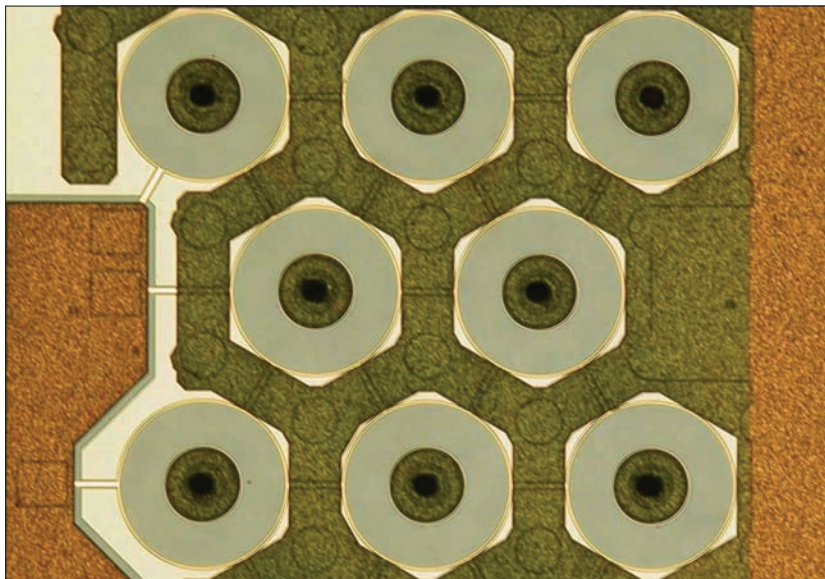
Our community is already exploiting the benefits of GaN in transistors and power diodes. However, further innovation in device design and processing is essential if these devices are to ever fulfill their true potential. In Japan, many companies are looking to do just this, and a scan through recent conference proceedings uncovers a wealth of claims for device records and novel processes.

One recent claim is for the highest frequency for a GaN transistor, which has been made by the National Institute of Information and Communications Technology (NICT), Tokyo. NICT reported an  $f_T$  and  $f_{max}$  of 190 and 241 GHz at last year's International Conference on Nitride Semiconductors in Las Vegas, from HEMTs that have a maximum drain current density of 1.6 A/mm and a peak transconductance of 424 mS/mm.

NICT plans to demonstrate that its high-speed HEMTs can deliver power performance in the millimeter-wave range, particularly at 60, 76 and 94 GHz. "Generally there is no good solid-state amplifier for frequencies above 50 GHz in the world," said former NICT researcher Masataka Higashiwaki, who is now a project scientist at the University of California, Santa Barbara. Amplification at 60 and 76 GHz is needed for high-speed wireless LAN and automotive radar, and the 94 GHz band is just starting to be used for ultra-high-speed wireless communications that can complement optical fiber networks. These applications all demand high-power transmitters that are not available today. "In my opinion, GaN is the only material that has the possibility to realize it," said Higashiwaki.

The HEMTs' high speed is partly the result of an alternative SiN passivation step – catalytic CVD. This is a simple process that was invented in the 1980s by Hideki Matsumura's group at the Japan Advanced Institute of Science and Technology. "We put a silane and ammonia mixture by a heated tungsten filament, and the filament decomposes the gas by catalytic effects. SiN is formed on the substrate."

The catalytic CVD process is superior to the more common plasma processes because it doesn't damage the very sensitive GaN surface. Degradation of this material can produce defects and surface states that impair device performance and reliability. "Additionally, the quality of the SiN film deposited by Cat-CVD is much better than that by plasma,"



Panasonic's high-voltage HEMTs feature an array of metal-filled vias to boost thermal conductivity.

said Higashiwaki, "and film coverage is excellent from the early stages of deposition."

Reducing the length of the gate to 60 nm also helps to increase the HEMTs' speed. Higashiwaki says that getting to smaller dimensions wasn't that difficult: "There is no challenge on patterning. We used a normal electron-beam writer with an acceleration voltage of 50 kV and a usual triple-layer resist process." He says that 30 nm gates have been realized with a very similar process.

Completing the gate-fabrication processes was more challenging, however, because it was tough to develop a satisfactory lift-off process for the gate metal. "We used titanium instead of nickel – which is commonly used as a Schottky gate – because titanium has stronger adhesion." Titanium evaporation directly onto GaN leads to a high gate leakage, so the researchers have sandwiched a SiN layer in the middle. However, Higashiwaki is not sure whether the gate structure is optimal, so he is currently looking into other processes.

The third factor behind the record-breaking HEMTs is their thin, aluminum-rich barrier layers. These reduce unwanted "short-channel" effects that degrade device performance and prevent gate-length scaling. The MOCVD-grown high-quality epitaxial

**Mitsubishi Electric** carries out GaN electronics research at its Advanced Technology Research and Development Center in Amagasaki, Japan (right). Developments at this facility include a silicon ion implantation technique that holds the key to low-resistance contacts on aluminum-rich HEMTs. **Fig. 1.** (far right) Fujitsu's record-breaking high-speed HEMTs feature gates with a length of just 60 nm, a narrower aluminum-rich AlGaN channel and a SiN passivation layer that is deposited by catalytic CVD.



structure features a 6 nm thick  $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$  barrier, a 1 nm thick AlN spacer and a 2  $\mu\text{m}$  thick GaN buffer on 4H-SiC (figure 1). The high aluminum content in the barrier increases polarization and the density of the two-dimensional electron gas, which gets a further hike from the catalytic deposition of SiN.

The positive effect of catalytic CVD on the electron density is still to be understood fully, but Higashiwaki believes that the AlGaN surface barrier height is decreased after SiN deposition. Calculations can support this scenario, but Higashiwaki admits that they have no idea if the model provides an accurate account of what is taking place.

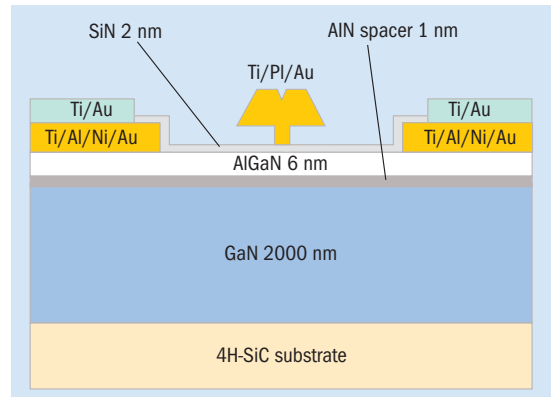
### GaN overpowers silicon

One company improving the performance of power devices is Panasonic, which has been developing a novel laser process for producing via holes through sapphire. AlGaN/GaN power HFETs with a blocking voltage of 10.4 kV were made by this method, with the details unveiled at December's International Electron Devices Meeting (IEDM) in Washington, DC.

This type of device can be used in various high-voltage applications, such as electric trains and electric power transmission. "10 kV blocking by GaN is the first demonstration that GaN can also be competitive with SiC, which has been the only choice for such high-voltage applications," said Panasonic's Tetsuzo Ueda, who is general manager of the company's Semiconductor Device Research Center.

Today's silicon devices can't compete at such high voltages, with insulated-gate bipolar transistors topping out at 6.5 kV, light-triggered thyristors doing no better than 8 kV and gate turn-off transistors restricted to 6 kV. The on-resistance of these devices is also inferior to wide-bandgap alternatives.

Panasonic's device has a major cost advantage



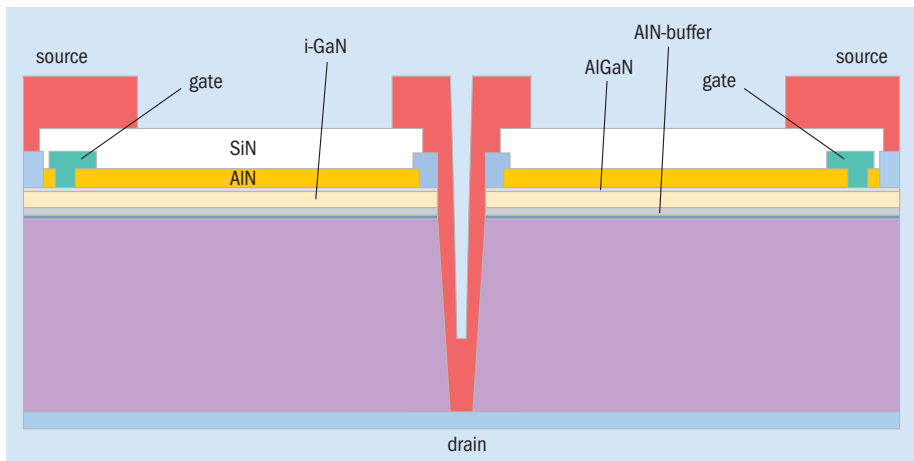
over SiC competitors thanks to the cheaper prices of sapphire substrates. However, sapphire is an inferior thermal conductor. To address this weakness, via holes are formed and filled with metal, and the surface is passivated by polycrystalline AlN, which has a far lower thermal resistance than SiN (figure 2).

Ueda is rather coy about the details of the DC-sputtering step used to deposit the 1  $\mu\text{m}$  thick layer of polycrystalline AlN. However, the research team has revealed that this film has a thermal conductivity 200 times as good as that of SiN. The breakdown electric field strength is also twice as high at 6 MV/cm, and this, alongside field plates and metal vias, gives the HFET its high performance.

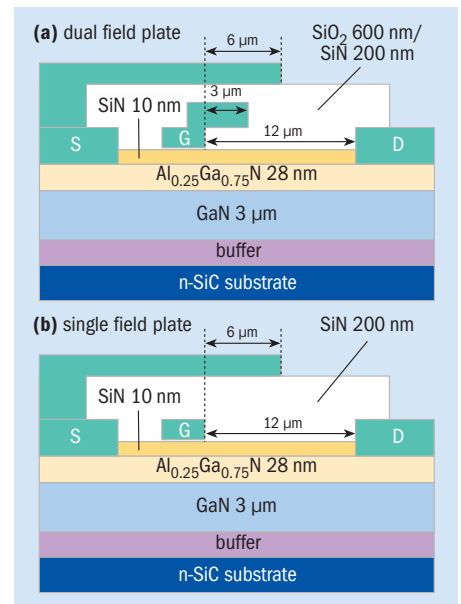
Panasonic has improved and adapted its via hole technology for millimeter-wave devices, and it unveiled a 26 GHz amplifier delivering 22 dB of gain at the recent IEEE International Microwave Symposium in Atlanta. This record-breaking gain from a single-chip three-stage amplifier was attributed to integrated microstrip lines, which require the fabrication of via holes.

Higher breakdown voltages would also improve the performance of high-frequency HEMTs. The obvious way to do this is to add more aluminum to the channel layers. Conventional processes would then encounter the problem of a higher contact resistance, which limits output power. However, silicon ion implantation can be used instead, which produces a far lower contact resistance, according to a partnership between researchers at Mitsubishi Electric, RIKEN and Tokyo Institute of Technology, who also reported their findings at IEDM 2007.

The researchers assessed the impact of ion implantation by studying its effects on devices with three different channel and barrier structures:  $\text{Al}_{0.53}\text{Ga}_{0.47}\text{N}/\text{Al}_{0.38}\text{Ga}_{0.62}\text{N}$ ;  $\text{Al}_{0.39}\text{Ga}_{0.61}\text{N}/\text{Al}_{0.16}\text{Ga}_{0.84}\text{N}$ ; and  $\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ . A silicon ion concentration of  $1 \times 10^{15} \text{ cm}^{-2}$  was added by room-temperature implantation with a 50 keV tool. Five minutes of rapid thermal annealing under nitrogen gas at 1200°C followed. During this the structures were capped with a 30 nm layer of SiN, which was deposited by plasma-enhanced CVD. The cap was subsequently etched and ohmic contacts added, before devices were isolated by zinc ion implantation.



**Fig. 2.** (above) Panasonic employs a high-power, short-pulse laser to produce vias in the sapphire substrate. Filling these with metal boosts the thermal-management capability of the high-voltage HEMTs, which can block more than 10 kV. **Fig. 3.** (right) NEC described the first implementation of a dual field plate design in 2005, which was suitable for RF applications. Engineers at Toshiba have adapted the dual field plate for power applications by increasing the separation between the gate and the drain to 12  $\mu\text{m}$ .



Current-voltage curves were used to compare these devices and controls that had no silicon-ion implantation. The controls had a contact resistance in excess of  $1 \Omega \text{cm}^2$ , while the ion-implanted  $\text{Al}_{0.53}\text{Ga}_{0.47}\text{N}/\text{Al}_{0.38}\text{Ga}_{0.62}\text{N}$  and  $\text{Al}_{0.39}\text{Ga}_{0.61}\text{N}/\text{Al}_{0.16}\text{Ga}_{0.84}\text{N}$  structures had resistances of just  $5.3 \times 10^{-3} \Omega \text{cm}^2$  and  $1.8 \times 10^{-5} \Omega \text{cm}^2$ , respectively.

Ion implantation enabled the fabrication of HEMTs with high breakdown voltages. Conventional HEMTs with this design would typically break down at 200 V, but  $\text{Al}_{0.53}\text{Ga}_{0.47}\text{N}/\text{Al}_{0.38}\text{Ga}_{0.62}\text{N}$  transistors with gate-drain distances of 3 and  $10 \mu\text{m}$  failed at 463 and 1650 V, respectively.

The researchers say that these results show that aluminum-rich AlGaIn channel HEMTs are strong candidates for high-frequency devices, such as low-noise amplifiers, and they also make promising devices for high-power switching applications. Additional improvements are expected through the introduction of field plates that should deliver a further hike in breakdown voltage.

### GaN power supplies

One of the companies looking at HEMTs for switching applications is Toshiba, which is investigating this device for boost converters in PC power supplies. According to Toshiba's Wataru Saito, the GaN HEMT structure is attractive in this application, thanks to its combination of low channel resistance and high electron mobility. "This is an advantage of GaN HEMTs over conventional silicon and SiC power MOSFETs. The electron mobility in the SiC MOS-channel is 10 times lower than the AlGaIn/GaN heterostructure." However, it is much harder to produce a normally off device, which means that the gate threshold voltage tends to be more than 0 V.

GaN HEMTs also suffer from a modulation of the on-resistance by current collapse, which leads to an increase in conduction loss. "As a result, power

efficiency is degraded with the applied voltage," said Saito. Electron trapping is responsible, which is exacerbated by high electric fields that accelerate the electrons in the channel. However, this can be mitigated by the addition of field plates, which spread the electric field concentration over the gate and field plate edges.

Toshiba has evaluated the effects of single and dual field plate HEMTs (figure 3), and it presented the results at IEDM 2007. Dual field plates produce a far smaller on-resistance from 0 to 300 V, thanks to a reduction in the peak electric field strength.

The HEMTs are grown on n-type SiC, which can act as a back-side field plate that suppresses current collapse at voltages of 100 V or more. This type of substrate also produces a higher crystal quality than sapphire or silicon, and it cuts current collapse through a reduction of electron-trapping defects.

Measurements on a dual field plate 480 V 2 A HEMT revealed an on-resistance modulation of just 5% at 300 V. When the transistor was deployed in a boost converter circuit it delivered 92.7% efficiency at a 1 MHz switching frequency, which is comparable to a similar circuit based on a silicon MOSFET.

Saito says that more work is needed before these devices can be used in power electronic applications. "Power supply systems require a breakdown voltage of more than 600 V and a maximum current of more than 10 A. Our fabricated device characteristics were below those levels." Efforts are now being directed at improvements in breakdown voltage and the fabrication of large devices. ●

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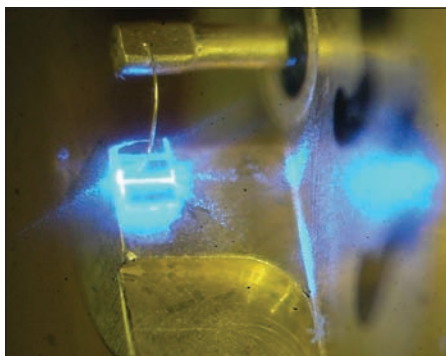
NON-POLAR DEVICES

# Rohm nears green laser diode target

Rohm is closing in on its goal of making a non-polar green laser diode for laser TV. The company has pushed the peak emission wavelength of its continuous-wave (CW) lasers to 481 nm, which is 39 nm short of its ultimate target. Slightly longer-wavelength GaN-based lasers have been built with conventional polar GaN, but the 488 nm leading effort by Nichia is now under threat, thanks to Rohm's rapid progress.

Rohm's recent increase in lasing wavelength has come through improvements in the structure's optical confinement, reduced mirror loss and a cut in operating voltage.

The researchers grew their devices by MOCVD on freestanding non-polar *m*-plane GaN substrates. The laser structures featured AlGaIn cladding, InGaIn wave-guiding layers, an AlGaIn electron-blocking layer and a



Rohm has fabricated blue-green CW non-polar lasers with a peak output power of more than 20 mW.

two-period InGaIn multiple quantum well.

Edge emitters were fabricated from these epiwafers that had stripe widths of 1.5–4.0 μm

and 400 μm long cavities. Distributed Bragg reflectors increased the laser's facets to an estimated 70 and 99%.

The lasers produced a CW output power of more than 20 mW, a threshold current density of 6.1 kA/cm<sup>2</sup> and a slope efficiency of 0.49 W/A. This is more than twice the maximum output power of conventional *c*-plane lasers operating at similar wavelengths, which are less than half as efficient.

Efforts are now focusing on increasing emission efficiency at longer wavelengths and reducing contact resistance at the metal–GaN interface, which will lead to lower operating voltages.

**Journal reference**

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GAN ICs

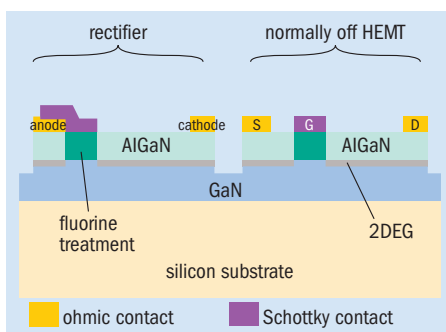
## Researchers unite HEMTs and rectifiers

GaN rectifiers and normally off HEMTs can now be built on the same chip, thanks to Kevin Chen and his team at Hong Kong University of Science and Technology.

According to Chen, this breakthrough in GaN power electronic ICs will enable the single-chip implementation of GaN-based switch-mode power converters. This includes buck and boost converters that can step up and step down voltages, respectively.

Unifying rectifiers and HEMTs on the same chip has been a major challenge for GaN developers, because the epitaxial structures of PIN rectifiers and low on-resistance Schottky barrier diodes are incompatible with this type of transistor.

Chen's team has overcome this problem with a lateral field-effect rectifier (LFER). This features a Schottky-gate-controlled two-



**Fabrication of the rectifier** involves the incorporation of fluorine ions under the Schottky contact by carbon tetrafluoride plasma treatment. This pinches off the conduction path and enables the rectifier to have a reverse blocking capability.

dimensional electron gas channel, which is in ohmic contact with the cathode and anode (see figure). The Schottky gate and anode are tied together, and the turn-on voltage is determined by the threshold voltage of the channel rather than the Schottky barrier.

A Nitronex Al<sub>0.26</sub>Ga<sub>0.74</sub>N HEMT wafer on a silicon (111) substrate was used to create the IC, which features a LFER with a drift length of 10 μm. This has a forward turn-on voltage of 0.63 V at 100 A/cm<sup>2</sup>, a breakdown voltage of 390 V at 1 mA/mm and a specific on-resistance of 1.4 mΩ cm<sup>2</sup>. The low turn-on voltage cuts power consumption in the on state and leads to higher power efficiencies when LFERs are used in power converters.

SiC is another promising material for power applications, but Chen believes that GaN devices have the potential to deliver a lower on-resistance, which boosts efficiency.

“In addition, AlGaIn/GaN HEMTs feature much higher switching frequencies, which enable size reduction of passive reactive components,” said Cheng. This is important because it should lead to compact, light-weight power converters.

**Journal reference**

W Chen et al. 2008 *Appl. Phys. Lett.* **92** 253501.

LEDs

## Dots improve whiteness

Researchers in Singapore have fabricated cool-white LEDs that feature indium-rich InGaIn connected-dot nanostructures rather than phosphors.

This switch can improve the color rendering index (CRI) of white LEDs. “The CRI of our device is in excess of 80 due to a larger color gamut arising from a broader spectrum,”

explained Chua Soo Jin from the Agency for Science, Technology and Research.

White light is produced by combining the output from blue-emitting multiple quantum wells and yellow-emitting quantum dot structures, which are produced in a single MOCVD growth run on sapphire substrates. The yellow-emitting region was formed by deposition of an InGaIn wetting layer, before the trimethylindium flow was increased to form indium-rich nanostructures.

LEDs delivered 40 lm/W at 30 mA. “We expect to achieve at least twice that value with improvements in light extraction,” said Chua. The researchers are aiming to improve their device's light extraction, optimize the growth process and switch to a low-defect-density GaIn template.

**Journal reference**

CB Soh et al. 2008 *Appl. Phys. Lett.* **92** 261909.

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