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Boosting HEMT blocking voltages

Deep UV lasers shine on silicon

Uniting red LEDs with silicon CMOS

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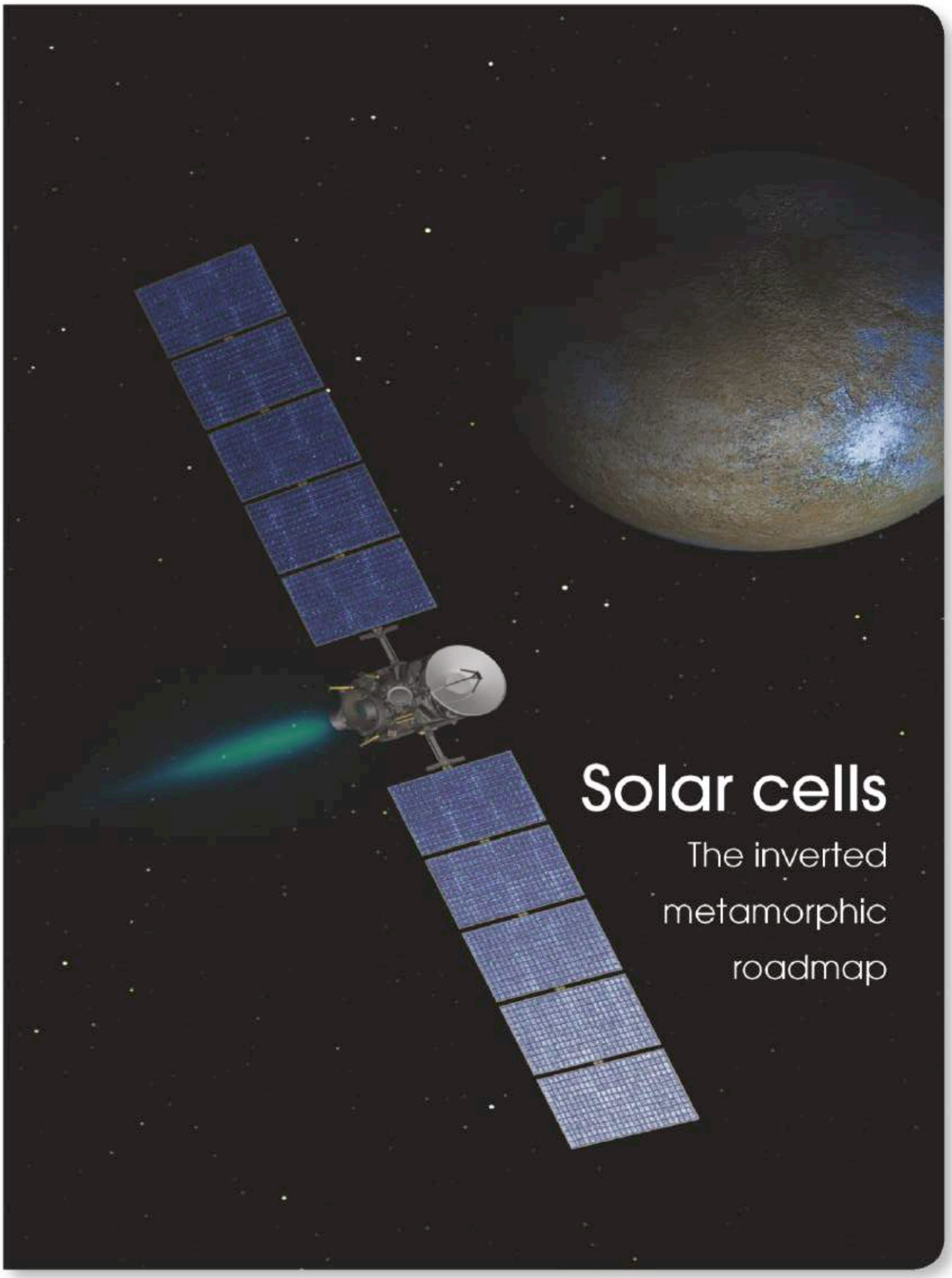

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AN ANGEL BUSINESS COMMUNICATIONS PUBLICATION

editorialview

by Dr Richard Stevenson, Editor

Making GaN even better

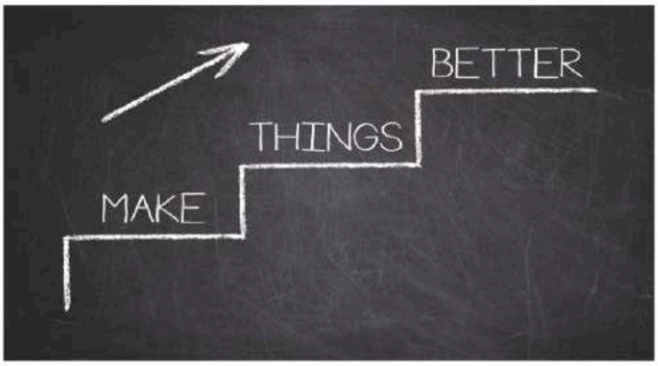
THERE IS A SENSE of smug satisfaction in producing a fully optimised device. No more can be done, and the future of the chip just depends on how much the market values its bang-per-buck.

But probably a more enviable position to be in is to be working with a device that is already winning significant sales, and still has much more to give. That's the case for today's GaN HEMT.

This form of GaN transistor is already shipping in volume, serving the power electronics market at voltages below 1 kV. For higher voltages, the most popular wide bandgap devices are SiC diodes and MOSFETs.

But can GaN devices start to win success at higher voltages? Probably not, argue the makers of SiC devices and market analysts that serve this sector.

However, it is not impossible for the GaN HEMT to excel at higher voltages – the electric fields that this material is capable of withstanding are far higher than those found in working devices. GaN HEMTs should be capable of handling electric field strengths of up to 3 MV/cm, but today's lateral devices that are grown on sapphire, SiC or silicon are limited to one-fifth of this.



To try and improve device performance a team from the University of Fukui, Japan, has grown a batch of GaN HEMTs on a native substrate – it is an approach that slashes the defect density in the transistor. Experiments involved varying the mesa isolation depth (for details see "Pushing the GaN HEMT towards its theoretical limit" on page p. 50), with results showing that the best performance comes from etching right down to the GaN substrate. However, even this device could only withstand one-third of the theoretical maximum electric field. The problem, argues the team, is a leakage current through the substrate.

To put this theory to the test, the researchers investigated substrates with vastly differing levels of iron-doping. Increasing the doping enabled an increase in the breakdown field to two-thirds of the theoretical maximum.

So significant progress is being made – and there is still room for improvement. Although a fully optimised, commercial GaN HEMT is still a distant dream, should it ever reach commercialisation, it is sure to provide stiff competition for SiC diodes and transistors.

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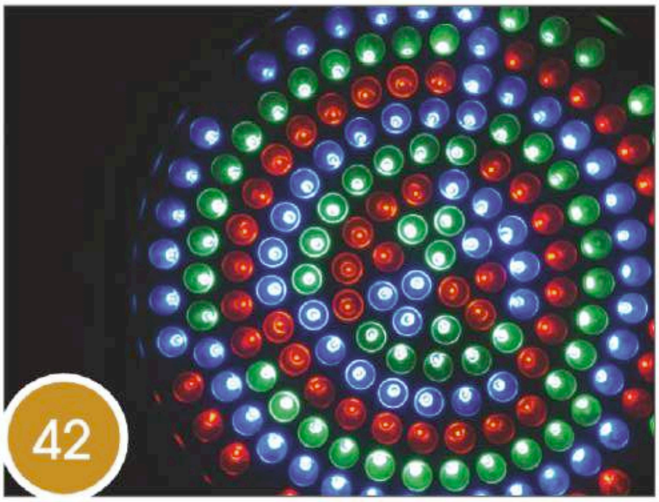


Wolfspeed completes wide bandwidth C-band radar line-up

WOLFSPEED, a supplier of MMICs and GaN-on-SiC HEMTs, has announced its complete line-up of high efficiency, high gain, and wide bandwidth C-Band radar parts with the introduction of the CGHV59070 GaN HEMT.

Designed to operate at 4.5 to 5.9 GHz from a 50 V rail, the new 70 W GaN HEMT is designed as a driver for the highest power C-Band radar device on the market: Wolfspeed's 350 W CGHV59350 GaN HEMT for 5.2 to 5.9 GHz operation, which was released in May of last year.

Delivering 90 W typical POUT at 50 V, in addition to 55 percent drain efficiency at high 14 dB power gain, the internally matched CGHV59070 offers a general purpose broadband solution for a variety of RF and microwave applications, and is especially ideal for use in linear and compressed amplifier circuits in marine radar, weather monitoring, air and maritime vessel traffic control, and port security applications.

"First demonstrated at this year's International Microwave Symposium, the market release of the new 70 W CGHV59070 pre-driver completes Wolfspeed's C-Band radar lineup of pre-drivers, drivers, and output stages, enabling 1 kW, all-GaN SSPAs for C-Band radar applications," said Jim Milligan, RF and microwave director, Wolfspeed.

"This latest introduction also further extends our comprehensive radar product portfolio, which helps designers achieve smaller, lighter, and higher power RF amplifiers that are critical for the development of the next-gen military, aerospace, and commercial radar applications."

Wolfspeed's CGHV59070 can be supplied in a ceramic/metal flange or pill package, and can be shipped individually, or alongside or installed on a test board.

Compared to conventional silicon and GaAs devices, Wolfspeed's GaN-on-SiC RF devices are said to deliver higher breakdown voltage, higher temperature operation, higher efficiency, higher thermal conductivity, higher power density, and wider bandwidths, all of which are critical for achieving higher performing microwave and RF products needed for emerging systems across a variety of applications.

Wolfspeed says that in addition to C-Band radar power amplifiers, these GaN-on-SiC RF devices are also suitable for next-generation broadband, public safety, and ISM (industrial, scientific, and medical) amplifiers; broadcast, satellite, and tactical communications amplifiers; UAV data links; cellular infrastructure; test instrumentation; and two-way private radios.

Cree offers 25 improved LED bulbs

CREE has announced a new portfolio of next generation LED bulbs that are aimed at delivering better light experiences for consumers.

The new range consists of 25 new products, which are said to offer better light quality, better dimming, better lifetime, better warranty and better pricing.

Cree is committed to innovation and unlocking the true potential of LED technology," said Betty Noonan, Cree chief marketing officer and general manager, consumer lighting. "Many new LED products fail to live up to the promise of LED technology; shouldn't you choose a better bulb when it will live in your house for decades? Cree believes it's now more important than ever to give consumers a better choice." "The Home Depot continues to offer the latest innovations in LED lighting, as can be seen with this new portfolio of Cree LED bulbs. Our customers are looking for a high quality LED lighting experience that combines the latest technology with the benefits of energy savings and durability LEDs are known for," said Joey Corona, merchant, The Home Depot.

Notable features in the new bulbs include superior lifetimes, with most projected to last over 22 years and some up to 32 years. Colour rendition is improved, with smoother, quieter dimming to levels as low as 1 percent. Cree's 'Candlelight Dimming' available in the new candelabra bulb, mimics a candle flame with a warmer 1800K colour when dimmed.

According to Cree, the new bulbs meet or surpass the requirements for ENERGY STAR product certification and are covered by a 10 year 100 percent satisfaction guarantee. The new bulb portfolio includes new A-lamps, BR lamps, PAR lamps and Candelabra lamps, as well as a new series of recessed downlight retrofit products.

VLC market to grow at 90 percent CAGR

THE Visible Light Communication (VLC) market was valued around $300 million in 2014 and is expected to grow at least 90 percent CAGR over the forecast period to exceed $10 billion by 2023, according to Global Market Insights, a US market research company. VLC, also referred to as Li-Fi, uses LEDs for data transmission. VLC systems can be unidirectional or bidirectional and can be categorised by data rate and by operating distance (typically up to 10 m and above 10 m).

A major factor contributing to the growth of this market is the opening up a new area of bandwidth (visible light) for communications. Lack of standardisation and complexity in simultaneous data transmit and receipt within the same module, however, could hamper demand over the forecast period, according to Global Market Insights. Applications include connected devices, underwater communication, automobile & transport, retail indoor positioning, hospitality, in-flight infotainment, communications and light-based internet.

IQE reports double digit revenue and profit growth

ADVANCED WAFER COMPANY IQE has announced its unaudited half year results for the six months to 30 June 2016, with double digit growth in revenues, profits and cash generation.

Revenues were up 18 percent reflecting increasing revenues in all markets and adjusted fully diluted EPS was up 62 percent. Increased profitability converted into 176 percent increase in cash generated from operations Operational highlights include continuing diversification of revenues with non-wireless revenues accounting for 31 percent of sales (H1 2015: 24 percent). Accelerating photonics growth showed sales up 45 percent year on year. Wireless performed well with sales up 7 percent, and the company also reported improved sales in Infrared and CMOS++.

Drew Nelson, IQE CEO, said: "IQE's continued strong financial performance reflects the significant progress made in diversifying revenues over the past few years, and its growing portfolio of intellectual property. "A healthy performance in Wireless and IR has been supplemented by accelerated growth in photonics which is up 45 percent. The photonics market is being driven by a diverse range of applications, and is at an early stage in the growth cycle. We expect our photonics business to continue to grow strongly for the foreseeable future. He added: "IQE has developed a broad portfolio of intellectual property for advance semiconductor materials. In addition to the £3.5 million of license income generated in the first half, this IP portfolio is increasingly enabling IQE to differentiate itself, and create a platform for continuing growth across its current and emerging markets.

"IQE has a pipeline of new products and customer qualifications which underpin its growth ambitions, with programs expected to ramp through 2017 and 2018. This includes new photonic applications, wireless base stations, advanced solar, and power switching applications."

ON Semiconductor acquires Fairchild for $2.4 billion

ON Semiconductor has completed its previously announced $2.4 billion cash acquisition of Fairchild Semiconductor International.

"The acquisition of Fairchild is a transformative step in our quest to become the premier supplier of power management and analogue semiconductor solutions for a wide range of applications and end-markets," said Keith Jackson, president and CEO of ON Semiconductor. He added: "Fairchild provides us a platform to aggressively expand our profitability in a highly fragmented industry. With the addition of Fairchild, our industry leading cost structure has further improved in a significant manner and we are now well positioned to generate substantial shareholder value as we integrate operations of the two companies." The two companies have a limited portfolio of compound semiconductors. Fairchild offers a range of high voltage SiC Schottky diodes. ON Semiconductor sells some power GaN Cascode transistors made by Transphorm.

On September 16, 2016, ON Semiconductor received confirmation that clearance related to the completion of its proposed acquisition of Fairchild from the Ministry of Commerce in the People's Republic of China had been obtained and that ON Semiconductor was entitled to close the transactions under PRC law. The acquisition is expected to be accretive on a GAAP EPS basis in the second half of 2017 and immediately accretive on a non-GAAP basis. ON Semiconductor expects to achieve annual cost savings run rate of $160 million by the end of 2017, $200 million by the end of 2018, and $225 million by the end of 2019.

Northrop Grumman gets order for nine GaN G/ATOR systems

SECURITY COMPANY Northrop Grumman has received an award from the US Marine Corps for an additional nine AN/TPS-80 Ground/Air Task-Oriented Radar (G/ATOR) low rate initial production (LRIP) systems.

These nine additional systems and all subsequent G/ATOR systems incorporate GaN technology, which is reportedly providing the Marine Corps with nearly $2 million in life cycle cost savings per system.

Northrop Grumman says that GaN's lower input power needs, higher efficiency and higher output power can substantially increase threat detection and tracking ranges for all four G/ATOR mission capabilities: air surveillance, weapon cueing, counter-fire target acquisition and air traffic control.

Northrop Grumman is already on contract to provide six G/ATOR LRIP systems, the first of which will be delivered in February 2017. "There are no other GaN ground-based active electronically scanned array (AESA) radars in production today," said Roshan Roeder, director, mission solutions, Northrop Grumman.

"G/ATOR is the first DoD ground-based AESA system to incorporate GaN in a production program. We proposed this technology as a cost savings measure for the government and funded risk reduction internally to ensure a seamless insertion into the G/ATOR system. We are continuing to look at future technology insertions to continue providing the best capability out there to our warfighters at an affordable cost."

Consumer chargers to represent 30 percent of GaN power market in 2022

IN ITS RECENTLY released market report Applications & Markets for GaN in Power Electronics, market analysts Point the Power have identified the growing role of GaN devices in consumer power supplies, with laptop and electronic device chargers in the first row. By 2022, consumer chargers, it says, will represent 30 percent of GaN power device market "Consumer systems don't require the same lifetime and warranty as industrial systems," said Alex Avron, principal market analyst at Point the Power.

"Industry or energy segments like PV inverters need a minimum expected lifetime of ten, sometimes 15 years, when the lifetime of a laptop charger is five years at most."

Avron added: "It's a perfect playground for innovation and new product releases. Many start-ups have taken advantage of this, such as California-based companies FinSix and Avogy or Canada-based Appulse Power."

Laptop and smartphone charger markets are are a good test ground for wide band gap devices and new topologies because of their comparatively short lifetime needs, size reduction as a main driver, and lower price sensitivity. According to Point the Power, GaN is and will stay in direct competition with Super Junction MOSFET. They are already the most used devices for consumer power supplies of all kinds – with a total market of more than $800 million this year.

GaN will allow new applications to emerge for power converters, just as IGBTs and MOSFETs have done in the past; neither replaced Bipolar Junction transistors, but in fact, facilitated new applications.

"Each time a new device has arrived on the market, it did not eat its competing devices' market share, but rather enlarged the overall market size through new applications," added Avron.

Telcodium and Transphorm introduce first GaN-based redundant power supplies

TELCODIUM, a power supply design company, in collaboration with Transphorm, a GaN device maker, has released what is claimed to be the first redundant power supplies using GaN FETs. Telcodium's AC Series replaces a typical three-module power supply architecture (two power supply bricks and one intermediate bus converter (IBC)) with a single power module with redundant AC feeds. Telcodium's power module operates at 94 percent True System Efficiency (TSE) or higher-reducing average energy loss by 13 percent or more. To achieve the same TSE with the typical three-module power supply, the bricks and IBC would each need to yield a 97 percent efficiency-which exceeds the 80Plus Titanium specification and has yet to be demonstrated by any power supply manufacturer. Further, the new lightweight (1.3kg) module is at 260 x 100 x 40 mm, 30 percent smaller than the above mentioned two bricks and eliminates the standalone IBC-freeing considerable, critical space inside a host system. This design pairs patented front-end circuitry with a JEDEC-qualified 650 V GaN FET, available from Transphorm. The resulting AC Series enablesdatacentre, server and telecommunication manufacturers to develop smaller, high-performing systems that can virtually eliminate power supply-related failures.

Seoul announces 220 lm/W WICOP LED

SEOUL SEMICONDUCTOR has developed a WICOP package-less LED product offering 220 lm/W, claimed to be 25 percent brighter than conventional LEDs.
According to Seoul, the new product proves that an LED made of only a chip and phosphor (there is no other packaging such as frames and gold wires) can achieve higher luminous efficiency than packaged, conventional high power devices. The company says that the WICOP LED is also over 17 percent more luminously efficient than CSP (Chip Scale Package), which is similar in appearance.

Seoul Semiconductor has supplied WICOP to both IT and automobile manufacturers since 2012. In 2015, it launched two models of WICOP lighting products. The LED, which it is now in mass production, is expected to be widely used lighting, automobile, and TV applications.

Ki-bum Nam, CTO of Seoul Semiconductor, said: "The WICOP products which have been independently developed by Seoul Semiconductor would render the currently increasing investment in the packaging industry unnecessary, and will become the standard for next generation LEDs as it is an innovative product that reflects a new wind of change in the LED market.".

He added: "We will continue to develop various solutions related to WICOP for customers in addition to developing new WICOP products with a luminous efficiency of over 220 lm/W by 2020, thereby opening the door to a new LED period." Strategies Unlimited, a market survey company, showed that in 2015, the importance of super high power LED products with a high luminous efficiency such as WICOP, took up 20 percent of the total LED market, and by 2020, it is expected to reach more than 30 percent.

II-VI unveils wavelength-stabilised 980 nm laser

II-VI, a provider of pump laser modules and micro-optics for transceiver-embedded optical amplifiers, has introduced a new uncooled 980 nm pump laser module that features patent-pending in-package wavelength stabilisation within an 8-pin mini-DIL package.

High bit rate transceivers operating at 100 Gb/s and higher continue to be designed into smaller packages to meet the needs of telecom carriers and cloud service providers for equipment with greater bandwidth to form-factor density. II-VI's new module eliminates the need for an external fibre Bragg grating in the fibre pigtail assembly. Instead, it features an 80μ low-bend loss, small-bend radius and polarisation-maintaining fibre pigtail that enables optical amplification within small transceiver packages.

The new 980 nm pump laser modules house II-VI's G08 semiconductor lasers and are built on II-VI's OC-2 packaging platform with over two million modules shipped to date.

"With our existing portfolio of ultra-compact optical components, we are the leader in pump lasers and micro-optics for transceiver-embedded optical amplifiers for the fast growing 100 Gb/s CFP2-ACO market" said Sanjai Parthasarathi, VP, product marketing and strategy, Optical Communications Group.

VisIC at ECCE2016

VisIC displayed a new family of 1200 V GaN devices with integral ISO-driver at the IEEE Energy Conversion Congress and Exposition (ECCE2016). Designed for use as power converters for motor drives, three phase power supplies and other applications requiring current switching up to 50 A, the new 1200 V devices are high-voltage supplements to VisIC's existing ALL Switch line-up of 650 V GaN devices. Typical on resistance $R_{DS(on)}$ ratings are down to 0.04Ω, according to the company.

"These low loss GaN devices are setting new industry standards for performance and are based on the VisIC ALL Switch second generation HEMT technology, which combines high levels of cell integration with optimised cell design," said Gregory Bunin, CTO, VisIC. "This technology supports reduced gate charge and capacitances without losing the benefits of low $R_{DS(ON)}$, with our GaNs offering an ultra-low maximum switching energy down to 140 µJ."
Switching losses are said to be three to five times lower compared to SIC MOSFETs counterparts.

US researchers use SiC to boost vehicle range

RESEARCHERS at North Carolina State University in the US have developed an inverter based on SiC technology that they believe could greatly improve the fuel-efficiency and range of hybrid and electric vehicles.

"Our SiC prototype inverter can transfer 99 percent of energy to the motor, which is about two percent higher than the best silicon-based inverters under normal conditions," says Iqbal Husain, ABB Distinguished professor of Electrical and Computer Engineering at NC State and director of the FREEDM Centre.

"Equally important, the SiC inverters can be smaller and lighter than their silicon counterparts, further improving the range of electric vehicles," says Husain, who co-authored two papers related to the work. "And new advances we've made in inverter components should allow us to make the inverters even smaller still." Range is an important issue because so-called 'range anxiety' is a major factor limiting public acceptance of electric vehicles. People are afraid they won't be able to travel very far or that they'll get stuck on the side of the road.

The new SiC-based inverter is able to convey 12.1 kilowatts of power per litre (kW/L) – close to the U.S. Department of Energy's goal of developing inverters that can achieve 13.4 kW/L by 2020. By way of comparison, a 2010 electric vehicle could achieve only 4.1 kW/L.

"Conventional, silicon-based inverters have likely improved since 2010, but they're still nowhere near 12.1 kW/L," Husain says. "But, frankly, we are pretty sure that we can improve further on the energy density that we've shown with this prototype," Husain says.

"We predict that we'll be able to make an air-cooled inverter up to 35 kW using the new module, for use in motorcycles, hybrid vehicles and scooters," Husain says. "And it will boost energy density even when used with liquid cooling systems in more powerful vehicles." The current SiC inverter prototype was designed to go up to 55 kW – the sort of power you'd see in a hybrid vehicle. The researchers are now in the process of scaling it up to 100 kW – akin to what you'd see in a fully electric vehicle – using off-the-shelf components. And they're also in the process of developing inverters that make use of the new, ultra-high density SiC power component that they developed on-site.

A paper on the new inverter, 'Design Methodology for a Planarized High Power Density EV/HEV Traction Drive using SiC Power Modules', was presented at the IEEE Energy Conversion Congress and Exposition (ECCE) in Milwaukee. Lead author of the paper is Dhrubo Rahman, a Ph.D. student at NC State. The paper was co-authored by Adam Morgan, Yang Xu and Rui Gao, who are Ph.D. students at NC State; Wensong Yu and Douglas Hopkins, research professors in NC State's Department of Electrical and Computer Engineering; and Husain.

IHS Markit releases ranking of top LED suppliers

Research company IHS Markit has released its annual revenue-share ranking of the top LED suppliers in backlighting, automotive, lighting and other applications.

According to the 2016 edition of the IHS Markit Packaged LED Report, Nichia led in both lighting and mobile applications for 2015, with 12.9 percent share of the total packaged LED market. Nichia was followed by Osram and Lumileds with a combined share of 14.7 percent.

"It's not a surprise that Nichia led in more than one application," said Alice Tao, senior analyst, LEDs and lighting for IHS Markit. "In 2015, Nichia overtook Cree, which led the lighting category in 2014. Nichia was also very strong in mobile phone LEDs, since the company is a major supplier for Apple's iPhone." Samsung was the leading supplier in backlighting, which includes LEDs used in TVs, monitors, notebook PCs and tablet PCs. Nichia followed in second position and LG Innotek ranked third.

Osram has been the leading supplier of automotive LEDs for many years. Its market share was 35 percent in 2015 for LEDs used in the total automotive market and 40 percent for those used in the automotive exterior market. It also led in the 'other' application, which includes LEDs used for industrial, medical, security, projection, signage and off-specification applications.

Gallium and germanium production could be seven times higher

THE GLOBAL SUPPLY potential of the high-tech metals gallium and germanium is much greater than actual annual production levels.

This is the main conclusion from Max Frenzel's work. Frenzel, a postgraduate student at the Helmholtz Institute Freiberg for Resource Technology (HIF), which closely cooperates with the TU Bergakademie Freiberg, is one of two recipients of the Bernd Rendel Prize for Geosciences 2016.

The prize, awarded by the German Research Foundation (DFG), was presented on 28 September at the annual conference of the German Geological Society (DGGV) in Innsbruck.
The young scientist (27), born in Löbau/Saxony, impressed the DFG Jury not only with his diverse research background, but also with his international experience. Before he came to the HIF he studied Mineral Science and Geological Sciences at the University of Cambridge (2008 to 2012) obtaining first class honours degrees in both subjects.

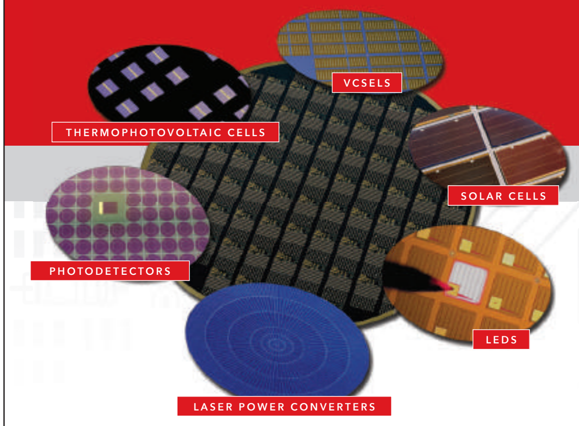
"In Freiberg, considerable experience is available concerning both mineral economics as well as the formation of mineral deposits; this was my reason for coming here in 2012", said Frenzel. Since then he has worked on the global availability of critical metals and their economic exploitation.
Gallium is essential for the production of high-performance chips used in smartphones and tablets, while germanium is required, for instance, for the production of fibre optic cables.

According to Frenzel's estimate, based on comprehensive calculations, the annual global production of gallium and germanium could be at least seven times higher than it is at present. He said: "At least 2,900 tonnes of gallium could be produced every year, while current (2014) production is 440 tonnes. For germanium, current (2014) production is 165 tonnes, while it could be at least 1,200 tonnes."

He explained, "Previously, the exact quantities of high-tech metals available to industry was not known"; giving this as the motivation for his research. Due to their low concentrations in primary ores, raw materials such as gallium and germanium are predominantly won as by-products from the mining of other quantitatively more important main products; whereas gallium is found in aluminium and zinc ores, germanium is obtained during the production of zinc and coal. Consequently, the availability of both of these elements is mainly constrained by geological factors. However, technological and economic factors also play their part.

At present, geoscientists assume that the availability of high-tech metals in the ground is high enough to cover demand. "None of them can be seen as critical in geological terms," said Jens Gutzmer, a mineral deposits expert at the TU Bergakademie Freiberg and director at the Helmholtz Institute Freiberg for Resource Technology. Gutzmer has advised and mentored Max Frenzel during his post-graduate studies, in which Frenzel developed the new raw material estimation method as part of his dissertation. Gallium and germanium are the first two high-tech metals whose availability Frenzel has examined using his new method. Very probably, the available amounts of both these metals will be sufficient to cover future demand. "However, the new estimation method might reveal potential supply risks for other metals", said Gutzmer.

To be able to forecast the global availability of mineral raw materials with greater accuracy, Frenzel determines the probable range of the supply potentials of a particular by-product, taking into account the effects of different recovery processes for the metals as well as various other factors. He estimates that, with a probability of 95 percent, the supply potential of gallium lies between 2,900 and 10,400 tonnes per annum, and that of germanium between 1,200 and 4,300 tonnes.



Plessey readies for latest LED market explosion

With horticultural LED lighting pioneer, PhytoLux, in tow, Plessey is poised to seize share of blossoming LED markets, reports Rebecca Pool

EARLIER THIS YEAR, Plessey signed a global exclusive license agreement to manufacture and sell horticultural lighting products from UK-based PhytoLux.

As part of the deal, the UK-based LED manufacturer took on all operational, technical and commercial activities of the horticultural lighting firm, transferring staff from the PhytoLux headquarters in Leatherhead to its Plymouth LED facility.

With a hefty range of LED grow-lights in tow, Plessey will now integrate its GaN-on-silicon LEDs to these lighting units ready for delivery to horticultural markets across the world.

As Plessey chief executive, Michael LeGoff said at the time: "Our MAGIC technology is perfect for these direct lighting applications where we have tight wavelength control... Our next-generation LEDs with electronics and optics will add to the intrinsic advantages of the PhytoLux products."

Plessey's move comes as the horticultural LED lighting market prepares for colossal growth. A recent report from WinterGreen Research, US, put the market value of LED grow-light modules at $395 million in 2014, forecasting this figure to mushroom to $1.8 billion come 2021.

Growth is expected to primarily come from commercial greenhouse and factory growers switching from sodium lights to LEDs in a bid to reduce energy consumption and running costs or adopting lighting to expand the growing season.

But at the same time, agricultural research organisations and vertical farming pioneers worldwide are also set to adopt the technology. And given this market potential, Steve Edwards, ex-managing director of PhytoLux and now product director of PhytoLux lighting systems at Plessey is excited.

"We actually believe that these [WinterGreen] figures are a little conservative," he highlights.

"If you look at the white LED market today, you'll struggle to find a new build that doesn't specify LED lighting while most domestic homes have transferred to LEDs," he adds. "It's inevitable that the migration to LEDs in horticulture will come."

So given the market potential, what are Plessey's plans for its PhytoLux products right now? According to Edwards, the company has spent the last few months stripping down units and looking for ways to improve efficiency, achieving gains as high as 50 percent.

"The key benefits that Plessey's GaN-on-silicon LEDs bring are the thermal characteristics of the LEDs as well as the ability to incorporate chip-scale optics, that is, the beam-forming technology," says Edwards. "So as well as better efficiency we've also ended up with a much smaller heat-sink, which means we can make the entire unit smaller."

As Edwards points out, lighter and smaller units mean less weight and fewer shadows on the glasshouse roof. And as he adds: "Unit cost will come down and this cost-saving will be passed on to the end user."

The PhytoLux LED growth lights are configured to provide a broad spectrum of light at specific wavelengths within 460 nm to 660 nm, to optimise

photosynthesis of a particular crop. As such, a lighting unit may contain more than 100 LEDs, which emit at red and blue wavelengths.

For blue LEDs, Plessey will use its own LEDs, manufactured at its Plymouth facility. But according to Edwards, red LEDs have been sourced from the likes of Osram and Cree – and this will continue, at least for now.

And while horticultural lighting units have been manufactured in the Far East, Plessey is now looking to transfer production to Europe, be it at Plymouth or elsewhere.

"We have a number of potential partners that we are looking to engage with on this," says Edwards. "However, we are also looking to bring some manufacturing of the unit into Plymouth itself, whether that's final assembly or sub-assembly work."

"Clearly the license agreement offers Plessey an opportunity to form some pretty good partnerships with new companies here," he adds.

Brave new markets

Looking to the future, Edwards believes commercial growers are ready to adopt the LEDs. "I've sensed a change in perception in the market place, from questioning whether the LED can deliver, to how do we make this work for our site," he claims. "We're going to see momentum build over the next five years and by then you will be hard-pressed to see sodium lights at a site."

At the same time, the product director is confident that Plessey will take a significant slice of this rapidly blossoming market. While Philips Lighting has led horticultural markets from as early as 2003, having already poured huge sums of money into this sector, PhytoLux, as a company, has dominated UK markets. And now as part of Plessey, PhytoLux products will be targeted at the rest of Europe and beyond.

"Philips will clearly dominate the market going forward, but this is a huge market and the opportunities are vast," says Edwards. "There's plenty of scope for us in this market, and if we get a five percent share in the market [by 2021] we would be happy; ten percent and we'd be delighted."

Horticultural LED lighting markets are growing; Plessey is ready.

SOLAR CELLS:

TAKING EFFICIENCY TO NEW HIGHS

An inverted metamorphic architecture offers a route to making lightweight, incredibly efficient, cost-competitive cells for space

BY PAUL SHARPS, DANIEL DERKACS AND ALEX HAAS FROM SOLAERO TECHNOLOGIES

ALTHOUGH III-V multi-junction cells have been deployed on earth to generate electricity, they are delivering their greatest commercial success in space. Out there they are highly valued for their high efficiency and robustness, particularly to particle radiation. What's more, they offer tremendous economic value at the system level by reducing satellite launch and operating costs. Together, these attributes make III-V cells ideal for supporting satellite missions requiring either a high specific power (W/kg) or a high power density (W/m^2).

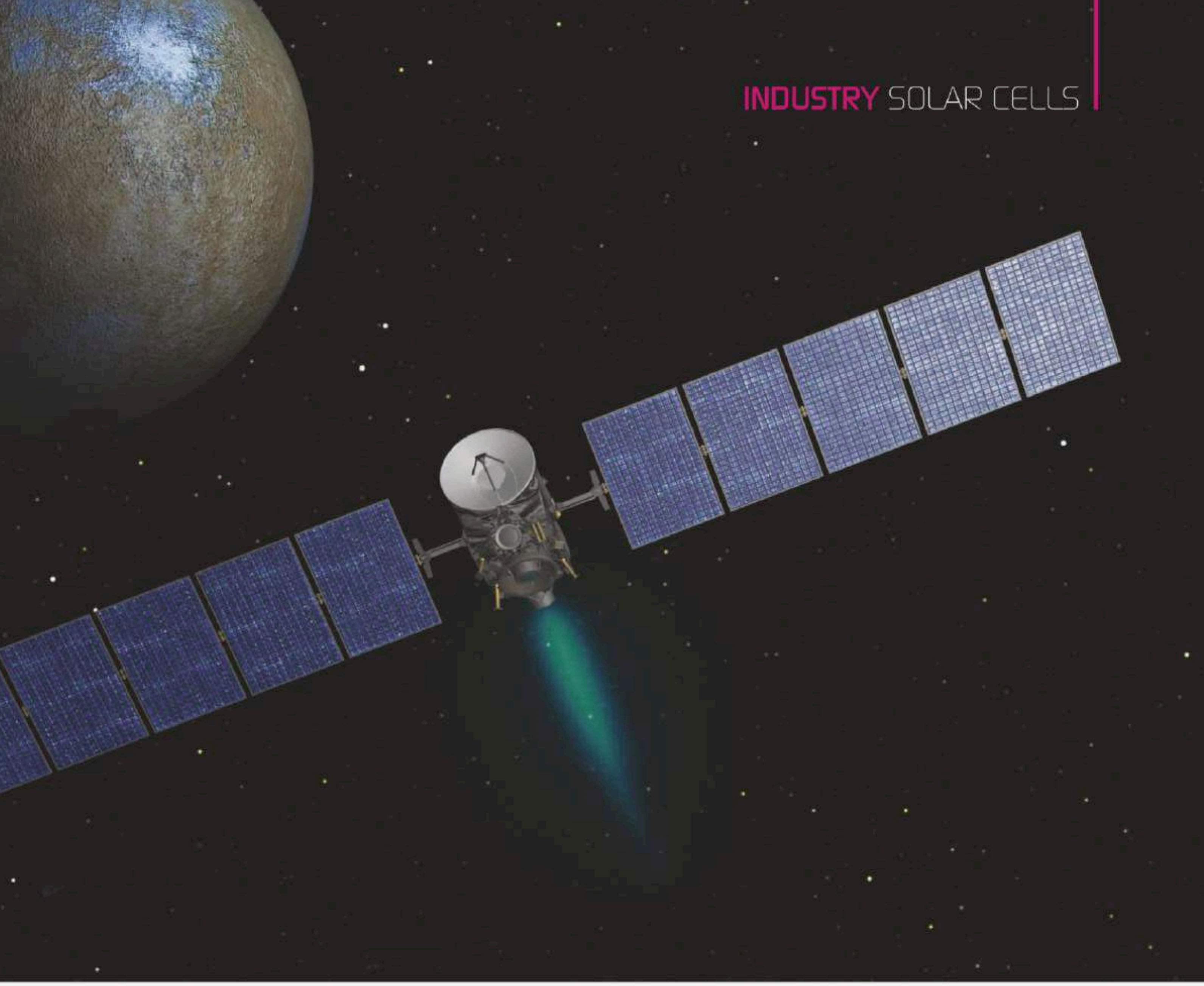
At SolAero Technologies of Albuquerque, NM – which took over Emcore's solar business in late 2014, while retaining all its expertise and capability – we have a great track record in improving the efficiency of our III-V multi-junction cells. Between 1998 and 2008 the measured efficiency of multi-junction cells under conditions replicating those in space increased from 23 percent to 29.5 percent (for these measurements, radiation was incident under no concentration (1 sun) with a spectrum mimicking that of the sun's before it passes through the earth's atmosphere (AM0)).

These efficiency figures might suggest that our focus is on the production of a handful of cells with incredibly high efficiencies. But that is certainly not the case: we pride ourselves on the production of vast numbers of highly efficient cells. Over the past 18 years we have manufactured more than 3 million large-area space cells, defined as having an area of at least 26 cm^2. The knowledge gained from this has helped us to produce cells that have an initial efficiency of 29.5 percent and deliver 85 percent of this value at the end of a 15-year geosynchronous mission. Even now, we are not resting on our laurels, but pursuing a roadmap that involves the development of far more efficient devices that incorporate metamorphic structures and more absorbing layers.

Solar designs

Manufacture of our solar cells is based on multi-junction designs, rather than single-junction variants, because this leads to better spectral utilization and reduced thermalization losses. Multi-terminal and mechanically stacked architectures are options for the fabrication of these multi-junction devices, but we prefer two terminal devices, because this trims costs associated with cell fabrication and system integration.

In a two-terminal device, the cells are connected by lattice-matched Zener tunnel diodes, which reverse



the polarity between each of the subcells. This allows multiple *n*-on-*p* subcells to be monolithically stacked on top of each other. The voltage produced by the multi-junction device is equal to the sum of those produced by each subcell, and optimisation requires the design of each *n*-on-*p* junction to produce the highest voltage possible without reducing the photo-generated current.

During the last two decades, the primary source of satellite power has been the triple-junction device formed from lattice-matched layers of GaInP, InGaAs and germanium (see Figure 1). The foundation for this is a *p*-type germanium substrate, on which GaInP and InGaAs layers are grown by MOCVD. During growth, the group V element from the nucleation layer diffuses into *p*-type germanium, converting a thin layer on the surface to *n*-type. This creates a diffused *n*-on-*p* junction. To provide precise lattice matching to the germanium substrate, a small amount of indium is added to the middle InGaAs junction.

With this device, the internal quantum efficiency of all sub-cells approaches 100 percent (see Figure 2). Consequently, there is little room left for improvement in the current collection in this device.

Where gains can be made is in photocurrent. In these monolithic, two-terminal multi-junction cells the subcells are connected in series, so the same current must flow through all of them. This means that it is possible for one or more subcell to fail to operate at its maximum power point. For example, in a device with a GaInP/InGaAs/germanium architecture and bandgaps of 1.88 eV/1.40eV/0.67 eV, the germanium subcell is capable of generating twice as much current as it does in this triple-junction stack (see Figure 3). Due to this, the multi-junction cell will deliver an inferior performance to that of a cell with all junctions operating at individual maximum power points.

Improvements could result from increasing the bandgap of the bottom junction so that it adds to the operating voltage while still generating enough current to avoid limiting the overall device. Alternatively, gains could be made by lowering the bandgap of the top two subcells to increase cell efficiency through superior spectral utilization and improved current matching at each subcell's maximum power point.

With either of these approaches, or by adding to the number of junctions, it is possible to improve upon the AM0 efficiency limit of approximately 30 percent for the GaInP/InGaAs/germanium device. It is worth noting, however, that the obvious approach of adding more junctions suffers from a law of diminishing returns. So, assuming that the cost of every added subcell is the same, there is a point at which the increased efficiency comes at a price that the market will not bear.

Attempts to increase solar efficiency tend to involve either employing mechanical stacks, turning to novel materials, or creating metamorphic structures. Here we will we briefly describe the first two, before discussing in more detail the third option, which is the one that we pursue. Note that there are many III-V semiconductor materials that can be combined into multi-junction devices (see Figure 4), and we limit ourselves to monolithic devices, because, as previously stated, this trims cell fabrication and integration costs.

Pros and cons of stacking…

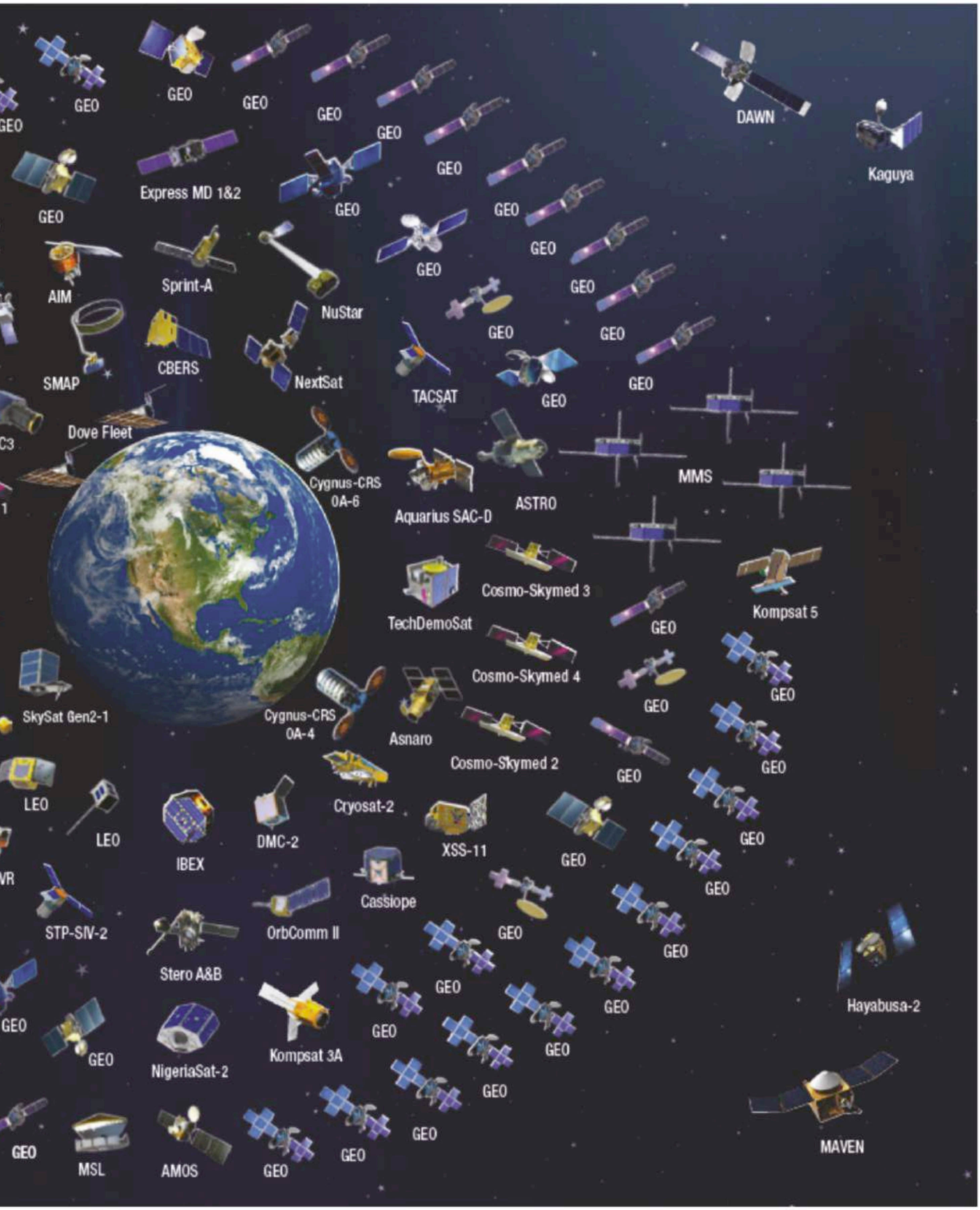
Mechanical stacking of cells to improve performance has made the headlines, because this class of device holds the efficiency record for devices operating under concentrated illumination (sunlight is focused by a factor of several hundred on to the cell). The great attraction of mechanical stacking is that it removes the bandgap/lattice constant constraint, opening the door to designs that combine a wide range of bandgaps with different lattice constants.

One example of a mechanically stacked cell is the pairing of a GaInP/GaAs dual junction grown on a GaAs substrate with a GaInAsP/GaInAs dual junction grown on InP. The resulting device, with bandgaps of 1.89 eV, 1.41 eV, 1.00 eV, and 0.73 eV, is close to ideal for the maximum conversion efficiency for the space spectrum.

This device is created by wafer bonding, a process that forms a mechanically robust, optically transparent, electrically conductive interface between the component multi-junction cells. The challenge is cost. This approach requires a separate growth for each of the component multi-junctions, one of which involves a very expensive InP substrate.

Costs could fall by turning to epitaxial lift-off, but this technology is still to be demonstrated to the degree required to significantly lower the substrate growth costs. Another drawback is that to ensure that the surfaces are adequately flat for wafer bonding, they must be polished with a chemical-mechanical process. If particles or growth imperfections are present, they prevent wafer bonding in local areas. Due to all these issues, despite its high efficiencies, mechanical stacking is simply too expensive to be considered for space applications.

Right: SolAero's Satellite Flight Heritage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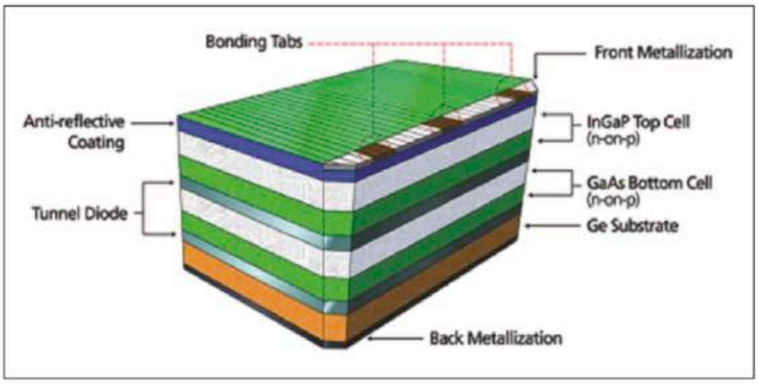

Figure 1. The GaInP/InGaAs/germanium lattice-matched, triple-junction cell is monolithic device that is grown on a germanium substrate.

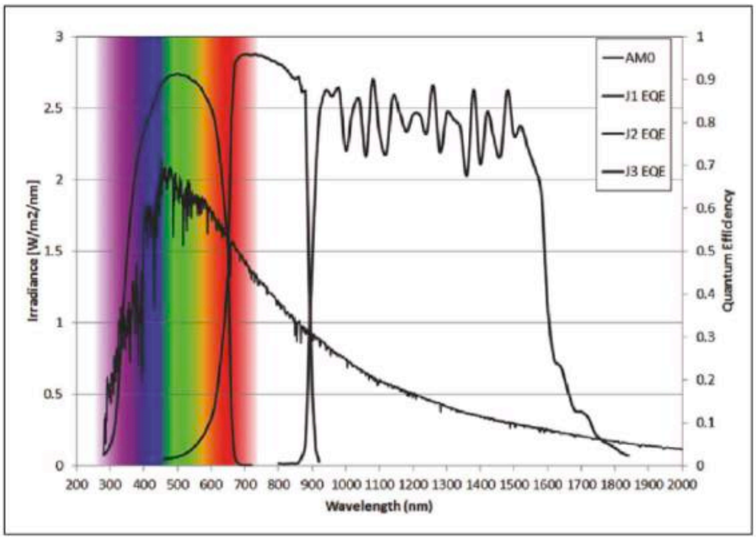

Figure 2. The internal quantum efficiency (IQE) of the Zener tunnel-junction cell overlaid on the space AM0 spectrum.

… and novel materials

Novel materials are attractive, because they provide the opportunity to replace the germanium subcell with one of a higher bandgap, or to insert a 1.00 eV subcell between the germanium and InGaAs subcells to create a four-junction device. With the latter approach, a 1.0 eV subcell is grown directly on the germanium substrate prior to the growth of GaInP and InGaAs subcells.

The two most popular candidates for a 1 eV cell are the dilute nitride InGaAsN(Sb) and the ternary SiGeSn. Both materials have the virtues of an independent lattice constant and bandgap (within ranges). This allows a tuning of bandgap while retaining lattice matching to GaAs or germanium.

A four-junction cell based on InGaP, GaAs, InGaAsN and germanium was first proposed in 1997 by a group at Sandia National Labs in Albuquerque, NM. However, due to the poor material quality of the MOCVD-grown InGaAsN junction, this cell never realised its expected performance. In addition, the device was expensive to grow. Progress has been made since then, by growing the InGaAsNSb layers by MBE, and incorporating them into triple-junction GaInP/GaAs/InGaAsNSb cells. These devices have produced an efficiency in excess of 30 percent under 1 sun, AM0 conditions, but the MBE growth process is expensive, partly because of the low throughput.

Development of the alternative, SiGeSn, is still in its infancy. Junctions made from this ternary are yet to produce voltages consistent with their bandgap. Another concern is that this material is meta-stable, and requires a growth temperature of less than 400°C. Further fundamental studies are needed before this ternary can be incorporated in a multi-junction device.

Mighty metamorphics

We advocate a metamorphic approach, which includes upright and inverted structures. If upright metamorphic multi-junction structures are produced, the lowest bandgap subcell should be grown first, followed by higher bandgap subcells (see Figure 5(a)). With this architecture, the bottom junction is typically made from germanium, and above this are the metamorphic grading layers and finally the metamorphic subcells.

For this class of metamorphic cell, which tends to feature GaInAs-based metamorphic subcells, compositions of the III-Vs follow the GaAs-InAs tie line. The indium content is gradually added to the step grades to reach the appropriate lattice constant.

A major downside of this approach is that all of the epitaxial layers are lattice mismatched with respect to the substrate, and consequently contain threading dislocations. This is a major drawback, because the threading dislocations act as carrier recombination sites that degrade solar cell performance through increased dark current and reduced photo-generated carrier collection. Since all of the epitaxial layers are metamorphic in these upright multi-junction structures, all tend to suffer from non-optimal performance for the particular bandgap.

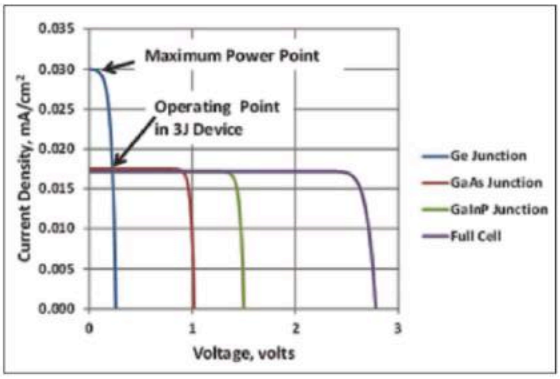

Figure 3. Individual and aggregate current-voltage curves for the GaInP/InGaAs/germanium solar cell. The germanium junction operates at the current-matched point in the complete triple-junction device, rather than at its maximum power point.

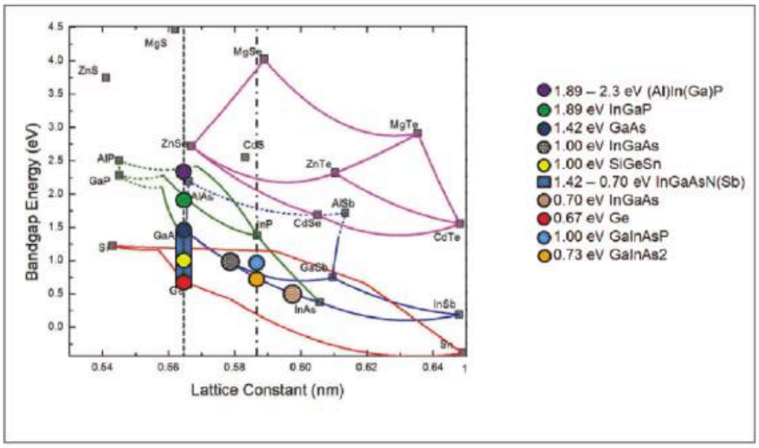

Figure 4: Bandgap and lattice constant for a number of semiconductor materials, with the III-V materials of particular interest for multi-junction cells noted.

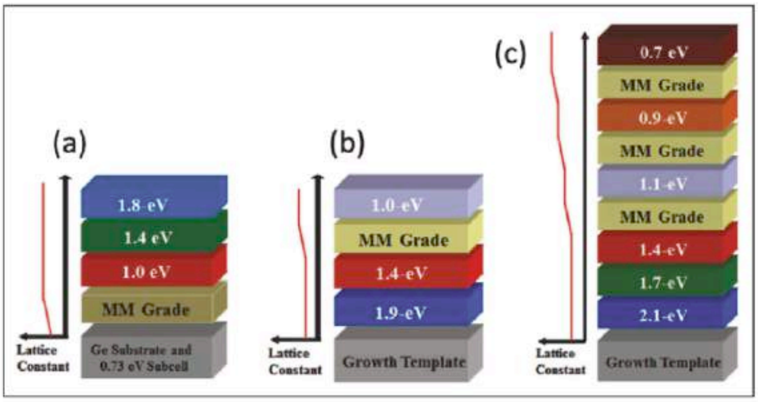

Figure 5: (a) The upright metamorphic four-junction cell has a performance that is compromised by threading dislocations through the entire structure. With inverted metamorphic cells with three (b) or six (c) junctions, only part of the structure suffers from threading dislocations.

Defects are minimised, and cell performance optimized, by using the other class of metamorphic – the inverted metamorphic multi-junction. In this case, devices are grown 'upside down'. This means that the high bandgap junctions are grown first, lattice matched to the substrate, followed by lower bandgap metamorphic 'boost' junctions.

An example of this – a triple-junction inverted metamorphic – is shown in Figure 5(b). It features two lattice-matched subcells and one metamorphic subcell. The initial high bandgap subcells, such as GaInP, GaAs, InGaAlP and AlInGaAs, are grown lattice matched to the germanium growth substrate, and they generate the majority of the power from the cell. The metamorphic subcells, meanwhile, produce a smaller proportion of the generated power than they would in an upright metamorphic multi-junction structure.

To produce this class of cell we attach the structure to a 'processing handle', such as silicon or kapton, before removing the growth substrate. Epitaxial layers are between 10 μm and 15 μm thick, depending on the number of subcells in the device, and the processing handle can be temporary, necessary only for processing; or it can be permanent, providing an integral part of the final device.

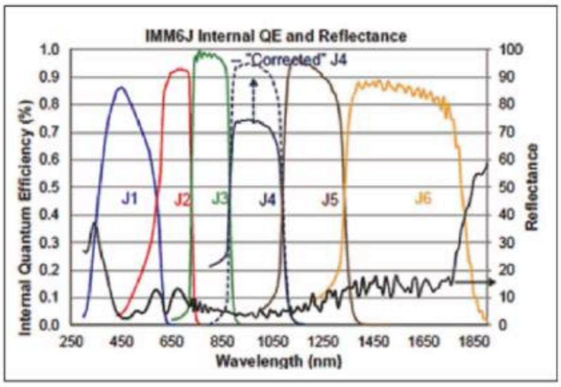

Figure 6: Internal quantum efficiency and reflectance for the inverted metamorphic, six-junction cell.

There is great freedom with this approach as devices can be flexible or rigid, and structures can be packaged for the end application. Selection of an appropriate permanent handle enables a very light cell, and ultimately a very high specific power (W/kg). This approach is ideal for epitaxial lift-off, where the epitaxial layers are removed from the substrate along a laterally etched release layer.

We have demonstrated inverted metamorphic cells with three, four and even six junctions (see Figure 5(c) for a representation of a six-junction cell, and Figure 6 for internal quantum efficiency and reflectance measurements from an actual six-junction cell). Using such a high number of junctions is cost competitive with current, commercially available space multi-junction cells, because production employs existing MOCVD growth technology and known fabrication practices.

We have also undertaken a comparison between modelled and verified efficiencies (see Table 1, where the numbers in red are the NASA verified measurements, and the black numbers are the results of our model). Note that the performance modelling is based on a 'practical' approach that considers the likes of optical reflectance and series resistance. Based on these findings, we have a path for increasing efficiency beyond 30 percent to nearly 38 percent. Given this promise, the inverted metamorphic cell is expected to be the core technology in the next generation of commercially available cells for space applications.

Device structure	Number of Metamorphic Junctions	Efficiency	Voc, volts	Jsc, mA/cm^2	FF
Three Junction	1	32.8	3.00	17.0	86.8
		32.4	3.02	16.9	85.6
Four Junction	2	34.8	3.28	16.6	86.5
		33.9	3.26	16.9	83.3
Six Junction	3	37.8	5.20	11.3	87.2

Table 1. Comparison between modelled space inverted metamorphic cell (black) performance and NASA verified (red) performance, for the 1 sun, AM0 spectrum.

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- **Eric Higham: Strategy Analytics**
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- **Daniel Green: Defence Advanced Research Projects Agency – US Agency of Defence**
  Advancing technology with heterogeneous integration

SPEAKERS

- **Soon-Fatt Yoon: Nanyang Technological University**
  Heterogeneous integration of III-V devices on silicon with ultra-thin buffer utilising interfacial misfit dislocations
- **Jesús A Del Alamo: Microsystems Technology Laboratories**
  Refining the III-V finFET
- **Nadine Collaert: imec**
  Looking for the ultimate low-power switch: the promise of tunnel FETs
- **Jean Fompeyrine: IBM**
  Advancing SRAM by adding III-Vs (COMPOSE project)
- **Shengkai Wang: Institute of Microelectronics of Chinese Academy of Sciences**
  III-Vs and germanium for future logic
- **Arnaud Furnemont: imec**
  3D NAND scaling: an opportunity for alternative channel material

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Can the best devices stem from the ultra-wide bandgap of gallium oxide? Or will they emerge from foundries processing GaN and SiC on silicon?

KEYNOTE

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  Unleashing the potential of gallium oxide

SPEAKERS

- **Tamara Baksht: VisIC Technologies**
  High efficiency at high power density: realization of GaN's promise for power electronics
- **Frédéric Dupont: Exagan**
  Driving the GaN power device roadmap for large scale adoption
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  Current topics in electronic devices based on wide band-gap semiconductors for power applications and energy efficiency
- **Sujit Banerjee: Monolith Semiconductor**
  Slashing chip costs with SiC-on-silicon
- **Anthony Sagneri: FINsix Corporation**
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- **EpiGaN**
  Topic to be announced
- **John Palmour: Wolfspeed**
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- **Speaker: Yole Développement**
  Topic to be announced

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- **Zach Griffith: Teledyne Technologies**
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- **Rocco Giofrè: University of Rome Tor Vergata**
  GaN Doherty amplifiers for backhaul radio links
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- **Oleg Shchekin: Philips Lumileds Lighting Co**
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- **Bedwyr Humphreys: Seren Photonics**
  Overcoming the green gap using semipolar gallium nitride

THE ATTRACTIVE ATTRIBUTES OF ATOMIC LAYER DEPOSITION

Ammonia-free atomic layer deposition can yield tremendously smooth layers of GaN with incredibly high levels of uniformity.

BY RICHARD STEVENSON

THE USE of MOCVD to grow GaN films lies at the heart of the production of numerous commercial devices. This growth technology is used to form the LEDs that backlight countless screens and illuminate homes, offices and public spaces; it is used to manufacture blue and green lasers employed for reading discs and projecting images; and it is used to produce HEMTs for RF and power electronics that are deployed in radar, wireless communication and power supplies.

Given this wide-ranging, tremendous success, GaN growth by MOCVD clearly has its merits. But there are also undesirable aspects of this process that creates a film of GaN through the interaction of a gallium-based precursor with ammonia at highly elevated temperatures.

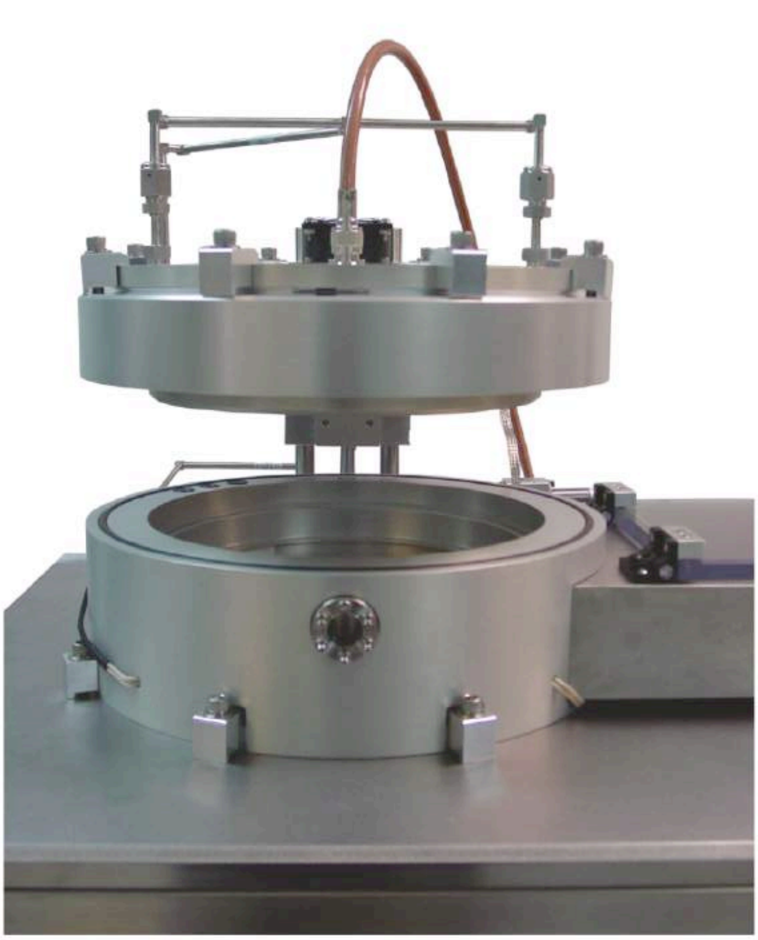
Some of the drawbacks are associated with the hardware that is used. MOCVD reactors designed for GaN growth must be capable of growth temperatures in excess of 1000 °C, which makes them expensive to build and run. These tools are also challenging to scale, so significant investment is required when developing reactors to accommodate larger wafers.

Another major downside is the use of ammonia as the nitrogen source. This caustic, extremely hazardous gas has to be handled with great care, with abatement systems needed downstream to deal with any ammonia that has not been consumed in the growth process.

There are also weaknesses associated with GaN films grown by MOCVD. The stoichiometry of the compound is imperfect, the films are not flat on

Precursors for the Nanomaster NLD-4000 are housed in a dedicated glove box.


GaN
InGaN
InAlN
AlGaN
GaSb
InSb
InP
InGaP
InAlGaN
GaAs
AlGaAs



Use of a planar inductively couple plasma leads to very fast pump-down times, thanks to a very small gap between the substrate and the pump chamber.

an atomic scale, and the material is plagued with hydrogen. This latter weakness can lead to variations in etch rates, and it can hamper device performance. For example, if hydrogen diffuses to the gate of a GaN transistor, it can shift the threshold voltage.

It is possible to address all of these weaknesses associated with the growth of films of GaN by a novel, ammonia-free form of atomic layer deposition (ALD) pioneered by Nano-Master of Austin, Texas.

The NLD-4000 tool made by this company retails for around $250,000, compared to $1 million or more for an MOCVD reactor, and it is straightforward to scale growth from 2-inch substrates to those of 450 mm in diameter.

While the conventional form of ALD involves the repeated cycling of one precursor and then another to create a film one atomic layer at a time, the process pioneered by Nano-Master has a key difference: in this case, the plasma-formed nitrogen source is applied continuously, cutting cycle times in half.

Tracing the tool

The approach employed in the ammonia-free ALD tool produced by Nano-Master has its roots in the work undertaken by company president and CEO Birol Kuyel. When working at AT&T in the 1980s, he investigated the growth of SiN by plasma-enhanced CVD.

"I found out that there is no way to get the uniformity and stoichiometry simultaneously using ammonia chemistry," says Kuyel. But when he turned to pre-activated nitrogen, they could independently control the stoichiometry and physical characteristics of SiN. "We were successful, had very low levels of hydrogen, and we filed a patent on that," explains Kuyel.

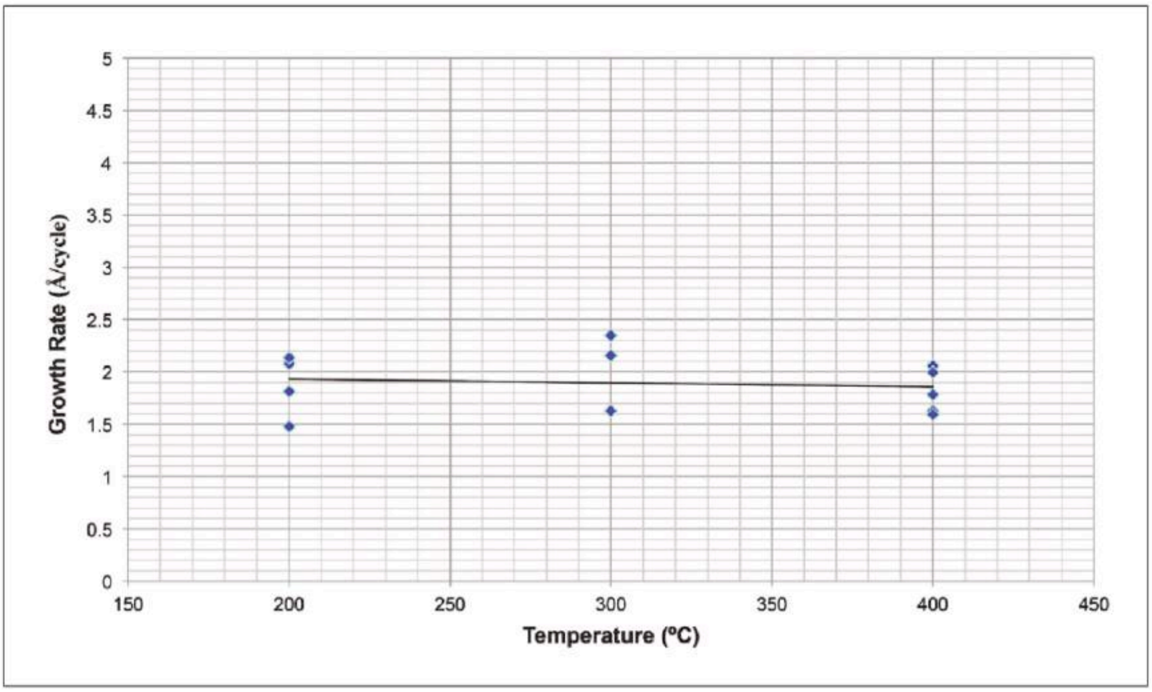
The next milestone came about ten years ago, when a professor at the University of Arkansas approached Kuyel, who by now was CEO at Nano-Master. The academic wanted a conventional MOCVD tool for GaN growth, but could not afford one, so Kuyel suggested a plasma-enhanced variant with N_2 rather than NH_3. This switch lowered the growth temperature to around 600 °C, which allowed the use of lower-cost, simpler hardware, and eliminated NH_3 abatement.

Plasma-enhanced MOCVD proved a great success. "They were saying that they were getting the world's best gallium nitride," explains Kuyel. So pleasing were these results to these academics that they were unwilling to share the details of their success with Nano-Master. What Kuyel does know, however, is that the growth involved plasma-activated N_2, and the GaN films had low levels of hydrogen.

The success led Kuyel and his colleagues to wonder what might be possible by applying a nitrogen-plasma process to ALD. But they did not have the finances to pursue this idea until early last year when they won an order for this novel growth tool. Thanks to the accumulated knowledge from manufacturing other growth systems, they were successful at the first attempt, getting the reactor out of the door before the end of 2015.

To prevent the plasma from damaging the GaN film, the tool features separate chambers for the plasma and for ALD. The nitrogen plasma is formed above the chamber and introduced through a showerhead that "kills" the plasma to inject activated nitrogen. "To do nitrogen chemistry, you don't need nitrogen ions – you need natural nitrogen, but in an activated state," says Kuyel.

To prevent oxidation, wafers can be placed in load-lock after growth, where they are flushed with nitrogen and cooled.



The growth rate is governed by the number of cycles, and has little dependence on temperature.

Using pulses of gallium precursors in bursts with a duration of typically 20 μs to 60 μs and growth temperatures of between 200 °C and 400 °C, the tool is capable of producing films with a thickness independent of temperature, pulse width and cycle time. "We were able to grow a number of [atomic] layers based only on the number of cycles we used," says Kuyel.

Another strength of the Nano-Master ALD tool is its very fast pump-down time to a typical growth pressure of 0.2-0.3 Torr. This stems from the use of a planar inductively coupled plasma system, rather than one based on a cylinder or a coil. By selecting this system architecture, the gap between the substrate and the pump chamber can be just a few centimetres.

Fantastically flat films

The tool is capable of producing some incredibly impressive results. For example, film thickness over a 6-inch substrate varies by less than 1 Å. "All those points [that are measured] have the same number of atoms," argues Kuyel. "MOCVD will depend on the flow patterns, reactivity concentrations and so on. This doesn't."

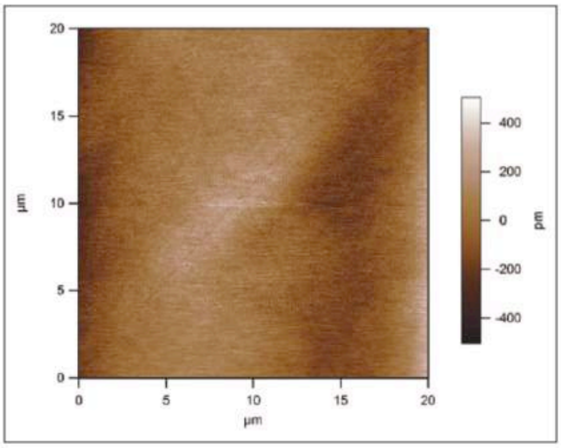
When films of GaN are grown on silicon they form a very strong bond with the substrate. "We did not even have to do special preparation of the silicon surface," remarks Kuyel.

The Achilles' heel of GaN growth with the Nano-Master ALD tool is the slow growth rate. Although it is faster than that of many ALD processes, thanks to pulsing of just the gallium source, growth rates are at best a few Angström per second. This effectively rules out the growth of thick films in a single-wafer processing chamber for chip production.

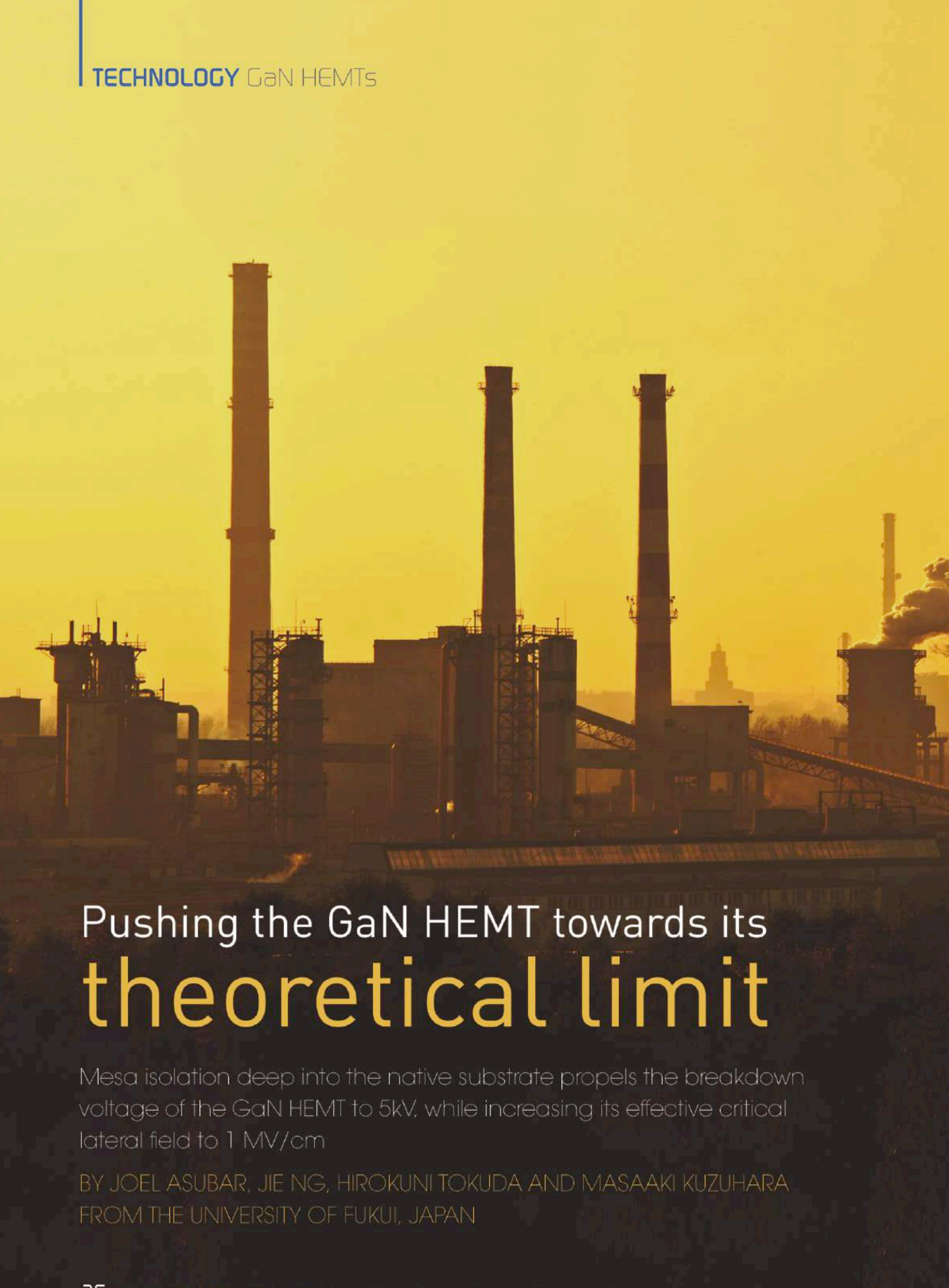
As the take-up of this tool is still in it infancy, it is not yet clear where it will find its greatest use. One option, says Kuyel, is to build a composite system with an ALD chamber and an MOCVD chamber and a transfer between them under high vacuum. He believes that such an approach could be used for making blue lasers, which would benefit from the high-quality foundation that results from ALD.

Another possible use of the Nano-Master ALD system is the production of mirrors. Using a gallium-tri-chloride source, it is possible to grow films with a surface roughness on the pico-metre scale. "This is better than mirror finishes that you obtain for optical elements," claims Kuyel. "That's why I'm thinking that making mirrors from multi-layer dielectrics would be possible."

The plans for the future involve raising awareness of the tool and driving up its sales. Kuyel wants to build dual-chamber systems, which could either be: a pair of ALD chambers; a combined ALD and MOCVD multi-chamber cluster tool; or multi-wafer batch processing tools. There is also the opportunity of using the tools to deposit oxides, such as HfO_2, that could aid development of next-generation logic. So there is clearly much promise for this novel ALD tool.



Films of GaN that are deposited by ammonia-free ALD have a tremendous degree of flatness.



Pushing the GaN HEMT towards its theoretical limit

Mesa isolation deep into the native substrate propels the breakdown voltage of the GaN HEMT to 5kV, while increasing its effective critical lateral field to 1 MV/cm

BY JOEL ASUBAR, JIE NG, HIROKUNI TOKUDA AND MASAAKI KUZUHARA FROM THE UNIVERSITY OF FUKUI, JAPAN

Despite global efforts to curb carbon emissions, a huge proportion of the world's energy is still produced by burning fossil fuels, which release greenhouse gases and contribute to global warming. In the last one hundred years, it is estimated that the average temperature in Tokyo has increased by about 3 °C, a clear manifestation of global climate change. Even putting concerns over global warming briefly to one side, the present consumption rates for the three big fossil fuels – coal, natural gas, and oil – will exhaust these sources of energy in about two hundred years. So it is clear that humanity is facing complex energy and climate challenges, which need to be addressed by not only the present generation, but those that follow.

Back in 2009, the Japanese Government, as one of its measures to sustain and strengthen Japan's efforts to balance the environment with the economy, launched a range of 'green' tax incentives. They included a scheme to encourage the purchase of more environmentally friendly cars. Up until that point, aside from the annual tonnage tax based on the car's weight, customers buying a new car had to pay an acquisition tax equal to about 5 percent of the vehicle's price. But from then on, if they bought an eco-friendly electric or hybrid car, they were exempt from these taxes. These changes enabled households to tap into a subsidy worth hundreds of thousands of yen by replacing a car that is 13 years old or more with a model complying with certain fuel efficiency standards.

Further incentives to encourage Japanese consumers to 'think green' when purchasing have come in the form of 'eco-points'. They are accrued through purchasing eco-friendly household appliances, such as television sets, refrigerators and air conditioners. The points can be exchanged for energy-efficient products and services.

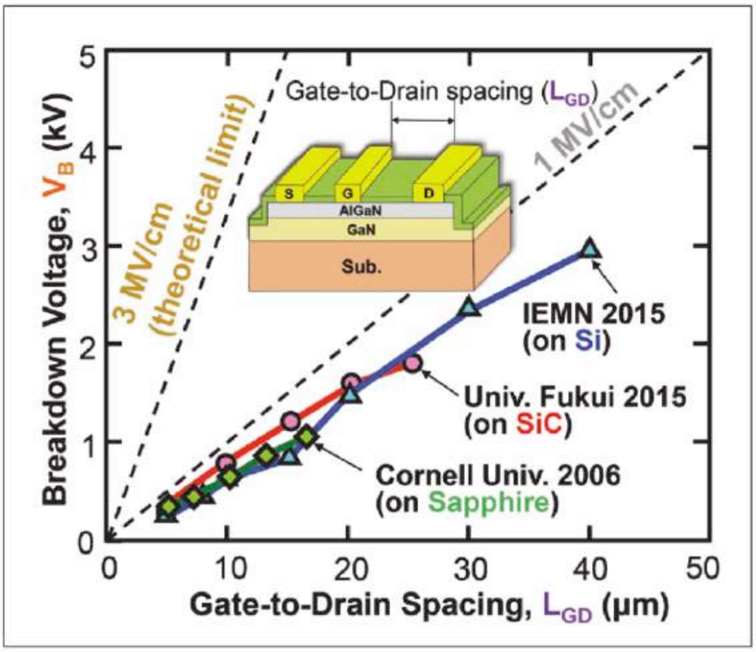


Figure 1. Lateral GaN-based devices typically exhibit an effective critical electric field – defined mathematically as the breakdown voltage divided by the gate-to-drain spacing – that is far less than the theoretical value of 3 MV/cm. According to experiment, a typical effective critical electric field, regardless of whether the device is formed on sapphire, SiC or silicon, is about 0.6 MV/cm.

In most electric consumer products, energy consumption is handled by a power electronic system. Power electronics actually plays a significant role at different pivotal points of an electricity distribution system – from generation at power plants through to conversion at electric substations and consumption by end-users. In other words, it impacts not only the industry, but the day-to-day lives of every one of us.

At the heart of all these power electronic systems are power devices, which switch electricity on and off and control the conversion and the regulation of voltage. These power devices are embedded in almost everything we use on a daily basis – from cellphones to laptop adapters, hybrid cars, trains and even elevators.

The majority of power devices are fabricated from silicon, a mature technology with well-understood properties. However, power devices made from this material are incapable of delivering the high voltages and ultra-low losses that are requisite for a highly-energy-efficient society. To withstand higher voltages, and prevent breakdown events where current would surge uncontrollably, silicon devices require longer device dimensions. This ensures that the electric field within a device is maintained below its critical value, which is 0.3 MV/cm. But a longer device has a higher on-state resistance, leading to a higher conduction loss and greater heat dissipation.

Wider bandgap

It is here that the so-called wide bandgap semiconductors SiC and GaN – with their superior intrinsic properties over silicon – can play a key role. Both have a bandgap about three times that of silicon, and as the critical electric field varies with the square of the bandgap, they promise to handle a field strength up to 3 MV/cm. What this means is that a GaN device designed to have the same breakdown voltage as another built from silicon can be shorter and less resistive, so will consume less energy and dissipate less heat.

Another great attribute of GaN-based devices is that they can operate at far higher temperatures than those made from silicon. GaN-devices can operate normally at temperatures as high as 300 °C, while those made from silicon usually reach their operating limit at 125 °C. This superiority stems from the wider bandgap. The maximum operating temperature of semiconductor devices is governed by thermally excited carriers, which are more abundant at higher temperatures, and can cause uncontrollable conduction. A higher bandgap naturally necessitates a higher temperature to excite electrons from the valence band to the conduction band. With GaN, fewer thermally excited carriers, coupled with less heat generation that results from a lower on-resistance, simplifies the cooling of this device compared with its silicon-based counterpart.

Thanks to these important and attractive advantages, a great deal of effort in industry and academia is being devoted to developing GaN devices and driving their adoption in consumer and industrial electronics. This includes our group at the University of Fukui, Japan, that has been tasked with pushing the capability of the GaN-based HEMT towards its limit. We are working under the Super Cluster Program, an Industry-Academia Collaborative organization backed by the Japan Science and Technology Agency.

A major weakness of the GaN HEMT is that it currently fails to fulfil its potential at withstanding high electric fields. Although it promise to handle an electric field strength of up to 3 MV/cm, experiments on lateral GaN-based devices, grown on sapphire, SiC and silicon, indicate that it is only able to cope with fields up to about 0.6 MV/cm (see Figure 1 for details).

This low value raises the question of whether parasitic leakage is compromising device performance. The

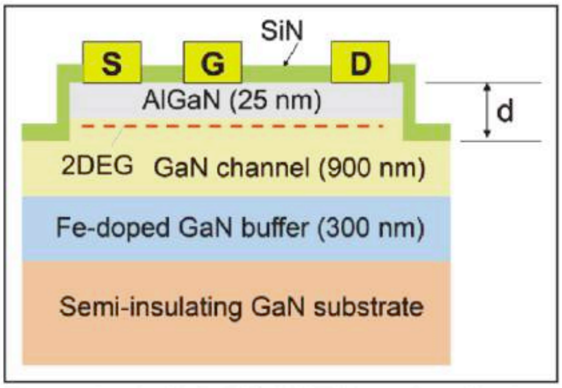


Figure 2. A typical AlGaN/GaN HEMT investigated by the team from the University of Fukui.

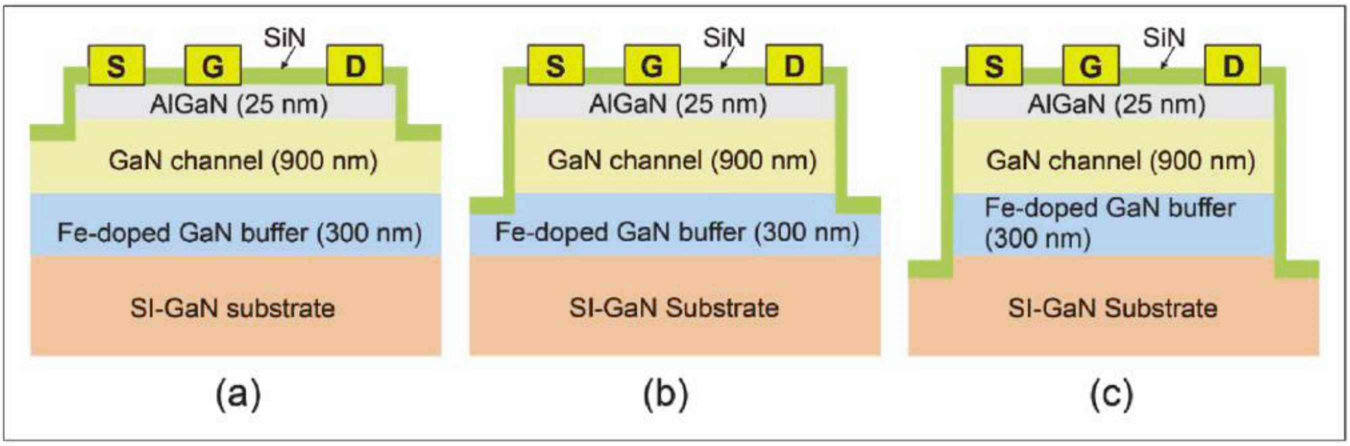


Figure 3. Cross-sectional views of three sets AlGaN/GaN HEMTs fabricated on semi-insulating GaN substrates with different mesa depths of (a) 200 nm, (b) 1000 nm, and (c) 1400 nm. The mesa isolation surfaces fall on an undoped GaN channel, an iron-doped GaN buffer layer, and a semi-insulating GaN substrate, respectively.

group of Farid Medjdoub at IEMN, France, have sought an answer to this, and suggested that one of the primary causes of premature breakdown in GaN-on-silicon devices (blue-coloured data points in Figure 1) is the leakage current through the underlying substrate under the gate-drain region. By etching this portion of the silicon substrate, they achieved a record breakdown voltage in their GaN-on-silicon lateral power devices of 3 kV.

Due to a lack of availability of high-quality, free-standing native substrates during the infancy of GaN epitaxial research, layers were usually grown on highly-lattice-mismatched foreign substrates, such as sapphire, SiC, and silicon. One downside of this approach is the high lattice mismatch between the GaN epilayer and the substrate. This leads to a high density of defects, which hamper device operation.

Making matters worse, there is a large difference between the coefficient of thermal expansion of the GaN epilayers and that of the foreign substrate. So, when the epiwafer is cooled from its growth temperature of more than 1000 °C to room temperature, the GaN lattice shrinks at a significantly different rate from that of the substrate. This induces a huge stress upon the structure that can lead to bowing of the epiwafer, and even cracking.

To prevent bowing and cracking, thick, complicated buffer structures are inserted between the foreign substrate and the GaN epilayers. A common approach is to add an AlN nucleation layer and a rather thick buffer. However, even with this combination, a high density of threading dislocations – typically 10^8 cm^{-2} to 10^{10} cm^{-2} – is generated in the epitaxial layer.

A native platform

A more attractive option, which tackles all these issues head-on, is to grow the GaN epilayer on a free-standing GaN substrate. This is feasible in research laboratories, thanks to advances in GaN growth technology, and it should not be long before it is commercially viable, given the pace of improvement in the production of GaN substrates.

In principle, the absence of material mismatches enables the growth of a GaN epilayer directly on a

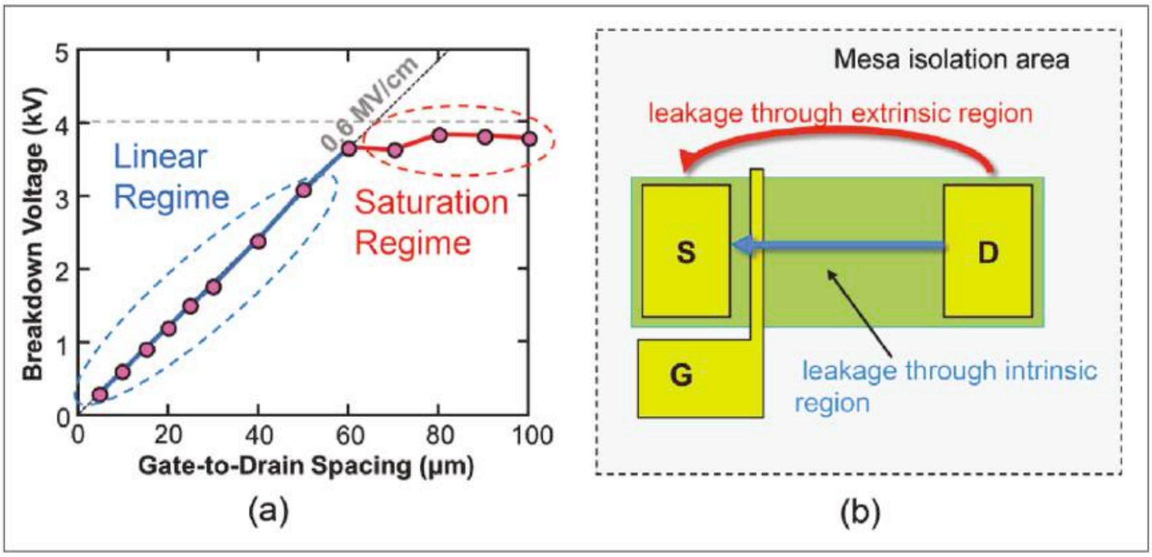


Figure 4. (a) Breakdown voltage as function of gate-to-drain spacing for devices with a mesa isolation depth of 200 nm. (b) Two possible leakage components are: leakage through the intrinsic region (blue), and leakage through the extrinsic region (red).

> "Further etching produces a fundamental change in breakdown behaviour. With these devices, which have a mesa isolation surface that falls within the GaN substrate, breakdown voltage increases linearly with gate-to-drain spacing up to 5 kV, and shows no sign of saturation."

free-standing GaN substrate. However, in practice, a thin GaN buffer layer is needed to ensure high-quality GaN epitaxial layers (see Figure 2).

The GaN-based HEMTs that we have used to develop high-blocking-voltage designs feature MOCVD-grown AlGaN/GaN heterostructures. These are formed on 2-inch, free-standing, HVPE-grown GaN substrates with a nominal threading dislocation density of 10^6 cm^{-2}. To ensure high resistivity of the GaN buffer and substrate – this is necessary for good electrical isolation between the devices fabricated on the wafer – the GaN substrate and buffer are iron-doped to a concentration of around 10^{18} cm^{-3}. The iron atoms act as deep acceptors, compensating and reducing residual donor carriers inherent in the grown GaN layers.

In our transistors, the aluminium composition in the topmost AlGaN layer is 20 percent. This produces a strong polarization field in the AlGaN/GaN heterostructure, resulting in a sheet of very mobile electrons, which tend to accumulate in the GaN channel layer very near the AlGaN/GaN interface. This sheet of electrons, called the two-dimensional electron gas, constitutes the channel between drain and source electrodes. This channel can be modulated by an external applied voltage on the gate.

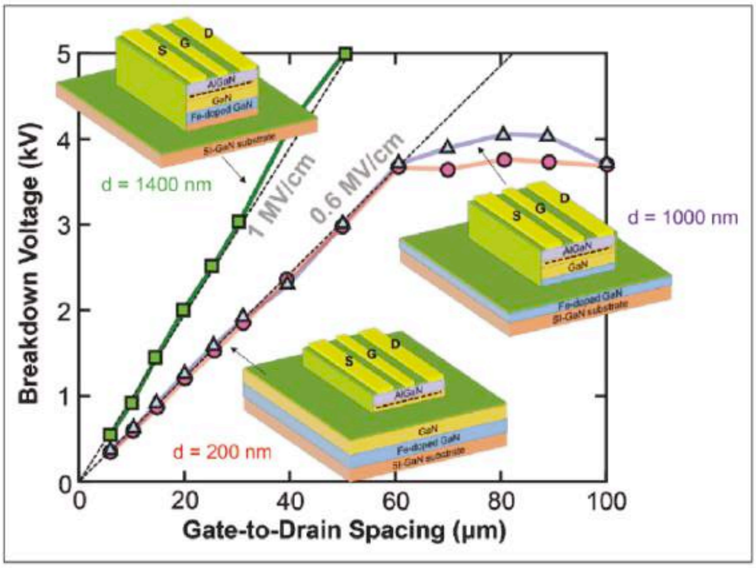


Figure 5. Breakdown voltage as function of gate-to-drain spacing for devices with a mesa isolation depth of 200 nm, 1000 nm, and 1400 nm, where the mesa isolation surfaces fall on undoped GaN channel, iron-doped GaN buffer layer, and semi-insulating GaN substrate, respectively.

We suspect that the mesa isolation depth impacts the leakage and thus the breakdown voltage. To test this hypothesis, we have fabricated three sets of devices, each with a different value for the mesa isolation depth (see Figure 3). In one set of devices, etched to a depth of 200 nm, the mesa falls on the channel layer; in another, etched 1000 nm, the mesa surface is on the buffer layer; and in the final set, etched to 1400 nm, the mesa surface is on the GaN substrate. For each set, HEMTs were formed with a range of gate-to-drain spacings to determine the critical electric field for the device. With these measurements, we defined the breakdown voltage as the drain-to-source voltage at which the drain current reaches 1 mA/mm, with an applied gate-to-source voltage of -7 V. Note that this bias depletes the two-dimensional electron gas beneath the gate.

For devices with a mesa isolation depth of 200 nm, the plot of breakdown voltage as a function of gate-to-drain spacing can be divided into two regimes: linear and saturation (see Figure 4). In the linear regime, the breakdown voltage increases with gate-to-drain spacing until this reaches 60 μm, indicating that the effective critical electric field in the device is about 0.6 MV/cm. In the saturation regime, the breakdown voltage nears 4 kV for gate-to-drain spacings of around 80 μm or more.

We believe that we can explain this two-regime behaviour with two different leakage currents. One, the leakage through either the active region or the intrinsic region of device, dominates in the linear regime; and the other, leakage through the isolation area or extrinsic region of the device, leads in the saturation regime, when the gate-to-drain spacing exceeds 60 μm. At these longer gate-to-drain spacings, the breakdown voltage saturates, because the parasitic leakage current in the isolation area, which is considered as an area-spreading distributed current component, has a weak dependence on the distance between the electrodes. In contrast, for gate-to-drain spacings of 60 μm or less, the dominant leakage current triggering breakdown runs through the intrinsic region between the gate and the drain. As the gate is close to the drain, leakage is sensitive to the gate-to-drain spacing – and as this gets longer, leakage falls, leading to an increase in breakdown voltage.

It is also worth noting that for devices with a gate-to-drain spacing of 60 μm or less, breakdown is catastrophic, with current surging after reaching the breakdown voltage. But that's not the case for HEMTs with a longer gate-to-drain spacing: they exhibit a soft breakdown, with current slowly increasing as the voltage exceeds the breakdown value.

For our devices that have been etched by 1000 nm to cause the mesa isolation surface to fall on the GaN buffer layer, plots of breakdown voltage as a function of gate-to-drain spacing mirror those with a 200 nm etch (see Figure 5). This suggests that the un-etched GaN channel layer in the isolation area (extrinsic region) does not induce a significant leakage current.

Further etching to a depth of 1400 nm produces a fundamental change in breakdown behaviour. With these devices, which have a mesa isolation surface that falls within the GaN substrate, breakdown voltage increases linearly with gate-to-drain spacing up to 5 kV, and shows no sign of saturation. With these devices, the critical electric field is about 1 MV/cm, which is 70 percent higher than that of the other two sets of devices.

We primarily attribute this increase in the breakdown field to the removal of the iron-doped GaN buffer layer in the extrinsic region. Results suggest that the GaN buffer layer permits leakage through the extrinsic part of the device, most likely through the GaN buffer/GaN substrate interface. This can lead to premature breakdown.

Higher fields

Alhough an increase in the effective critical electric field from 0.6 MV/cm to 1 MV/cm is a move in the right direction, but it is still a long way short of the theoretical limit, 3 MV/cm. We have puzzled over this shortfall, and initially thought that our devices were hampered by a leakage current through the underlying 'semi-insulating' GaN substrate. To test out our theory, we studied HVPE-grown GaN substrates with two different iron-doping concentrations: 1×10^{18} cm^{-3} and 9×10^{19} cm^{-3}. The substrate with higher doping produced a lower leakage current, due to a higher degree of residual donor compensation.

We went on to compare breakdown characteristics by forming ohmic contact pairs with varying distance directly on the surface of both substrates. We found that in both cases the breakdown voltage increased linearly with ohmic-to-ohmic spacing (see Figure 6), and the effective critical electric fields for substrates with iron concentrations of 1×10^{18} cm^{-3} and 9×10^{19} cm^{-3} were 1 MV/cm and 2 MV/cm, respectively – note that 2 MV/cm is the highest ever effective critical electric field reported from a lateral structure. From these results we can conclude that a highly resistive GaN substrate is a key ingredient in the fabrication of a GaN-based HEMT with a high breakdown voltage.

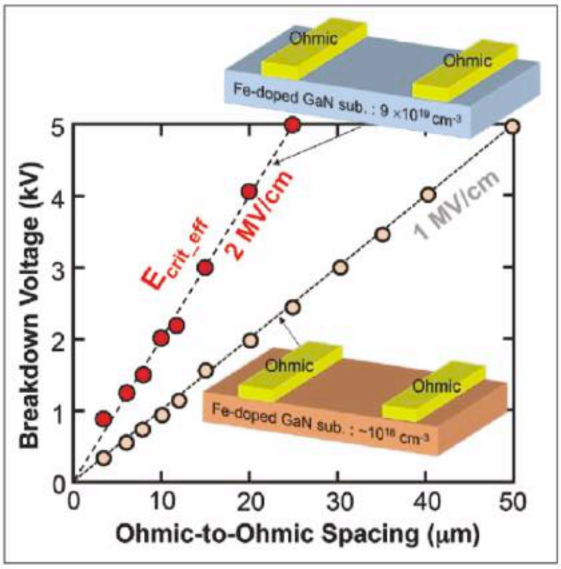


Figure 6. Breakdown voltage as a function of ohmic-to-ohmic spacing of ohmic electrodes formed on top of two different GaN substrates: one, with an iron-doping concentration of 1×10^{18} cm^{-3}; and another that is heavily compensated, with an iron-doping concentration 9×10^{19} cm^{-3}.

At first glance it might appear that to realise an even higher effective critical electric field in a GaN HEMT one should start with a highly resistive semi-insulating SiC or sapphire substrate. But this approach is flawed, because growth of a high-quality GaN-based heterostructures demands a more complicated, thicker and leaky buffer, and intermediate layers. It is only the free-standing GaN substrate that can facilitate the growth of very thin buffer GaN layers with controlled high-resistivity properties that are of particular importance for suppressing parasitic leakage current and avoiding premature breakdown.

On a final note, we believe that GaN-based electronic devices will play a very important role in meeting the ever-growing demand for faster, more efficient and 'greener' technologies. Although these HEMTs are still hounded by some technological issues, we are confident that they can be addressed with a better understanding of the underlying physics. This will, in turn, lead to innovative solutions.

○ This work is partially supported by the Super Cluster Program from JST. The authors would also like to acknowledge the contribution from Prof. Kazuyuki Tadamoto of Yamaguchi University who provided HVPE-grown, high-resistivity GaN substrate

Further reading

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How can PICs support traffic growth? And how can they deliver value to operators?

KEYNOTE

- **Geoff Bennett: Infinera**
  An in-depth look at the practical implications of PIC technology in long haul networks, plus a perspective on how PICs could be deployed in other areas of the network, and in other platforms (such as core routers)

SPEAKERS

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  Impact of integrated photonics on the optical communications market
- **Martin Guy: Ciena Corporation**
  Strategies for photonic integration for metro and long-haul networks
- **Tom Williams: Acacia Communications Inc.**
  Putting silicon photonics to work on metro and long haul applications
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  Integrated photonics systems to meet challenges in optical and wireless system convergence
- **Michael Wale: Oclaro Technology**
  PIC-enabled telecommunications and data centre interconnects: state of the art and future prospects

Supporting Data Centre Growth

Short reach communications could be a major win for PICs. But what are the customer priorities? And how can photonic integrated circuits come out on top?

KEYNOTE

- **Richard Pitwon – Seagate Technology**
  Opportunities for data centre optical interconnects

SPEAKERS

- **James Regan: EFFECT Photonics**
  InP as a platform for photonic integration
- **Karen Liu: Kaiam Corporation**
  Perspectives on hybrid integration as a rapid and flexible route to upgrading today's datacenters
- **Bert Jan Offrein: IBM**
  Scalable integration concepts to drive down the cost of data centre photonics
- **Robert Blum: Intel Corporation**
  Silicon photonics and the future of optical connectivity in the data centre

PIC Platforms

What are the key materials systems driving photonic integration? And how should these platforms evolve to unlock greater performance?

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- **Graham Reed: University of Southampton**
  Challenges left on the table regarding silicon photonics

SPEAKERS

- **Roel Baets: Ghent University**
  Silicon PIC-platforms: silicon-on-insulator and silicon nitride
- **Timo Aalto: VTT Research**
  Thick-SOI for PICs and I/O coupling
- **Dimitris Tsiokos: Phosnet Research Group, Aristotle University of Thessaloniki**
  CMOS compatible plasmo-photonics for mass-manufactured, powerful PICs
- **Michael Geiselmann: LiGenTec**
  Applications for thick film silicon nitride integrated circuits
- **Arne Leinse: LioniX International**
  TriPleX™: The low loss industrial silicon nitride waveguide platform. Application examples from VIS to IR

Optimising PIC Design, Manufacturing & Packaging

What are the best resources for creating and delivering photonic integrated circuits?

KEYNOTE

- **Michael Watts: MIT**
  Bringing resources together to drive photonic integration

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- **Peter O'Brien: Tyndall National Institute**
  Overcoming packaging hurdles for PIC devices
- **Suresh Venkatesan: POET Technologies**
  Realizing gains in energy efficiency, component cost and size-reduction through photonic integrated solutions
- **Peter de Dobbelaere: Luxtera**
  The design and processing of advanced transceiver integrated circuits
- **Gilles Lamant: Cadence Design Systems**
  Providing mainstream design flow for PICs
- **André Richter: VPIphotonics**
  Advances in layout-aware schematic-driven design automation for integrated photonic and optoelectronics
- **Niek Nijenhuis: PhoeniX Software**
  PhoeniX Software's unique position in the photonic IC landscape

New markets: Sensing, Medical?

What are the prospects for developers more broadly? And how does the supply chain need to adapt?

KEYNOTE

- **Liesbet Lagae: imec**

imec's progress as the pix4life project in the field of SiN photonics in the visible range for life science applications

SPEAKERS

- **Pim Kat: Technobis Group**
  Extreme fibre sensing: PIC opportunities beyond datacoms and telecoms
- **Iain McKenzie: European Space Agency**
  PICs: The final frontier
- **Ewit Roos: Photon Delta**
  Why European photonics is undervalued and a fast-track plan of how to change it

NANOWIRES ENHANCE LASER PERFORMANCE IN THE DEEP UV

Deep UV lasers can realise incredibly low threshold current densities when formed with self-organized AlGaN nanowires

BY SONGRUI ZHAO, XIANHE LIU, AND ZETIAN MI FROM McGILL UNIVERSITY, CANADA

ULTRAVIOLET LIGHT plays a crucial role in countless tasks that benefit humanity. Uses include sterilization, water purification, preventing counterfeiting, and the analysis of chemical and biological samples.

Today, the dominant sources of UV emission are mercury lamps, a few types of gas laser, and lasers based on frequency conversion. Unfortunately, all these UV sources tend to suffer from a low efficiency and a large footprint. What's more, their operation requires a toxic gas and produces a significant amount of mercury emission, which contaminates our environment. For example, back in 2005, more than 200 tons of mercury was emitted to air from mercury containing products, such as mercury lamps. Exposure to mercury has a devastating impact, deteriorating the health of millions of people and damaging the developing fetus. Clearly, what the world needs are greener, more efficient UV sources. Thankfully, this is possible by turning to compact compound semiconductor devices.

Given the drawbacks of the incumbent UV sources, it is not surprising that development of AlGaN-based, deep-UV lamps has attracted significant attention during the past decade. AlGaN is an ideal alloy for making a UV laser, as its bandgap can be tuned to deliver emission that spans from 200 nm to 364 nm. However, with the III-N material system, efficient sources are far harder to realise in the deep UV than in the blue, green, and near-UV. External quantum efficiencies of AlGaN quantum well deep-UV LEDs are typically just a few percent. Additional concerns are an operating wavelength for electrically injected quantum-well laser diodes that is limited to 336 nm, and a threshold current density on the order of tens of kA/cm^2. These weaknesses stem from material issues: dislocation and defect densities in the AlGaN material system are high, and current conduction in aluminium-rich AlGaN is incredibly inefficient.

Recently, our team at McGill University has tackled these critical challenges with AlGaN nanowire structures, which are grown on a silicon substrate by plasma-assisted MBE under nitrogen-rich conditions. The devices that we form are nearly free of defects and dislocations, and benefit from a tremendous reduction in the formation energy of the magnesium-dopant near the surface of the nanowires. This enhances magnesium-dopant incorporation and increases the efficiency of current conduction.

Another great attribute of our devices is that they incorporate quantum-dot-like nanostructures into core-shell AlGaN nanowire arrays. This leads to a significantly reduced transparency current density, thanks to the three-dimensional quantum confinement of charge carriers. Thanks to this, we have been able to produce electrically injected semiconductor lasers operating in the UV-AII, UV-B, and UV-C bands.

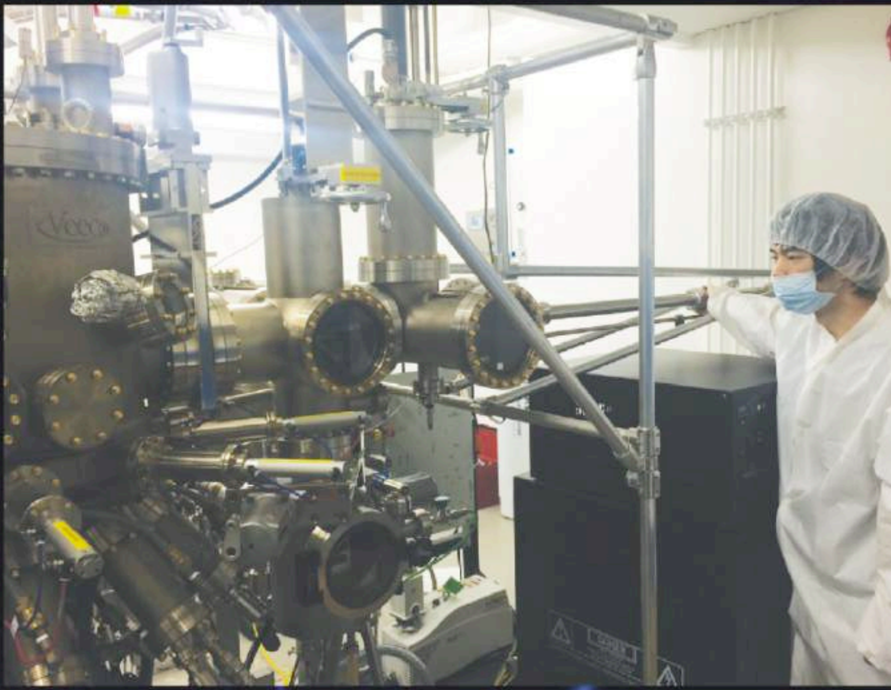
Nanowire lasers

Regardless of the form of laser, it must provide optical feedback, because this holds the key to increasing the population of photons and ensuring lasing. With a conventional Fabry-Pérot laser, feedback is realised with mirror facets and a long gain medium; and in our sub-wavelength scale nanowire arrays, it occurs via a phenomena known as Anderson localization, wherein the recurrent light scattering leads to strong photon confinement (see Figure 1 (a)). Note that the strength of the light localization is governed by the orientation, size, and filling fraction of the nanowire arrays.

In our devices, AlGaN random nanowire arrays are vertically aligned on a silicon substrate (see Figure 1(b) for a typical scanning electron microscopy image). The nanowires also function as a gain medium – it has a very small cavity size compared with that of a Fabry-Perot laser.

Detailed simulations reveal that there is a high probability of forming high-Q cavity nanowire arrays when the average diameter of the nanowire is 60 nm to 75 nm, the fill factor of the array ranges from 15 percent to 55 percent, and the emission wavelength of the source is 290 nm (see Figure 1(c)).

We have also simulated the in-plane electric field component of the optical field (see Figure 1(d), where image size is 2.35 μm x 2.35 μm). These calculations highlight the strong confinement present in randomly arranged nanowire arrays.



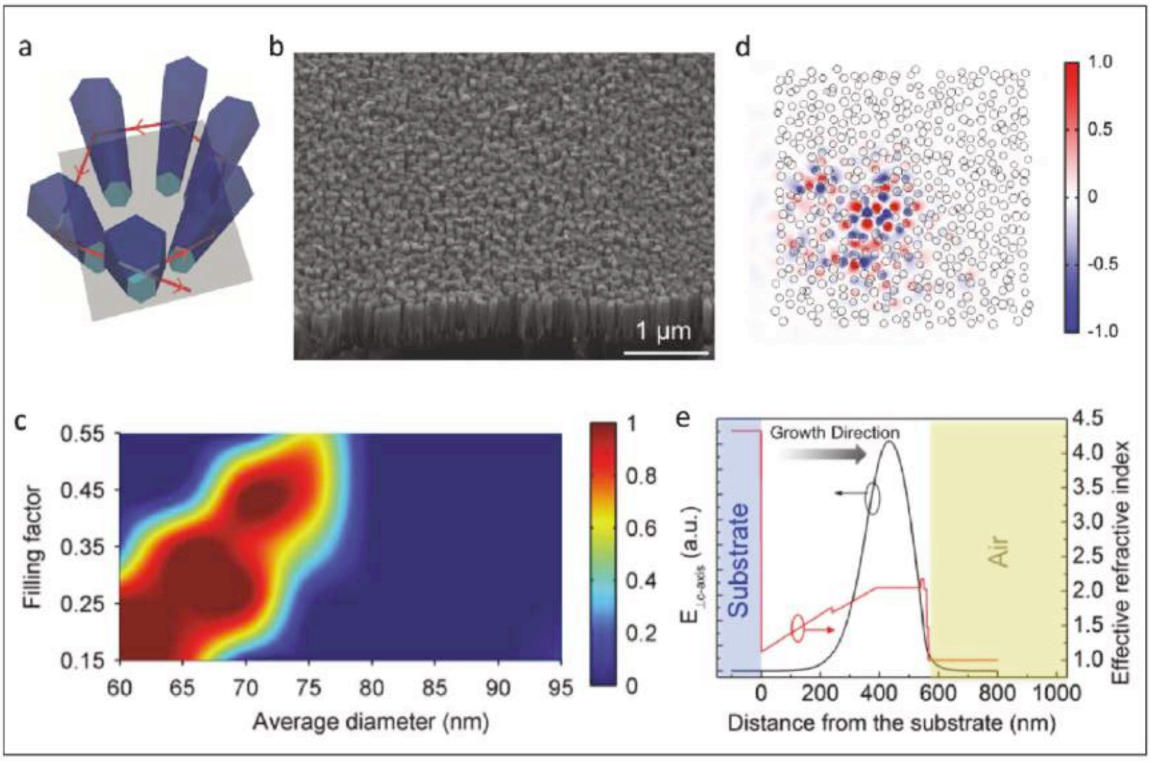


Figure 1: (a) Light recurrent scattering in AlGaN nanowire arrays provides the optical feedback required for lasing. (b) Scanning electron microscopy reveals the nature of the self-organized AlGaN nanowires on silicon. (c) The probability of forming cavities with a Q-factor higher than 1,000 for a wavelength of 290 nm, as a function of average nanowire diameter and filling factor. (d) In-plane electric field distribution. (e) The electric field (left axis) and effective refractive index (right axis) as a function of the distance from the substrate, showing the optical confinement along the nanowire vertical direction by the tapered nanowire morphology.

In our nanowire lasers, vertical optical confinement results from the effective refractive index variations along the nanowire growth direction. Due to the tapered nanowire morphology, the effective refractive index reaches a minimum at the nanowire bottom, and has a maximum value at the nanowire top (see Figure 1 (e)). Consequently, phonons are strongly confined near the nanowire laser active region. This is beneficial, reducing optical leakage through the underlying silicon substrate.

Strain benefits

Due to the large surface-to-volume ratio and the resulting highly efficient strain relaxation, nanowires offer several advantages, including direct growth on foreign substrates, such as silicon, low defect and dislocation densities, and smaller polarization fields, compared to conventional planar structures. Often, however, this has failed to lead to impressive optical emission efficiencies, due to significant non-radiative surface recombination.

To address this challenge, we have developed AlGaN core-shell nanowire heterostructures that suppress non-radiative surface recombination with a wide bandgap, aluminium-rich AlGaN shell. The structure of our single AlGaN nanowire consists, along the growth direction, of *n*-GaN, *n*-AlGaN, *i*-AlGaN, *p*-AlGaN, and *p*-GaN (see Figure 2(a)).

The presence of an aluminium-rich AlGaN shell is clearly revealed with energy dispersive X-ray spectrometry (see Figure 2 (b)). The aluminium-rich AlGaN shell is spontaneously formed during epitaxial growth, due to aluminium adatoms undergoing slower migration than those of gallium. The resulting increase in the aluminium content in the near-surface region is beneficial, leading to a strong carrier confinement, which slashes non-radiative surface recombination and boosts the carrier injection efficiency into the active region.

Fabrication of electrically injected deep-UV lasers is not easy, so some groups have developed optically pumped AlGaN quantum well lasers in the UV-B (280 nm to 315 nm) and UV-C (200 nm to 280 nm) bands. Threshold powers are of the order of 0.1 MW/cm^2 to 1 MW/cm^2; and due to the large bandgap and the large effective mass of electrons and holes in AlGaN, to reach transparency, the carrier densities must be of the order of 10^{19} cm^{-3} or higher – that is, the carrier density must reach this value to realise the onset of population inversion in conventional AlGaN quantum wells.

Turning to three-dimensionally quantum-confined nanostructures, such as quantum dots, enables a dramatic reduction in the transparency carrier concentration – and ultimately, the lasing threshold.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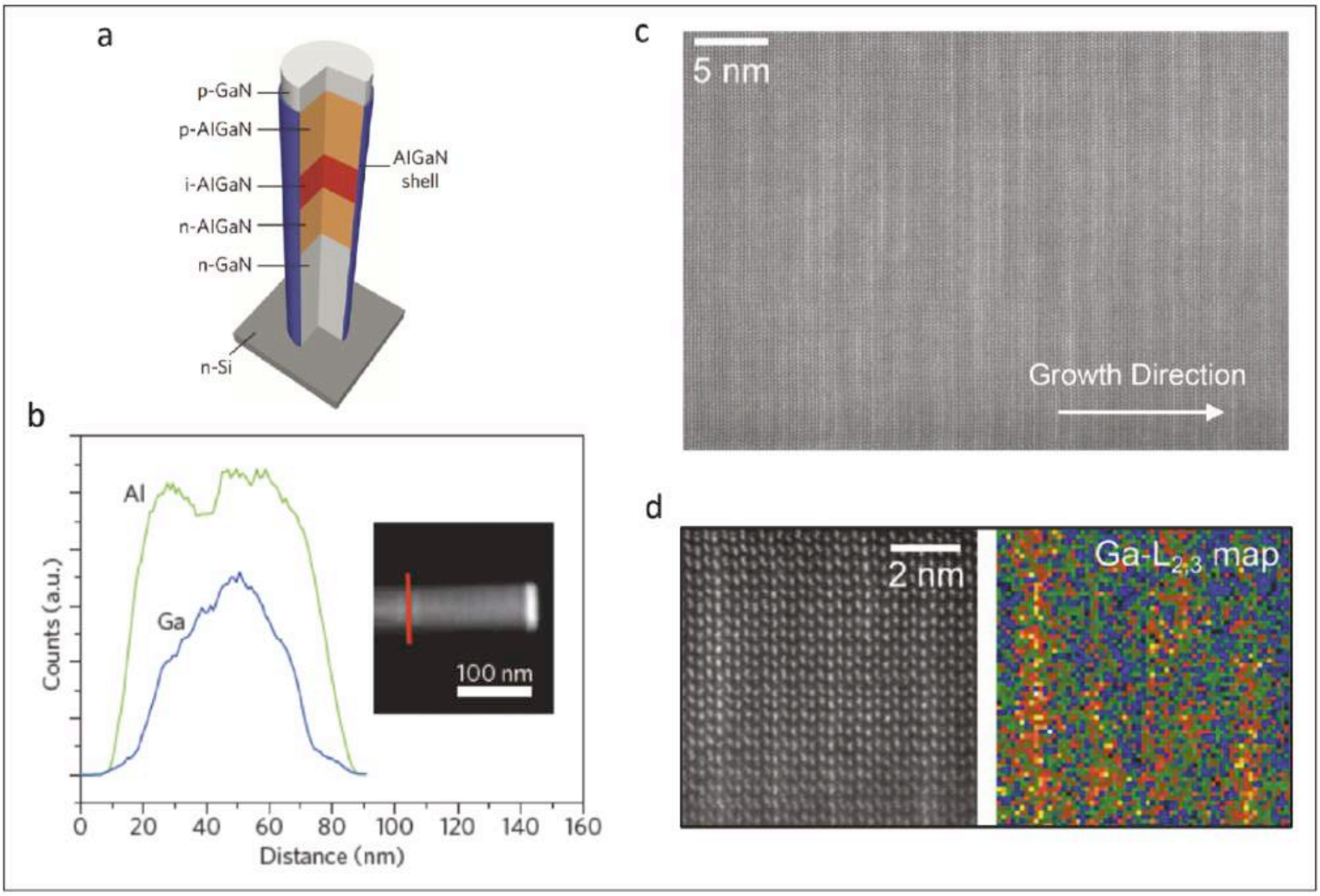
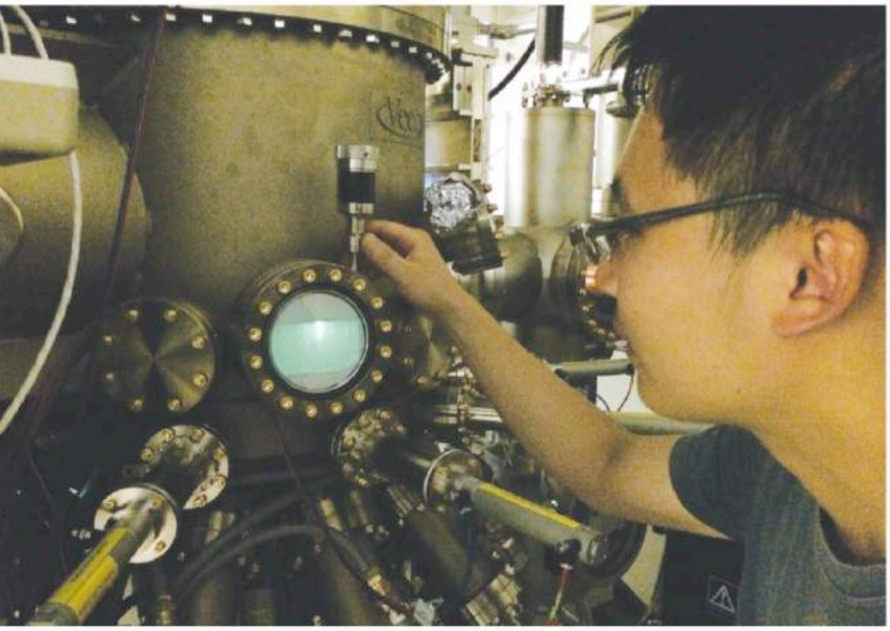


Figure 2: (a) Schematic of AlGaN core-shell nanowire heterostructures. (b) Energy-dispersive X-ray spectrometry (EDXS) line scans along the radial direction of the active region indicate the presence of aluminium-rich, AlGaN shells. The red line in the inset denotes where EDXS line scans were performed. (c) High-resolution scanning tunnelling electron microscopy reveals highly localized compositional modulations of alternating gallium-rich(brighter)/aluminium-rich(darker) planes at the atomic-scale. (d) The gallium-map (displayed in temperature-scale) and concurrently acquired annular dark-field (ADF) signal from electron energy loss spectroscopy – spectral imaging (EELS-SI) at atomic-resolution, showing a direct correspondence between the local increases in gallium-signal with the ADF signal within single atomic-planes.



Growth of GaN-based, deep UV lasers on silicon substrates is carried out in a Veeco MBE tool

However, prior to our work, there were no demonstrations of AlGaN quantum dot lasers in the deep UV.

Our success stems from discovering a new mechanism for forming quantum-dot-like nanostructures in nearly defect-free AlGaN nanowire arrays. According to detailed scanning transmission electron microscopy images, our aluminium-rich AlGaN nanowires feature extensive gallium-rich nanoclusters (see Figure 2(c)). They are between 0.25 nm and 2 nm high (height measured in nanowire axial direction, which is the growth direction), and 2 nm to 5 nm wide (the nanowire radial dimension).

Electron energy-loss spectroscopy enables elemental mapping of the gallium atoms in this structure (see Figure 2(d), which also show a corresponding high-resolution, dark-field scanning tunnelling electron microscopy image). This spectroscopic technique provides an estimate of the localized variation in the gallium concentration of 5-10 atomic percent. The formation of quantum-dot-like nanostructures in the AlGaN nanowires is directly related to the interplay between the chemical ordering and the non-uniform incorporation of gallium and aluminium adatoms at the nanowire growth front.

Conduction challenges

One of the greatest challenges associated with the fabrication of an electrically pumped AlGaN laser in the mid or deep UV is the realisation of sufficient current conduction. There is a tendency for this to be extremely poor, due to the large activation energies for silicon and magnesium dopants, and significant carbon impurity incorporation in the conventional MOCVD growth process. Making matters worse, defects, such as nitrogen vacancies, can further compensate holes in magnesium-doped AlGaN.

To overcome this challenge we have systematically investigated magnesium dopant incorporation in AlN nanowires from a theoretical and an experimental standpoint (see Figure 3 for the result of a first-principle calculation of aluminium-substitutional magnesium formation energy as a function of doping position in AlN). Our calculations show that magnesium-dopant formation energy is significantly reduced in the near-surface region of the nanowires. This implies that magnesium-dopant incorporation in nanowire structures will be significantly higher than that in conventional planar structures. What's more, experiments show that growth under nitrogen-rich conditions can suppress the formation of defect-related nitrogen vacancies.

Another key finding is that the primary *p*-type conduction in AlN nanowires is through the magnesium impurity band. That is good news, because it enables extremely efficient, nearly temperature-invariant current conduction, which was not previously possible in Al(Ga)N epilayers. The activation energy in magnesium-doped AlN nanowires is just 20-30 meV, compared with 500-600 meV for magnesium-doped AlN epilayers.

Armed with these insights, we have demonstrated the first AlN nanowire LEDs. These 300 μm by 300 μm chips have a forward voltage of only around 7 V at 20 mA. This very promising current-voltage characteristic highlights the efficient current conduction in AlN nanostructures, and lays a great foundation for the fabrication of electrically injected AlGaN deep UV lasers.

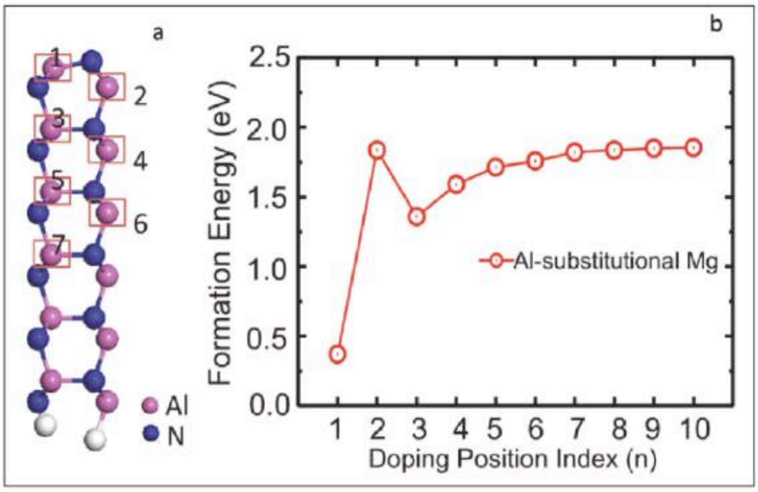


Figure 3: *Ab-initio* calculation of magnesium doping into AlN nanowires. (a) Illustration of the structure used for calculation. (b) Aluminium-substitutional magnesium formation energy along the nanowire radial direction. Index "1" indicates the surface. As this number increases, it denotes the position towards the bulk region of nanowires. It is seen that the near-surface region has much lower formation energy than in the bulk region.

We produce these lasers with standard optical lithography and metallization techniques. Fabrication of conventional, large-area nanowire devices often involves the use of polymers for surface passivation and planarization. However, they are not suitable for our devices, because they are strong absorber of deep UV light. So we use a relatively thin *p*-metal contact, which is directly deposited on the top surface of the AlGaN nanowires at a tilting angle (see the inset of Figure 4(a)).

Our device exhibits excellent current-voltage characteristics (see Figure 4(a)), and it can produce a CW output at 6K (Figure 4(b)). As the injection current increases, a sharp lasing peak appears around

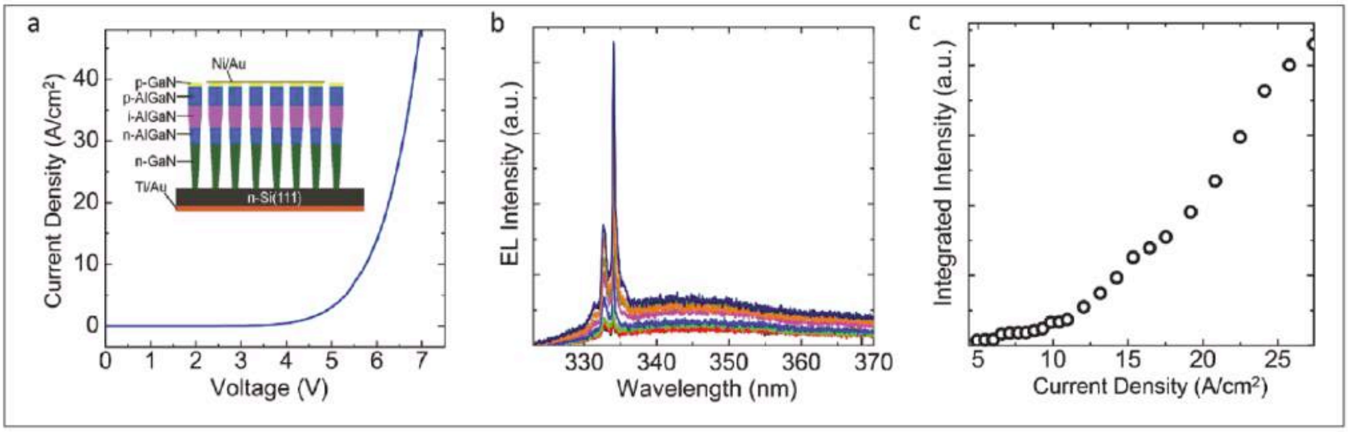


Figure 4: (a) Current-voltage characteristics of a 334 nm AlGaN nanowire laser, with the inset showing the fabricated device. (b) The lasing spectra measured at 6 K from 7.7 A/cm² to 22 A/cm². (c) Integrated intensity as a function of injection current.

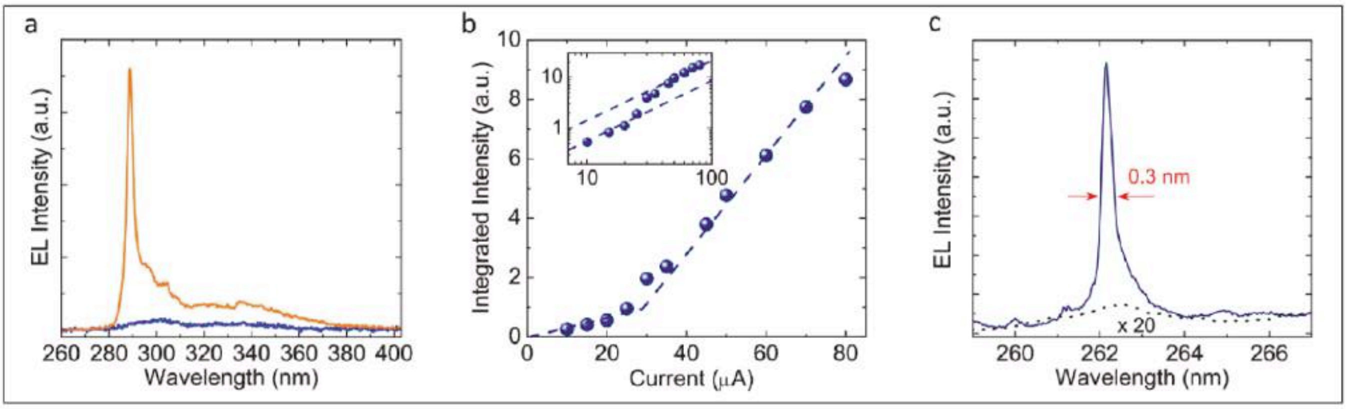


Figure 5: (a) The emission spectra of a 289 nm AlGaN nanowire laser measured under continuous-wave operation at 10 μA (below threshold) and 80 μA (above threshold) at room temperature. (b) The integrated electroluminescence intensity as a function of injection current. The inset shows the plot in a logarithmic scale. (c) Emission spectra of a 262 nm AlGaN nanowire laser measured at an injection of 50 μA (above threshold) and 7 μA (below threshold) at 77 K.

334 nm, superimposed on a background emission (see Figure 3). A clear lasing threshold occurs at around 10 A/cm², a current density that is several orders of magnitude lower than that of a conventional AlGaN quantum well laser operating at 336 nm. We attribute this ultralow threshold to the excellent carrier confinement and the high quality of the optical cavity.

Tuning the alloy composition enables the production of electrically injected AlGaN nanowire lasers in the UV-B and UV-C bands. For our 289 nm laser, a broad emission spectrum is produced at a low injection current, while a clear threshold occurs at 30 μA, and by 80 μA a sharp lasing peak has emerged (see Figures 5 (a) and 5 (b)). Plotting the light output on a logarithmic scale reveals a clear S-shape dependence, which corresponds to a transition from linear spontaneous emission to super-linear amplified spontaneous emission and then on to linear lasing emission (see the inset of Figure 5(b)). This behaviour provides unambiguous evidence for lasing.

Emission from the nanowire lasers can be as short as 262 nm.

Lasers at even shorter wavelengths can be produced with our nanowire laser technology. We have realised a 262 nm laser, which produces a sharp lasing peak when the current is ramped from 7 μA to 50 μA and the device is held at cryogenic temperatures. The threshold is 20 μA.

Our AlGaN nanowire laser technology offers a new route to the realization of electrically injected, deep-UV lasers. It could underpin the next revolution in photonics, which will see efficient, small-scale, solid-state UV light sources replacing conventional mercury lamps. Such progress can slash mercury emissions to air, soil and water. Our novel nanowire sources also promise more efficient, greener, manufacturing processes for sterilization, security, and medical diagnostics. Great opportunities lie ahead for the electrically injected, deep UV nanowire laser.

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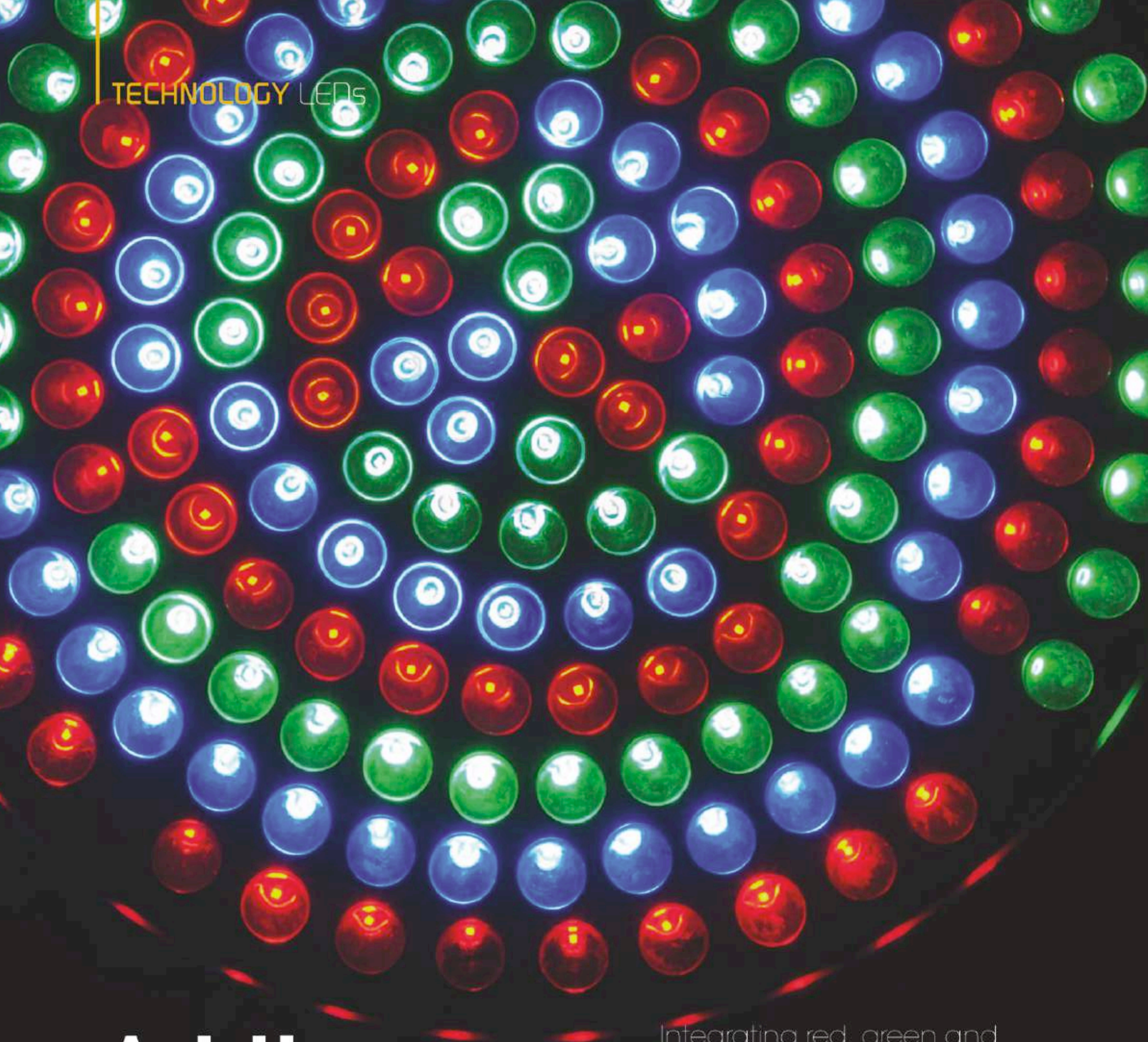

Adding colour to future silicon ICs

Integrating red, green and blue LEDs with silicon CMOS opens up many applications, including smart and integrated lighting, micro-displays and LiFi

BY BING WANG, LI ZHANG, KENNETH ENG KIAN LEE, FAYYAZ MOIZ SINGAPOREWALA, EUGENE A. FITZGERALD AND JURGEN MICHEL FROM SINGAPORE-MIT ALLIANCE FOR RESEARCH AND TECHNOLOGY

GaN-BASED LED LIGHTING is now commonplace. High-brightness, white-light emitting chips that hit the market about two decades ago are in our light bulbs, and they are backlighting our smart phones, tablets and TVs.

Unlike many compound semiconductor devices, the GaN LED is grown on a variety of substrates. Due to the lack of an affordable native platform, makers of these emitters are predominantly producing them on sapphire, although several firms are undertaking high-volume manufacture on SiC or silicon. Although heteroepitaxy on all these substrates leads to the formation of many dislocations, fortunately these imperfections do not prevent the manufacture of LEDs with very impressive levels of efficiency.

There are several compelling reasons for selecting silicon as the foundation for GaN LED production. Manufacturing on this material enables the use of a more common substrate, which has been employed in the microelectronics industry for over half a century. This substrate is also cheaper than any of the alternatives, it is available in larger sizes, and it is compatible with well-established CMOS wafer and chip processing and packaging technology. Together these benefits lead to substantial cost savings, with a switch in production from GaN-on-sapphire to 200 mm GaN-on-silicon epiwafers generating cost savings of 60 percent, according to estimates by Samsung. What's more, with this particular material technology, it is possible to address markets beyond general lighting, by integrating GaN LEDs with silicon CMOS circuits.

Given this wonderful set of attributes, it is not surprising that many manufacturers of LEDs are evaluating devices made on silicon. Although performance was initially inferior to the GaN-on-sapphire LED, thanks to advances in epitaxy, this difference is now very small.

The growth of GaN-on-silicon creates LEDs that can span the green and blue regions of the visible spectrum. For a white light source, emission in the red is also required, which can be realised by adding phosphors to these chips. But this leads to losses associated with down-conversion, so for next-generation, ultra-efficient solid-state lighting, green and blue emitters must be combined with red LEDs.

Realising red LEDs

Red LEDs are typically made with AlGaInP, a semiconductor with a smaller bandgap than GaN and a higher electrical-to-optical conversion efficiency. These devices are grown on GaAs substrates, which are smaller, far more fragile and more expensive than silicon. So a switch to a silicon substrate would be beneficial. Implementing this, however, is very challenging for several reasons.

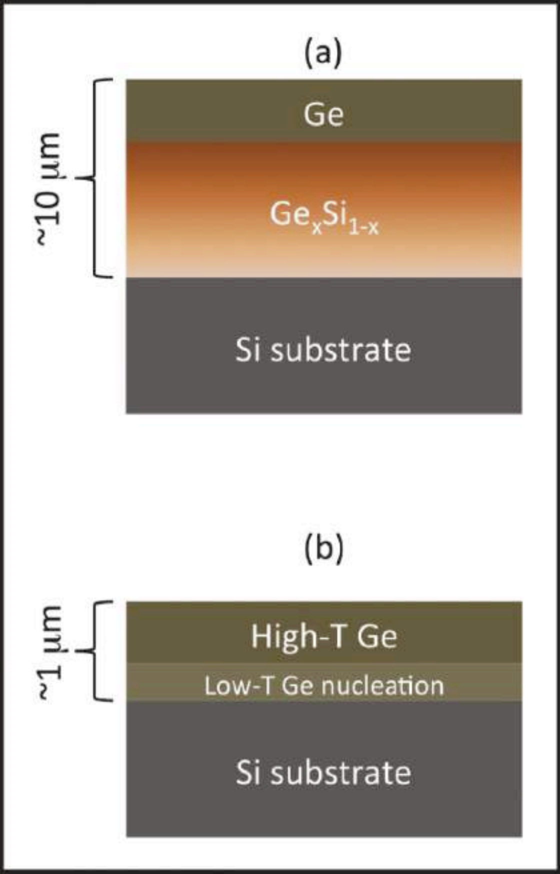

Figure 1 (a): A low threading dislocation density can be realised with compositional-graded Ge_xSi_{1-x} buffers. However, the total thickness of the layers is typically 10 µm. (b) Using low temperature nucleation and high temperature growth, the germanium grown on silicon can achieve a low threading dislocation density of around 10^7 cm^{-2}, but with a total thickness that can be as low as about 1 µm. By using arsenic doping in the nucleation stage, the low threading dislocation density can be further decreased by a factor of 5.

One of the biggest issues is that the AlGaInP used for making red and yellow LEDs has a 4 percent lattice-mismatch with silicon. This mismatch across a single interface leads to the generation of many threading dislocations, which are detrimental to the performance of the AlGaInP LED. Another downside is that the interface between AlGaInP and silicon is heterovalent, so films of the quaternary are riddled with other forms of defects, such as anti-phase domains and stacking faults. Due to these issues, progress with AlGaInP LEDs on silicon substrates has been slow, with performance lagging that of their GaN-on-silicon cousins.

To address the high density of dislocations that result from direct epitaxy of GaAs and/or AlGaInP on silicon,

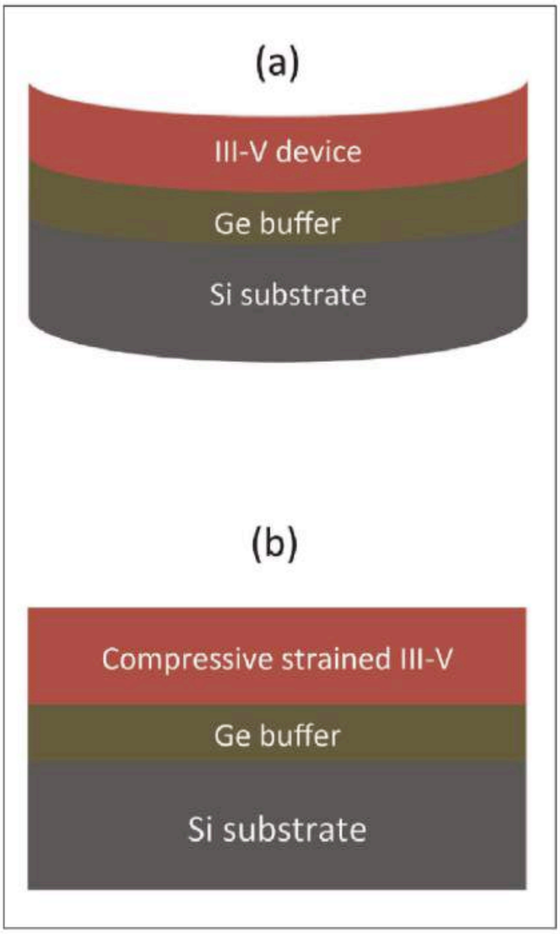

Figure 2: (a) Due to the thermal expansion mismatch between III-V layers and silicon, the wafer has a concave bow after epitaxy. (b) It is possible to decrease wafer bow by applying compressive strain in III-V layers.

it is possible to employ a high-quality buffer layer with an intermediate lattice constant to bridge the lattice mismatch. Germanium is a great choice, thanks to a lattice-mismatch with GaAs that is significantly smaller than that between silicon and GaAs.

A high-quality heterostructure results from the cyclical annealing of germanium. This yields the lowest possible threading dislocation density for a single mismatched interface in this lattice constant range. Dislocations can be driven even lower by gradually adding germanium into silicon to create a compositional-graded Ge_xSi_{1-x} buffer with a thickness of approximately 10 μm. Such a structure has already provided the foundation for AlGaInP micro-LED arrays.

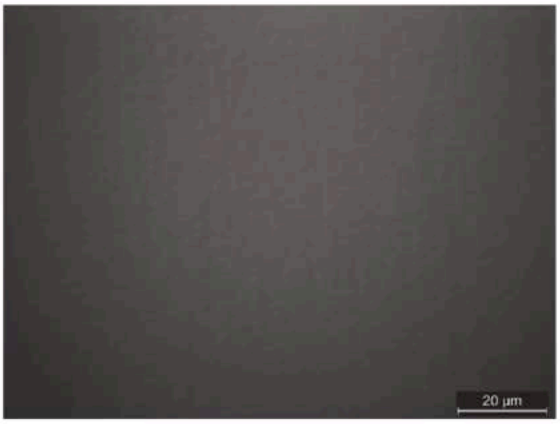

Figure 3: Nomarski microscopy image of an AlGaInP LED 200 mm wafer. The wafer bow is about 45 μm.

Thinning the buffer

At the Singapore-MIT Alliance for Research and Technology (SMART) Low Energy Electronic Systems (LEES), we are following in the footsteps of the pioneers of red LEDs on silicon by developing a high-quality germanium buffer with a two-step growth method. Our approach involves depositing a thin germanium nucleation layer at low temperature, followed by regular high temperature growth.

Although this approach is not new, care must still be taken to ensure uniform high-quality films on the 200 mm silicon substrates. By optimizing growth parameters, the threading dislocation density can plummet to the mid-$10^7/cm^2$ range after the growth of just 1 μm of germanium. This creates a high-quality germanium buffer, which can serve as an excellent template for subsequent III-V epitaxy. (Note that it is possible to realise a further five-fold reduction in the dislocation density by introducing high arsenic doping in the nucleation stage. However, this technology for reducing defect density has not been used in the LEDs described in this feature.)

The next challenge is the growth of the heterovalent interface. If anti-phase domains and stacking faults are present at the heterointerface, GaAs-on-germanium films will be riddled with threading dislocations. These dislocations, and the anti-phase domains and stacking faults, act as non-radiative recombination centres, slashing the efficiency of LEDs grown on this heterostructure. What's more, the anti-phase domains propagate to the film's surface, resulting in rough surfaces.

The anti-phase domains arise from the exact (001) silicon and germanium surfaces, which have a plethora of mono-atomic steps. So, to avoid them, we use (001) wafers that are 6° offcut to the nearest <111> direction. This approach ensures the formation of double atomic-stepped surfaces.

To realise high-quality epitaxy, we found that in addition to using a high-temperature, pre-growth bake of the germanium buffer to fully activate double-atomic stepped surfaces, it is critical to optimise the arsine partial pressure. Do this, and defects are suppressed during GaAs nucleation, so this layer has a threading dislocation density that is as low as that in the germanium layer.

Another downside of the growth of III-V-on-silicon device layers is the mismatch of coefficients of thermal expansion. This difference induces stress in the epitaxial layers and causes wafer bow, which can be particularly severe when large silicon wafers are used.

For AlGaInP LEDs grown on 200 mm silicon, bowing can exceed 100 μm. This level of bow hinders many critical wafer-scale processes, such as wafer bonding and lithography. Complicating matters, strain in the AlGaInP leads to a rough surface – and it also produces changes to the bandstructure, which push emission from the active region to longer wavelengths.

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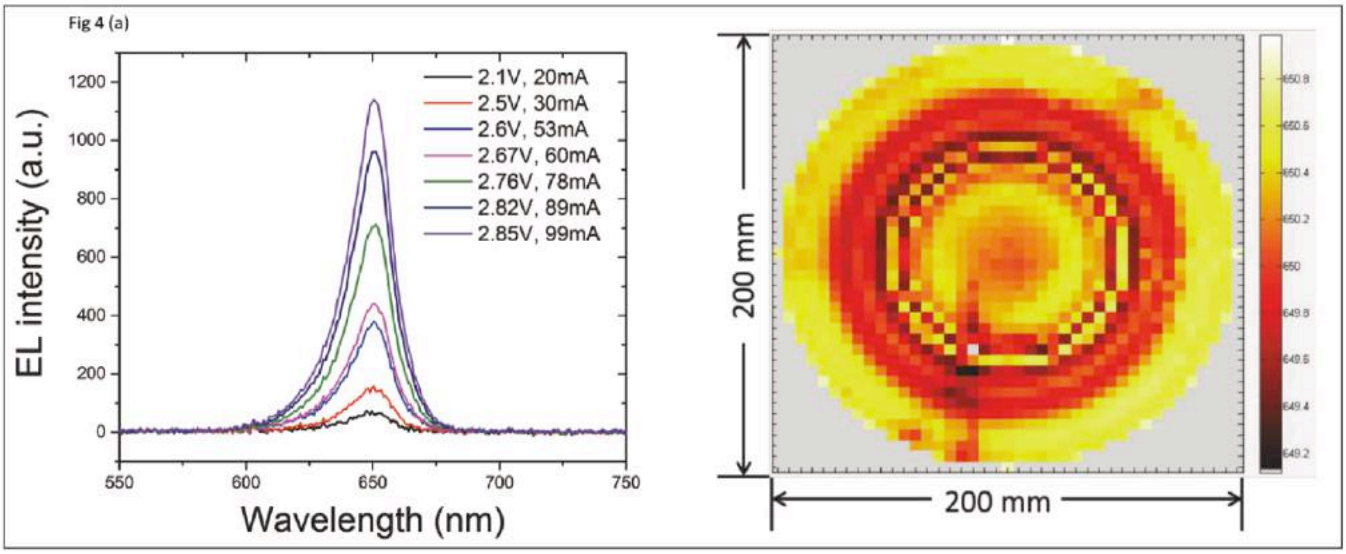

Figure 4 (a) Current-voltage characteristics and electroluminescence spectra under different injection currents of a 1 µm × 1 µm LED. (b) Photoluminescence peak wavelength mapping across a 200 mm LED wafer.

To overcome all these problems, we incorporate compressive strain in our AlGaInP layers. This compensates for the tensile strain from thermal expansion mismatch. Taking this approach creates wafers that are flatter and have a better surface morphology. Typically, our wafers have a concave wafer bowing below 50 µm, which is acceptable for most 200 mm wafer bonding, processing and lithography steps.

Using this approach, we have produced, we believe for the first time, red LEDs with AlGaInP multiple-quantum-wells on 200 mm silicon substrates. Photoluminescence mapping reveals excellent uniformity, with a wavelength variation across the whole wafer of less than 2 nm. We have also demonstrated the operation of these red LEDs. While we have not made fully quantitative power measurements, we estimate our devices to emit in the microwatt range and above based on simple photodiode measurements.

As well as optimizing epitaxy, we have explored wafer-scale processing and CMOS-integration. This has enabled our group to create novel engineered substrates by transferring layers from front-end silicon CMOS wafers onto 200 mm AlGaInP-on-silicon LED wafers. Good bonding occurs across the entire wafer, according to infrared transmission measurements.

Our successes to date lay the foundation for processing 200 mm LED wafers and higher-valued integrated silicon CMOS products. We are currently using the aforementioned LED wafers in one of our design platforms to unite red LEDs with silicon CMOS technology. Engineered wafers that unite both technologies are formed before windows are opened through the top silicon CMOS layer to expose III-V epitaxial layers. LEDs are fabricated in these windows, before adding interconnect vias, which are co-planar with the silicon front-end transistors.

By adopting this approach, wafers can be returned to

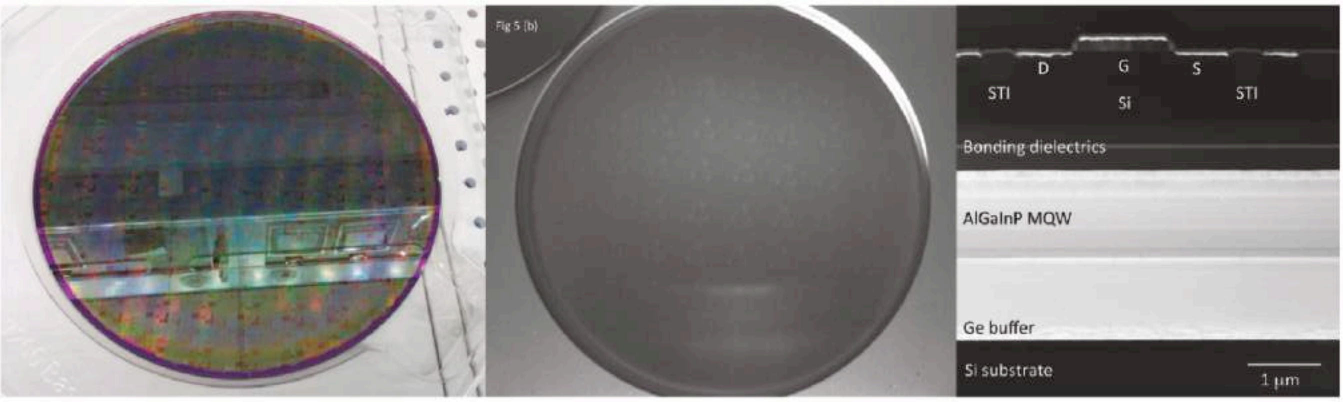

Figure 5. (a): Photograph of a 200 mm engineered wafer consisting of a silicon-CMOS layer that is bonded onto an AlGaInP LED wafer. (b): Transmission infrared image of the silicon-CMOS + AlGaInP LED engineered wafer. (c) Cross-sectional TEM image of the silicon-CMOS + AlGaInP LED engineered wafer. A Si transistor (S: source, D: drain, G: gate), bonding interface, and the AlGaInP MQW LED layers are indicated.

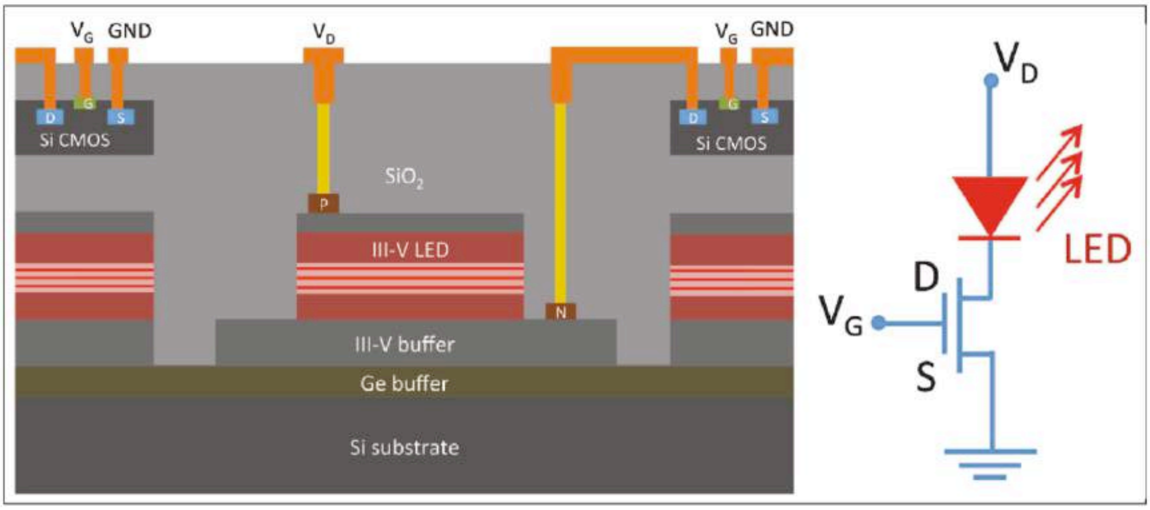

Figure 6 Cross-section illustration and schematic of an integrated AlGaInP LED with silicon CMOS on a 200 mm silicon substrate.

the foundry for standard back-end processing, where interconnects are made between the silicon transistors and the III-V devices. With this methodology, silicon CMOS processes are completely separated from III-V processes, while retaining a monolithic flow that is consistent with current industry practice. We are currently running test chips that combine AlGaInP LEDs with silicon CMOS, in conjunction with our partner foundries.

A similar technology that we have developed brings together GaN LEDs with silicon CMOS. Unite these two platforms, and it will be possible to realise red, green and blue full-colour LEDs on silicon. And thanks to the silicon CMOS technology that would be present, complex control functions could be brought to individual LEDs and micro-LED arrays.

We believe that this could unlock the door to many new markets for integrated LEDs, such as smart and integrated lighting, internet of things (IoT) systems, LiFi, micro-displays, low cost smart tags, and projection displays with small form factors. Our integrated LED technology platform will shine a new light on future silicon ICs.

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SOI: A GREAT FOUNDATION FOR THE GaN HEMT

Switching the substrate from silicon to SOI increases the RF performance of the GaN HEMT, thanks to a foundation with lower loss and better isolation

BY HSIEN-CHIN CHIU, LI-YI PENG, HSIANG-CHUN WANG AND HOU-YU WANG FROM CHANG GUNG UNIVERSITY, TAIWAN, AND G.-Y. LEE AND JEN-INN CHYI NATIONAL CENTRAL UNIVERSITY, TAIWAN

THANKS TO RAPID ADVANCES in silicon technology, the performance of nanoscale devices for microwave and millimetre-wave integrated circuits is rising fast. However, with silicon, the output power density at millimetre-wave frequencies is limited, while signal loss is significant.

To realise a high output power and a wide bandwidth, the tried and tested solution is to heterogeneously integrate silicon with another semiconductor material on the same substrate.

A common option is to unite silicon with the GaN HEMT. This pairing is capable of producing a high output at high frequencies, due to the wide bandgap of GaN and its capability to handle high power densities. Additional merits of the GaN-on-silicon HEMT are that it can be manufactured at a very competitive cost, and production is scalable, due to the widespread availability of silicon substrates of various sizes.

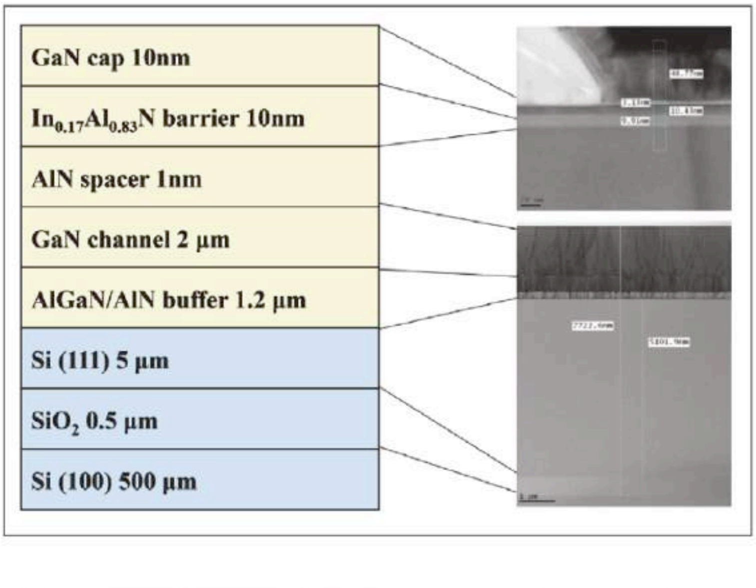


Figure 1. InAlN/AlN/GaN HEMTs are produced on a 6-inch SOI substrate.

However, the GaN-on-silicon HEMT has a number of flaws. A significant one is that electrical breakdown occurs vertically through the silicon substrate, due to the large lattice mismatch between the two semiconductors and the comparatively low electrical field strength of silicon – it is just 0.3 MV/cm. Another downside is that the best plane of silicon for GaN growth is (111), while the plane for traditional silicon devices is (100); and third significant issue is that the silicon substrate is lossy, especially at radio frequencies, due to its low resistivity and its high loss tangent characteristics.

To address all these issues several research groups, including our team from Taiwan – a partnership between researchers at Chang Gung University and National Central University – has turned to the silicon-on-insulator (SOI) substrate as a foundation for the GaN HEMT.

During the last decade, this substrate has proven its capability in commercial applications in harsh environments, where there can be high temperatures and intense levels of radiation; and it has shown its effectiveness at millimetre-wave frequencies, with cut-off frequencies approaching 500 GHz. Another key attribute of the SOI foundation is its high resistivity, which slashes substrate losses in RF integrated circuits. SOI substrates have a higher degree of isolation than those made from silicon, thanks to the oxide layer buried beneath the active region. This design also eliminates substrate noise stemming from crosstalk propagation.

Thanks to all these strengths, in 2004 the SOI trailblazer Peregrine was able to report at the RFIC Symposium that is had used this technology to fabricate RF switches for mobile communication that could contend with power levels up to 35 dBm at frequencies of approximately 2 GHz. Since then, this US chipmaker has ramped production of these SOI devices, which have replaced GaAs pHEMTs as the most common class of switch in handsets.

The strengths of the SOI substrate at high frequencies make it a very promising foundation for producing microwave devices with a high output power density.

Laying the groundwork for such efforts, in 2013 a team from Hong Kong University of Science and Technology reported the first GaN-based HEMT on a SOI substrate. These transistors exhibited a high breakdown voltage, a low on-resistance, and a reduced vertical leakage – three characteristics that are beneficial for switching power device applications.

Our efforts have focused on microwave devices, and involved the use of a silicon (111) handle substrate, which can be used to realize traditional analogue and digital CMOS devices. The first step, SOI substrate preparation, involves bonding a silicon substrate with a (111) crystallographic orientation to the surface of a handle silicon substrate with a (100) crystallographic orientation. This creates a buried SiO_2 layer, sandwiched between two silicon crystallographic orientation layers.

Pairing GaN with AlGaN

Armed with this hybrid substrate, we have set ourselves the goal of increasing the operating speed of a GaN-based device. We have selected the lattice-matched InAlN/GaN HEMT, which is one of the most promising alternatives to the conventional, commercial GaN-based HEMT, because it features a strong spontaneous polarization and high carrier mobility.

In addition, the InAlN barrier layers offers a route to reducing strain in the heterostructure, because the $In_xAl_{1-x}N$ alloy can be lattice-matched to GaN. This pairing promises superior device reliability to that of AlGaN and GaN, especially in high-voltage and high-temperature environments.

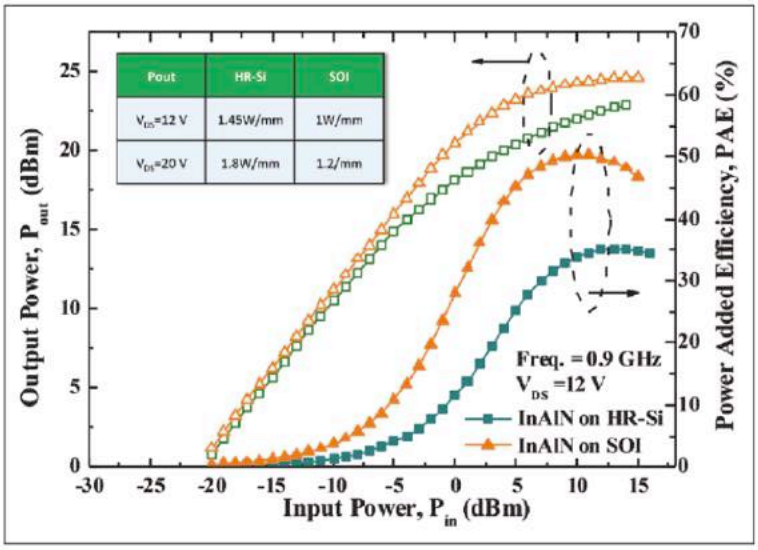


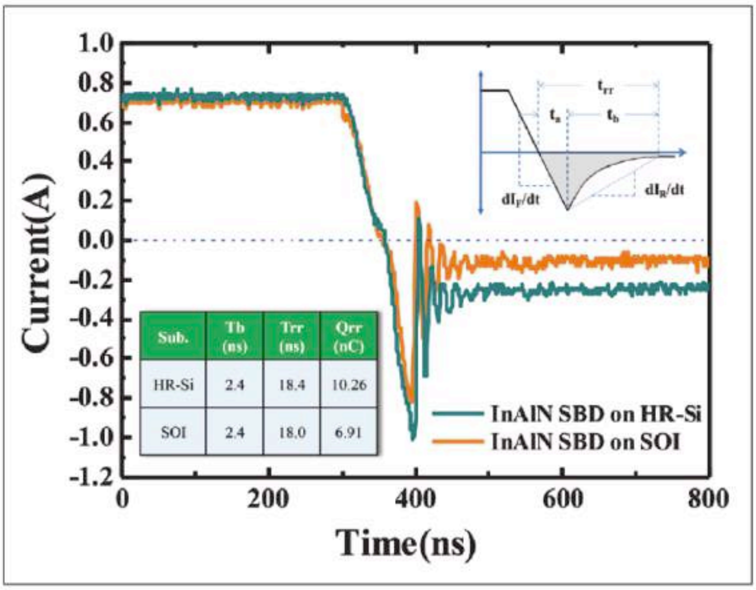
Figure 2. The output power of InAlN HEMTs in the microwave spectrum is higher when the devices are formed on SOI than when grown on high-resistivity silicon.

We have fabricated and assessed InAlN/GaN HEMTs that are formed on a 6-inch SOI substrate. Note that this approach parallels efforts in the silicon industry, where complementary MOSFET SOI technology has been applied extensively to the development of microwave and millimetre-wave integrated circuits. In that case, the SOI technology isolates the transistor from the silicon substrate, and allows for stacking, thereby improving circuit power handling and accommodating wide signal swings.

Our InAlN/AlN/GaN HEMTs were produced by MOCVD on a 6-inch *p*-type (111) silicon SOI substrate with a *p*-type (100) silicon handle wafer with a thickness of 500 μm (see Figure 1 for a cross-sectional diagram and a scanning electron microscope profile). In this structure, the *c*-type (111) silicon layer and the buried SiO_2 were 5 μm-thick and 0.5 μm-thick, respectively. With this SOI substrate design, heterogeneous integration with silicon (100) CMOS-compatible technology is possible by removing the top material: it could be GaN, (111) silicon or SiO_2.

To form our devices, we grew a 2 μm-thick GaN layer on top of a 1.2 μm-thick AlGaN/AlN buffer/transition layer. Increases in the carrier concentration and the mobility of the two-dimensional electron gas resulted from the insertion of a 1 nm-thick AlN spacer layer between the GaN channel and the 10 nm-thick, $In_{0.17}Al_{0.83}N$ Schottky layer. The addition of a 10 nm GaN cap prevents moisture from oxidizing InAlN.

Following device fabrication, we protected the active area of our devices with a low-κ polymer material or a photoresist. The rest of the area is etched and removed using an inductively coupled plasma etcher, until the (111) crystallographic orientation of the



Sub.	Tb (ns)	Trr (ns)	Qrr (nC)
HR-Si	2.4	18.4	10.26
SOI	2.4	18.0	6.91

Figure 3. Reverse recovery characteristics of the InAlN/GaN Schottky barrier diode are better when the device has an SOI foundation, rather than high resistivity silicon. Measurements were made by switching this device from forward (I_F = 1 A) to reverse bias (-30 V) with a dI/dt of 60 A/ms.

handle silicon substrate is exposed. At this stage, traditional silicon CMOS devices can be added to the (111) silicon substrate to provide analogue or logic functions.

We performed on-wafer assessments of our HEMTs, which have a 1 μm-long gate, with a common-source configuration, using a PNA network analyser in conjunction with Cascade direct probes. For comparison, we measured an identical InAlN/AlN/GaN HEMT grown on a high-resistivity silicon substrate.

S-parameter measurements revealed a maximum current gain cut-off frequency (f_T) of 8.4 GHz and a maximum oscillation frequency (f_{max}) of 16.3 GHz for our HEMT formed on SOI. In comparison, the equivalent device on high-resistivity silicon has an f_T of 6.3 GHz and an f_{max} of 12.1 GHz. We attribute the higher frequencies of the SOI-based device to a higher peak transconductance and a smaller loss tangent behaviour associated with the substrate.

The power of SOI

The microwave load-pull power performance of our InAlN HEMTs has been evaluated at 0.9 GHz and a drain bias of 12.0 V. The device on SOI produced a saturated output power of 24.6 dBm and a power-added efficiency of 50.2 percent. In comparison, the figures for the HEMT on high-resistivity silicon were 23 dBm and 35.2 percent (see Figure 2).

The increase in the power-added efficiency for the HEMT grown on SOI is due to a combination of a lower leakage current and a higher f_{max}. Thanks to the lower substrate-induced lateral leakage, the saturated output power of the InAlN HEMT on SOI was higher, especially at high drain-source voltages.

We have also evaluated the potential of our device for power switching applications, by forming a Schottky barrier diode on our InAlN HEMT on SOI. This device shows reverse recovery characteristics when switched from forward to reverse bias, due to the parasitic capacitance of the Schottky diode (see Figure 3).

The magnitude of the reverse recovery charge depends on several factors: the diode junction capacitance, the concentration of deep levels in the bandgap, and the parasitic capacitance shunt to the Schottky diode. The device grown on SOI has a lower reverse recovery charge than that grown on high-resistivity silicon (see inset in Figure 3 for details), thanks to a reduction in the concentration of deep levels in the bandgap.

Our work shows that SOI substrates deliver significant benefits over high-resistivity silicon, including superior electrical characteristics, such as higher operating frequencies, greater load-pull powers and smaller reverse recovery charges. All these characteristics benefit from the reduced stress associated with SOI substrates.

However, the InAlN HEMT on the SOI substrate still requires considerable refinement. Although SOI trims substrate capacitance and lowers crosstalk noise, thanks to the presence of the buried-oxide, this thick subterranean layer increases self-heating in the InAlN HEMT and the Schottky barrier diode. To address this, packaging is needed to provide superior thermal management. A second significant issue is that although the SOI substrate can reduce growth stress compared to the traditional silicon substrate, it is challenging to control the bowing of the substrate during GaN film growth.

Both these issues are not insurmountable, however, and InAlN devices on SOI substrates have a bright future as reliable, high-speed and high-power electronic devices.

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Improving GaSb growth for III-V MOSFETs

Treating the interface between GaSb and GaAs with antimony enables thin, high-quality layers for III-V MOSFETs

GaSb is a very promising material for making III-V MOSFETs, due to its excellent transport properties. It has a hole mobility that is at least twice that of GaAs, and an electron mobility five times that of silicon.

However, progress with this material has been slow. The problem: thick layers of GaSb are needed to ensure high-material quality, but thin layers are a pre-requisite for fabricating ultra-thin body MOSFETs which are promising candidates for next-generation logic, because they can avoid short channel effects through good electrostatic control of the channel potential.

But there is now a solution, thanks to the development of a growth process by researchers at National Cheng Kung University, Taiwan. This work shows how to form a high-quality GaSb layer that is just 10 nm-thick on a GaAs substrate.

High-quality material is an essential ingredient in any high-performance III-V MOSFET. If there are more misfit dislocations, surface roughness is higher, leading to an increase in carrier scattering at the interface. What's more, if the density of misfit dislocations gets too high, it can lead to anisotropy in strain relaxation.

The growth of GaSb on GaAs is not easy, due to a 7.8 percent lattice mismatch between this pair of materials. However, it is possible to produce good-quality GaSb with an approach pioneered by Diana Huffaker's group (her team performed this work at UCLA, and have recently moved to the Institute for Compound Semiconductors, Cardiff).

Huffaker and her co-workers have shown that applying a growth mode that involves interfacial misfit dislocations enables the relief of strain via the formation of 90° misfit dislocations in the [110] and $[\bar{1}10]$ crystallographic directions. Producing dislocations in this particular direction requires the careful selection of the growth temperature.

The team from National Cheng Kung University draws on the work of Huffaker's group, but pursues different goals. "They use an MBE system and focus on optoelectronic device applications," says Hsiao, "but in our case, we used MOCVD and focus on high-quality, ultra-thin layer growth for MOSFET applications."

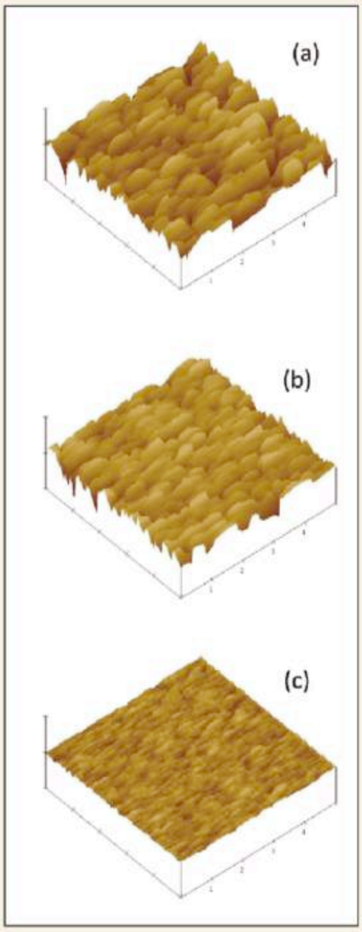
Development of high-quality, MOCVD-grown films by Hsiao and co-workers involved an investigation of the impact of interfacial treatment on the growth of 10 nm-thick GaSb layers at temperatures ranging from 490 °C to 550 °C and V/III ratios of 0.625 to 2.5.

Gallium interfacial treatment resulted in a three-dimensional growth mode; antimony treatment produced a quasi-two-dimensional growth mode; and no interfacial treatment led to a two-dimensional growth mode.

"The quasi-two-dimensional growth mode is better than other modes," says Hsiao. "In others modes, such as the three-dimensional mode, when coalescence occurred between islands, there is a probability to form defects at an island boundary."

Island densities in films formed with antimony treatment were 1.9×10^9 cm^{-2}, compared with 5.1×10^9 cm^{-2} and 2.8×10^9 cm^{-2} for gallium treatment and no treatment, respectively. The team believe that the superiority of the antimony-treated films stems from the increased sticking coefficient of group III adatoms at $[\bar{1}10]$ step edges.

Using antimony treatment, Hsiao grew films at 490 °C, 520 °C and 550 °C and discovered that the morphology follows the kinetics of material growth: at low temperatures, gallium adatoms have a shorter diffusion length, and the density of GaSb islands is higher.



Reducing the III-V ratio from 2.5 (a) to 1.25 (b) and on to 0.625 (c) leads to a smoother film of GaSb.

Calculations suggest that the distance between two 90° misfit dislocations should be 5.6 nm. This is close to the 5.67 nm obtained at 520°C, according to measurements obtained by cross-sectional transmission electron microscopy. The low value is said to occur for misfit dislocations at 90°, due to the slight redistribution of interfacial misfit dislocations via gliding along the interface. This minimises strain energy.

Varying the III-V ratio produced a substantial variation in surface roughness, with the smoothest film obtained for a value of 0.625 (see Figure).

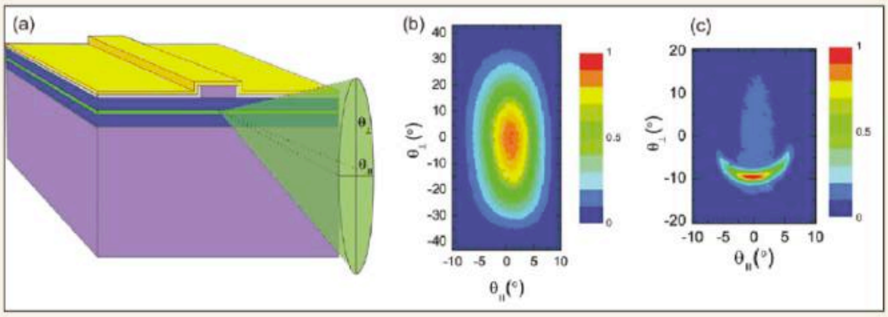
Combining this III-V ratio with growth at 520 °C and antimony treatment yielded a 10 nm-thick GaSb film with a hole mobility of 241 cm^2 V^{-1}s^{-1}.

"We plan to fabricate ultra-thin body GaSb MOSFET using HfO$_2$ as a high-κ dielectric material and e-beam lithography to make metal contacts," says Hsiao.

C. -J. Hsiao *et. al.* Appl. Phys. Express 9 095502 (2016)

Simple, high-performance GaN lasers

Careful selection of the composition and thickness of InGaN waveguides enables the fabrication of GaN lasers with a high beam quality



Beam quality of the laser diode (a) depends on the indium content of the waveguide. For $In_{0.08}Ga_{0.92}N$ (b) beam quality is high, leading to no leakage; but for $In_{0.04}Ga_{0.96}N$ (c), optical modes leak into the substrate and beam quality suffers.

A TEAM OF POLISH RESEARCHERS are claiming to have pioneered the development of a highly effective, simple laser architecture that slashes optical leakage and yields high beam quality. The device that results is an attractive candidate for data storage and laser projection.

Spokesman for the team, Grzegorz Muziol from The Institute of High Pressure Physics, explains that their approach, which involves the use of InGaN waveguides, is one of many technologies for preventing leakage to the substrate.

One alternative is to increase the thickness of the *n*-type AlGaN cladding, but this can lead to cracking in the layer after the critical thickness is exceeded. For AlGaN with an aluminium content of 8 percent, the critical thickness is only about 1 μm.

Another option to trim leakage is to replace AlGaN with AlInN, but realising good conductivity with the latter ternary is challenging; and there are highly doped substrates, but availability is limited.

In addition, there are reports of AlGaN-free lasers grown on semi-polar and non-polar planes.

"These lasers do not suffer from leakage losses and their beam quality is very good, but the confinement of the optical mode with the quantum wells is lower," explains Muziol. One upshot is a higher threshold current.

With the approach pioneered by the Polish team, the only significant downside is that it requires an increase indium content, which impairs crystal quality and leads to higher internal optical losses.

Efforts at understanding optical losses in laser diodes date back to the late 1990s, when devices were grown on sapphire and simulated by a standing wave model. This model allowed the optical mode to leak through the *n*-type, AlGaN cladding into a GaN buffer layer, and be reflected off of the epilayer-substrate interface. Results with this model include the prediction of a far-field pattern with two symmetrical peaks. Increasing the thickness of the AlGaN can cut leakage, leading to far better beam quality.

Switching growth to GaN substrates does not eradicate mode leakage. However, a different model is needed to describe this type of device – it produces an asymmetrical peak, due to leakage from the substrate.

Muziol and co-workers have used this newer model to study laser losses. Calculations reveal that the higher the aluminium content in the cladding, the lower the leakage. That's because the intensity of the optical field in the bottom cladding decreases more rapidly with high aluminium content.

Leakage loss also falls when the indium content in InGaN increases. More indium means greater confinement in the InGaN waveguide and a reduction in the intensity of the optical field beside the AlGaN cladding.

Calculations also show it is helpful to consider the effective refractive index of the waveguide. Its value depends on the aluminium content in AlGaN, and when it exceeds the refractive index of the substrate, leakage is fully suppressed. The effective refractive index also depends on the thickness and composition of the InGaN waveguide. The lower the indium content, the thicker the waveguide should be – full elimination of the leaky mode is possible for $In_{0.08}Ga_{0.92}N$ that is 90 nm thick, or $In_{0.04}Ga_{0.96}N$ that is 200 nm thick.

Armed with these insights, the team produced a range of laser structures to verify the results of their calculations. Lasers with a 145 nm-thick $In_{0.04}Ga_{0.96}N$ waveguide produced a very strong, sharp intensity peak – it had a magnitude seven times that of the maximum of the Gaussian profile in the far field. This is due to strong leakage into the GaN substrate.

Meanwhile, measurements of devices with an indium content of $In_{0.05}Ga_{0.95}N$ or more, and a waveguide thickness of at least 145 nm, do not suffer from mode leakage and emit a high-quality beam.

According to Muziol, the team's next step is to decrease the internal losses of the laser via an increase in the crystal quality of the InGaN layers.

"This will improve the operating parameters of these devices, and hopefully allow us to try and commercialise them in co-operation with TopGaN, in applications which require high optical beam quality."

G. Muziol *et. al.* Appl. Phys. Express 9 092103 (2016)

Heterojunction improves terahertz detection

A hetero-barrier rectifier formed from InP and InGaAs delivers terahertz detection with great linearity and very low noise

A pair of Japanese researchers has built a novel diode that delivers low-noise terahertz detection while operating at room temperature.

This device could be used in several applications, including imaging, spectroscopy, and broadband wireless communications, according to corresponding author Hiroshi Ito from Kitasato University.

The diode, produced by Ito and his co-worker Tadao Ishibashi from NTT Electronics Techno Corporation, offers several advantages over the Schottky barrier diodes currently used for terahertz detection.

One of the major weaknesses of the incumbent diodes is that they have a barrier height that depends on less-controllable surface states. In addition, they are hampered by a large differential resistance, especially under zero bias, that makes it challenging to realise impedance matching between the diode, input antenna and readout circuit.

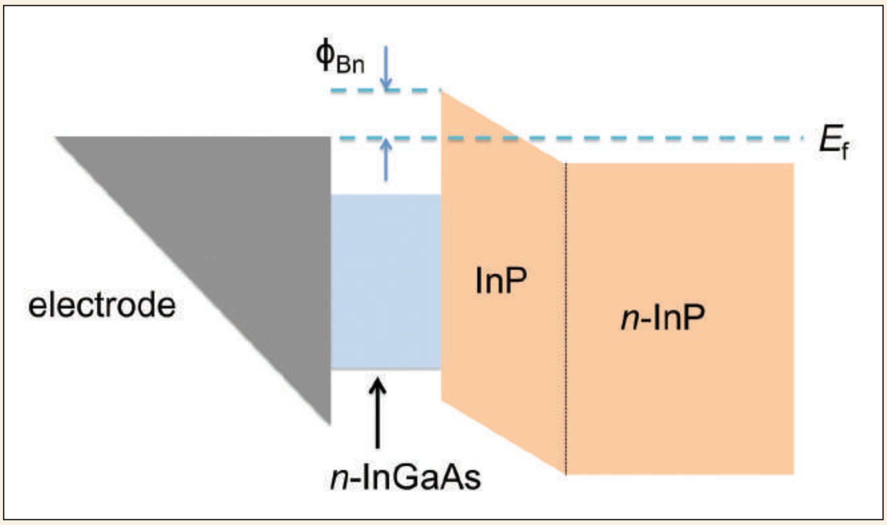
All these drawbacks are addressed with the duo's InP/InGaAs hetero-barrier rectifier, which they refer to as a Fermi-level managed barrier.

"[It] can realise a very low barrier height, and thus a very low intrinsic differential resistance," explains Ito.

The other key attribute of this device is a heterobarrier structure that is fixed during epitaxial growth, leading to stable, controllable, reproducible characteristics.

Three layers lie at the heart of the device: *n*-type InGaAs, undoped InP, and *n*-type InP. In the heavily doped *n*-type InGaAs, the Fermi level is located above the conduction band edge, with a position that depends on the carrier density. This enables the barrier height to be varied from 0 meV to 250 meV by adjusting the doping concentration in the InGaAs layer.

Reducing the barrier height leads to a very low differential resistance, which simplifies impendence matching and leads to lower noise for the output amplifier. A lower barrier height also results in a higher output current density, allowing the diode to be paired with a low-noise current amplifier.



Strengths of the Fermi-level managed barrier diode include a very low differential resistance, which simplifies impendence matching.

Ito and Ishibashi formed their Fermi-level managed barrier diode by dry etching, to create a junction area of 0.38 μm^2. The device has a doping level of 5×10^{18} cm^{-3} in the *n*-type InGaAs, enabling a 100 meV barrier height. The barrier layer was 50 nm-thick InP.

The duo monolithically integrated their diode with a fan-shaped, 180 μm radius broadband bowtie antenna, before housing the resulting structure in a compact, quasi-optical package.

Static current-voltage measurements of the diode were fitted to a model of the device. These efforts revealed an intrinsic differential resistance, under zero bias, of 109 Ω. This value, which is claimed to be very small for a junction of that area, along with an estimated effective barrier height of 69 meV, indicates that the Fermi-level managed barrier diode displays the desired characteristics.

Measurements of the diode at a range of frequencies revealed broadband detection from 160 GHz to 1.4 THz, with a peak of 3.2 MV/W at 300 GHz.

The reduction in sensitivity beyond 300 GHz is related to the second power of frequency, a behaviour that can be attributed to the capacitance-resistance time constant of the diode. Below 300 GHz, sensitivity decreases with frequency, due to a spot size of the input signal that exceeds the dimensions of the antenna.

Plots of output voltage as a function of input power at 300 GHz reveal excellent linearity and a dynamic range stretching over more than five decades.

The researchers estimate a noise-equivalent power for the device of 30 pW/√Hz at 300 GHz, and 33 pW/√Hz at 1 THz. "The noise-equivalent power obtained so far looks better than that of commercially available Schottky barrier diodes," says Ito.

He and his co-worker will now focus on improving the performance of their barrier diode.

H. Ito *et. al.* Appl. Phys. Express **9** 092401 (2016)

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