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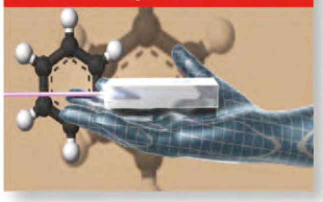

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AN ANGEL BUSINESS COMMUNICATIONS PUBLICATION

editorialview

by Dr Richard Stevenson, Editor

The silver lining

ONE WAY to assess the health of an industry is to take a look at the share prices of the stalwarts within its sector.

Judged in these terms, the compound semiconductor industry is not having it easy – Cree, Aixtron, Qorvo and Skyworks have all undergone a fall in valuation of at least 20 percent in the last 12 months. And this heavyweight quartet are not alone. In our yearly assessment of share price performance, only four out of our 15 firms included in this survey had a higher valuation than they did the previous year – and of those, only two delivered double-digit growth (see p.28).

I have to admit that the identity of the darling amongst the CS stocks came as a surprise to me. It's not a company that is making headlines with massive growth margins and a great earnings-per-share. But it is undoubtedly on an upward trajectory, following some very difficult times.

Before I reveal its identity, I'll give you a clue: it is operating in the optical communications market, where it is one of several companies that are working close to their capacity. Within this sector, demand is up in both the telecom and datacom markets, and firms are launching new products to enable increases in network capacity (to keep pace with developments, I recommend you subscribe to our new publication, *PIC Magazine*, which launches this June – see www.picmagazine.net).

So who is topping this year's share price leader board with a valuation that has increased by over 160 percent in the last 12 months? It's Oclaro, a company that took bold steps in 2014 to bring down its costs by slashing its workforce from 3000 to 1500 and halving its number of sites to 10.

Oclaro has clearly turned the corner since those dark days, and there is hope of healthy profits very soon. In the last fiscal quarter, Oclaro made $2.5 million on sales of $101 million, and in the next quarter it anticipates earnings of up to $11 million on sales ranging from $115 million to $123 million.

Alongside Oclaro, the only other firm on our leader board delivering double-digit growth is JDSU spin-out Lumentum. Its revenue is also rising, and it expects a profit of up to $22 million in the next quarter, on sales of up to $242 million.

Since the burst of the dot.com bubble telecom firms have endured many tough years, so I'm delighted to see their recovery. But I hope it will not be long before they are not just a silver lining in a grey cloud, but part of a portfolio of CS stocks that are rising.

Editor Richard Stevenson richardstevenson@angelbc.com +44 (0)1291 629640
Contributing Editor Rebecca Pool editorial@rebeccapool.com
News Editor Christine Evans-Pughe chrise-p@dircon.co.uk
Publisher Jackie Cannon jackie.cannon@angelbc.com +44 (0)1923 690205
Senior Sales Executive Robin Halder robin.halder@angelbc.com +44 (0)2476 718109
Sales Manager Shehzad Munshi shehzad.munshi@angelbc.com +44 (0)1923 690215
USA Representatives Tom Brun Brun Media tbrun@brunmedia.com +001 724 539-2404
Janice Jenkins jjenkins@brunmedia.com +001 724-929-3550
Amy Rogers arogers@brunmedia.com +001 678-714-6775
Director of Logistics Sharon Cowley sharon.cowley@angelbc.com +44 (0)1923 690200
Design & Production Manager Mitch Gaynor mitch.gaynor@angelbc.com +44 (0)1923 690214

Circulation Director Jan Smoothy jan.smoothy@angelbc.com +44 (0)1923 690200
Chief Operating Officer Stephen Whitehurst stephen.whitehurst@angelbc.com +44 (0)2476 718970
Directors Bill Dunlop Uprichard – CEO, Stephen Whitehurst – COO, Jan Smoothy – CFO, Jackie Cannon, Scott Adams, Sharon Cowley, Sukhi Bhadal, Jason Holloway

Published by Angel Business Communications Ltd, Hannay House, 39 Clarendon Road, Watford, Herts WD17 1JA, UK. T: +44 (0)1923 690200 F: +44 (0)1923 690201 E: ask@angelbc.com

Angel Business Communications Ltd, Unit 6, Bow Court, Fletchworth Gate, Burnsall Road, Coventry CV5 6SP. UK. T: +44 (0)2476 718 970 F: +44 (0)2476 718 971 E: info@angelbc.com

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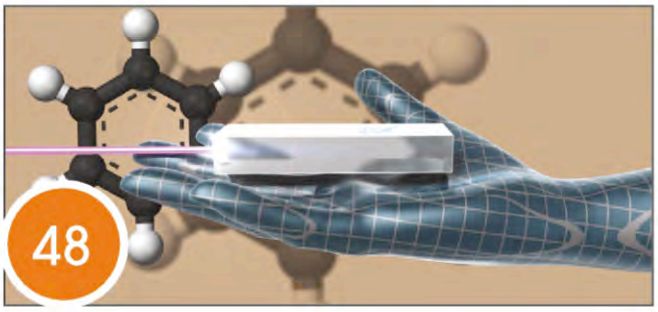


Chinese investment fund launch offer for Aixtron

GERMAN semiconductor deposition firm Aixtron and Grand Chip Investment GmbH, a 100 percent indirect subsidiary of Fujian Grand Chip Investment Fund LP have entered into an agreement to take over Aixtron.

Fujian Grand Chip Investment Fund is a Chinese investment fund; 51 percent of which is held by the Chinese business man Zhendong Liu and 49 percent by Xiamen Bohao Investment Ltd.

Under the terms of the agreement, Aixtron shareholders will be offered €6.00 in cash per each ordinary share. The transaction values Aixtron's equity, including net cash, at approximately €670 million and reflects a 50.7 percent premium to the three-month volume weighted average share price prior to announcement.

The offer shall be subject to certain closing conditions, including regulatory approvals and a minimum acceptance threshold of 60 percent of all of Aixtron's outstanding shares.

The agreement sets out the purpose and the principal terms of the transaction with FGC and the future strategy. FGC intends to support Aixtron's strategy going forward. R&D competency and Aixtron's

existing technology shall be maintained at the existing technology centers. FGC has also agreed that Aixtron shall further strengthen its technology and IP Portfolio, which shall remain vested with Aixtron, including in Germany.

Aixtron's existing global set up will be maintained and expanded with Aixtron's three technology hubs in Herzogenrath (Germany), Cambridge (UK) and Sunnyvale (USA). Further international technology hubs may be established. Aixtron's legal domicile and headquarters shall remain in Herzogenrath, Germany.

In the event the takeover is successful, Martin Goetzeler is to remain CEO of Aixtron and Bernd Schulte is to remain in his function as COO. Following a successful closing of the transaction it is anticipated that Grand Chip Investment will nominate four candidates to the six-member Supervisory Board.

Macom launches plastic packaged chip for RF energy applications

ANALOGUE RF and microwave company Macom has announced a plastic-packaged 300 W GaN-on-silicon rugged power transistor for use in commercial scale solid-state RF energy applications.

Based on Macom's Gen4 GaN technology, the new MAGe-102425-300 is said to deliver performance that defies the inherent power efficiency and density limitations of LDMOS at an equivalent price profile at scaled volume production levels.

The combination of GaN performance and silicon cost structures offers an opportunity to use solid-state RF energy as an efficient and precise heat and power source for many commercial applications including microwave ovens, automotive ignition, lighting systems and industrial, scientific and medical (ISM) applications including RF plasma lighting, material drying, blood and tissue heating and ablation, and beyond.

Providing 300 W output power and 70 percent efficiency at 2.45 GHz, the MAGe-102425-300 meets the core technical requirements for next generation power amplifiers proposed by the RF Energy Alliance, a non-profit technical association dedicated to unlocking the potential of RF energy.

POET Technologies to acquire BB Photonics

POET TECHNOLOGIES, a developer of opto-electronics fabrication processes, has signed an agreement to acquire all the shares of BB Photonics, a private designer of photonic integrated circuits (PICs) for the datacommunications market.

BB Photonics, a pre-revenue, New Jersey-based privately held photonics company currently develops PICs using a platform technology approach using embedded dielectric technology that is intended to enable on-chip athermal wavelength control and lower the total solution cost of datacentre photonic integrated circuits.

This strategic acquisition of BB Photonics will provide POET with additional differentiated IP and knowhow for future product development at its facilities in Singapore recently acquired through the DenseLight transaction. Collectively this will enable POET to better service the end to end datacoms market and augment its sensing roadmap.

"The acquisition of BB Photonics helps bolster our intellectual property and know how in integrated photonic solutions and enables broad applications through its unique performance and cost capabilities. It is anticipated that these factors will allow us to expand, accelerate and complement our current roadmap", said Suresh Venkatesan, POET's CEO. "This is another synergistic and timely acquisition for us as we focus on providing our existing and future customers a broader range of differentiated photonics technologies."

"BB Photonics is excited to be part of POET Technologies and to enable athermal multi-wavelength photonic integration in high speed indium phosphide devices", said Bill Ring, CEO of BB Photonics. "We look forward to working closely with POET and DenseLight to bring our differentiated IP to market and deliver meaningful shareholder value".

UNSW nudges closer to physical limits of solar cell efficiency

A NEW SOLAR CELL configuration developed by engineers at the University of New South Wales in Sydney has pushed sunlight-to-electricity conversion efficiency to 34.5 percent – establishing a new world record for unfocussed sunlight and nudging closer to the theoretical limits for such a device.

The record was set by Mark Keevers and Martin Green, senior research fellow and director, respectively, of UNSW's Australian Centre for Advanced Photovoltaics, using a 28 cm^2 four-junction mini-module – embedded in a prism – that extracts the maximum energy from sunlight.

The record-setting UNSW mini-module combines a silicon cell on one face of a glass prism, with a triple-junction solar cell on the other.

The triple-junction cell targets discrete bands of the incoming sunlight, using a combination of three layers: InGaP; InGaAs; and germanium. As sunlight passes through each layer, energy is extracted by each junction at its most efficient wavelength, while the unused part of the light passes through to the next layer, and so on.

Some of the infrared band of incoming sunlight, unused by the triple-junction cell, is filtered out and bounced onto the silicon cell, thereby extracting just about all of the energy from each beam of sunlight hitting the mini-module.

The new UNSW result, confirmed by the US National Renewable Energy Laboratory, is almost 44 percent better than the previous record – made by Alta Devices of the USA, which reached 24 percent efficiency, but over a larger surface area of 800cm^2.

"This encouraging result shows that there are still advances to come in photovoltaics research to make solar cells even more efficient," said Keevers. "Extracting more energy from every beam of sunlight is critical to reducing the cost of electricity generated by solar cells as it lowers the investment needed, and delivering payback faster."
The result was obtained by the same UNSW team that set a world record in 2014, achieving an electricity conversion rate of over 40 percent by using mirrors to concentrate the light – a technique known as CPV (concentrator photovoltaics) – and then similarly splitting out various wavelengths.

The new result, however, was achieved using normal sunlight with no concentrators.

"What's remarkable is that this level of efficiency had not been expected for many years," said Green, a pioneer who has led the field for much of his 40 years at UNSW.

A recent study by Germany's Agora Energiewende think tank set an aggressive target of 35 percent efficiency by 2050 for a module that uses unconcentrated sunlight, such as the standard ones on family homes.

"So things are moving faster in solar cell efficiency than many experts expected, and that's good news for solar energy," he added. "But we must maintain the pace of photovoltaic research in Australia to ensure that we not only build on such tremendous results, but continue to bring benefits back to society."

Australia's research in photovoltaics has already generated flow-on benefits of more than $8 billion to the country, Green said. Gains in efficiency alone, made possible by UNSW's PERC cells, are forecast to save $750 million in domestic electricity generation in the next decade. PERC cells were invented at UNSW and are now becoming the commercial standard globally.

US team builds first quantum cascade laser on silicon

A TEAM of researchers led by Alexander Spott, University of California, Santa Barbara, USA, have built the first quantum cascade laser on silicon.

Integrating lasers directly on silicon chips is challenging, but it is much more efficient and compact than coupling external laser light to the chips. The indirect bandgap of silicon makes it difficult to build a laser out of silicon, but diode lasers can be built with III-V materials such as InP or GaAs.

By directly bonding an III-V layer on top of the silicon wafer and then using the III-V layers to generate gain for the laser, this same group has integrated a multiple quantum well laser on silicon that operates at 2 μm. Limitations in diode lasers prevent going to longer wavelengths where there are many more applications, so the group turned their attention to using quantum cascade lasers instead. Building a quantum cascade laser on silicon was a challenging task made more difficult by the fact that silicon dioxide becomes heavily absorptive at longer wavelengths in the mid-infrared.

"This meant that not only did we have to build a different type of laser on silicon, we had to build a different silicon waveguide too," Spott explained. "We built a type of waveguide called a SONOI waveguide (silicon-on-nitride-on-insulator), which uses a layer of SiN underneath the silicon waveguide, rather than just SiO_2."

The breakthrough could lead to several applications, Spott explained. "Traditionally, silicon photonic devices operate at near-infrared wavelengths, with applications in data transmission and telecommunications." However, there is emerging research interest in building these silicon photonic devices for longer mid-infrared wavelengths. The next step for the team is to improve the heat dissipation to improve the performance of these QCLs and to allow them to make continuous-wave QCLs on silicon. "We generally hope to improve the design to get higher powers and efficiency," Spott said.

"This brings us closer to building fully integrated mid-infrared devices on a silicon chip, such as spectrometers or gas sensors. Silicon is inexpensive, the fabrication can be scaled up to significantly reduce the cost of individual chips, and many small devices can be built on the same silicon chip - for example multiple different types of sensors operating at different mid-infrared wavelengths."

IQE transfers Translucent process to US plant

SEMICONDUCTOR WAFER and services company IQE has announced the successful transfer of Translucent's cREO growth technology to its North Carolina facility. It has also announced the demonstration of interface charge tuning using cREO for GaN products.
IQE licensed cREO (Rare Earth Oxide) technology from Translucent in September 2015. The cREO process is an IP-protected technique for manufacturing compound semiconductor on silicon wafers, in particular GaN on silicon. This enables the benefits of GaN to be combined with the scale benefits of the silicon chip manufacturing supply chain.

The first of these systems (production tool) has been installed at the facility in Greensboro and is now producing cREO templates on silicon. The template structural and morphological characteristics are an excellent match to previously achieved results by Translucent, according to IQE. The second (R&D) tool is due to be online in approximately one month. The production tool will produce standard templates for the IQE group and select

partners, with initial focus on III-N materials.

Using cREO templates IQE has also demonstrated that it is able to tune the interfacial characteristics for GaN on silicon. For RF applications, GaN on silicon typically exhibits an undesirable *p*-type channel at the GaN / silicon interface (parasitic channel) that detrimentally affects RF efficiency. Using its patented technology, IQE has demonstrated that the parasitic channel can be completely eliminated.

In addition, IQE has shown that growth conditions can be tuned to generate and rationally engineer an *n*-type layer between the GaN and silicon. This enables applications that require buried conductors for III-N on Si applications.
Rodney Pelzel, VP, IQE Group Technology commented: "We have demonstrated that we are able to rationally manipulate the cREO characteristics to tune the conductivity of the III-N / silicon interface. This is a significant enabler for GaN HEMT technology on silicon for RF applications. In addition, it is an enabler for other III-N technology on silicon such as RF filter technology.

"IQE is committed to fully exploiting cREO technology for GaN as well as other III-V and group IV materials. This technology offers exciting opportunities for fully realising III-V growth on silicon thereby eliminating the cost-prohibitive issue with native substrates such as InP.

Furthermore, it enables heterointegration at the epi-level allowing previously incompatible materials systems to be successfully combined. cREO is an excellent complement to IQE's well-established wireless, photonics, power, and CMOS products and will enable novel solutions for our customers."

Ozark to build SiC UV imager for NASA

NASA has awarded $754,000 to Ozark Integrated Circuits, a spin-off from University of Arkansas, to build a SiC-based ultraviolet imager prototype for planetary exploration and Earth observation from space, among other applications.

The complex photo-detecting microchip will be designed to operate in temperatures ranging from 200° to 500°C.

"The uniqueness of our approach is the extreme responsiveness of our imager's sensor and our ability to integrate it with the readout electronics to turn the detector readings into images for a computer or spacecraft system," said Matt Francis, Ozark IC's president and chief executive officer. "NASA would be able to use the imager to observe areas on Earth from space as well as other objects in space."

The use of SiC means the imager can operate at low voltage over a very wide temperature range. That makes it well-suited for planetary exploration that requires space-borne instruments capable of measuring light in the ultraviolet spectrum. Two examples are NASA's Discovery and New Horizons missions – which intend to image planets from orbit or on the surface – and those proposed for Venus, where the imager would need to operate at nearly 500°C.

Francis and Jim Holmes, the company's chief technology officer, have worked with University of Arkansas electrical engineering professor Alan Mantooth and computer science and engineering professor Jia Di over the last several years to perfect design procedures, tools, characterisation and modelling approaches that enable them to design high-temperature electronics capable of operating at conditions well beyond 300°C.

Ozark IC will also use the integrated circuit packaging expertise and facilities of the U of A's High Density Electronics Research Centre (HiDEC). In electronics

manufacturing, circuit packaging is the final stage of semiconductor device fabrication.

The NASA Phase II contract came through the Small Business Innovation Research Program, which allows federal agencies to stimulate technological innovation in the private sector by strengthening small businesses that meet federal research and development needs. The program also is intended to increase the commercial application of federally supported research results.

STMicroelectronics unveils advanced automotive SiC devices

STMICROELECTRONICS has announced advanced high-efficiency SiC power semiconductors for hybrid and electric vehicles (EVs) with a timetable for qualification to the automotive quality standard AEC-Q101.

In EVs and hybrids, where better electrical efficiency means greater mileage, ST's latest SiC technology enables car makers to create vehicles that travel further, recharge faster, and fit better into owners' lives, according to the company.

ST is among the first companies to present new-generation rectifiers and MOSFETs for high-voltage power modules and discrete solutions addressing all the vehicle's main electrical blocks. These include the traction inverter, on-board battery charger, and auxiliary DC-DC converter. "Major carmakers and automotive Tier-1s are now committing to SiC technology for future product development to leverage its higher aggregate efficiency compared to standard silicon in a wide range of operating scenarios," said Mario Aleo, group VP and general manager, power transistor division, STMicroelectronics. "Our SiC devices have demonstrated superior performance and reached an advanced stage of qualification as we support customers preparing to launch new products in the 2017 timeframe."

ST has been among the first companies to produce SiC high-voltage MOSFETs, with its first 1200 V SiC MOSFET introduced back in 2014, achieving 200°C rating for more efficient and simplified designs.

The company is currently fabricating SiC MOSFETs and diodes on 4-inch wafers and will be scaling-up production to 6-inch wafers by the end of 2016. It has already qualified its 650 V SiC diodes to AEC-Q101, and will complete qualification of the latest 650 V SiC MOSFETs and 1200V SiC diodes in early 2017. The qualification of the new-generation 1200 V SiC MOSFETs will be completed by the end of 2017.

The STPSC20065WY 650 V SiC diode is in full production now in DO-247. The range also includes lower current ratings and smaller form-factor TO-220 package options. The STPSC10H12D 1200 V SiC diode is sampling now to lead customers in the TO-220 AC package and goes to production this month, with volume production of the automotive-grade version planned for Q4 2016. Multiple current ratings from 6A to 20A and packaging options will also be available. The SCTW100N65G2AG 650 V SiC MOSFET is sampling now to lead customers in the HiP247 package. It will ramp up in volumes in H1 2017. To enable more compact designs, a 650V SiC MOSFET in the surface-mount H2PAK will also be qualified to AEC-Q101 in H1 2017.

According to the company, using the 650 V SCTW100N65G2AG SiC MOSFET in the EV/HEV main inverter increases the efficiency compared with an equivalent IGBT solution by up to 3 percent. The SiC MOSFET reduces power losses in the inverter (up to 80 percent lower at light/medium load), enabling higher switching frequencies for more compact designs.

Exagan signs partnership with TÜV Nord Group

EXAGAN, a GaN semiconductor technology company, has begun a strategic partnership to develop and commercialise GaN-on-silicon products with Hirex Engineering, a company of Alter Technology Group, which is part of TÜV Nord Group's Aerospace and Electronics Business Unit.

TÜV Nord is a multi-national technical services provider to aerospace, industrial, mobile communications and IT markets. The partnership's goal is to establish the reliability of GaN-on-silicon while also demonstrating to users the performance improvements to be gained and the low risk of integrating the energy-efficient technology in their own products.

Exagan will work closely with Hirex Engineering, a company specialising in reliability testing and qualification of ICs and discrete semiconductors for aerospace and industrial high-reliability applications. Hirex Engineering is located near Toulouse, France.

Together, the companies will test and qualify Exagan's G-FET products, which are fabricated with standard 200 mm silicon processing and proprietary G-Stack technology. G-FETs are used in making smaller, more efficient power converters that have a broad range of applications in high-growth markets including plug-in hybrid and full-electric vehicles, solar energy and industrial applications as well as efficient charging of all mobile electronic devices.

"This dynamic partnership will help to propel GaN market development by pioneering test methodologies and measurement processes that make it easier for makers of electrical converters to implement GaN in improving their products," said Frédéric Dupont, president and CEO of Exagan.

"This timing is perfect to combine Exagan's strengths with those of the top European specialist in high-reliability testing. GaN technology has matured to deliver the high performance of SiC devices at silicon ICs' price and quality levels, and our key markets are ready for this next-generation solution."

"Through its participation, Hirex Engineering will expand its expertise and business portfolio to include advanced power GaN technology and the end products it enables. We hope to establish robust and easy-to-reference product parameters for GaN that will allow fast integration in electrical converters," said Luis Gomez, Alter Technology Group CEO.

Cree and Kingbright settle patent dispute

LED lighting firm Cree has reached a confidential settlement in its patent infringement lawsuit with Kingbright. Kingbright and Cree have agreed to a royalty bearing, worldwide license to the Cree patents-in-suit, ending the lawsuit between the parties.

"Cree is committed to protecting the investment of our current licensees, shareholders and customers by defending our rights in court when necessary and by licensing our patents when appropriate," stated Brad Kohn, vice president legal and general counsel for Cree. "With this settlement and license agreement, Cree has once again obtained value for our extensive IP portfolio."

Cree has developed a broad LED patent portfolio after many years of intensive R&D, with numerous patent applications pending. Major LED manufacturers make use of Cree's patented technology and have signed license agreements with Cree to secure these rights.

Finnish team gets funding to commercialise III-V interface technology

JOHNNY DAHL OF UNIVERSITY OF TURKU (UTU) in Finland has been granted €0.5 million funding for a new project titled *'Commercialisation of Novel Interfaces'* to prepare for a market entry of a new compound semiconductor interface technology. The project is the culmination of long-term research into III-V/oxide interfaces at UTU, in which the group has developed dielectric/III-V interfaces with a much lower density of interface defects (97.5 percent reduction) compared to industry standard interfaces. The technique involves passivating the III-V surface first with a crystalline structure, which works as a platform for subsequent dielectric growth.

"This significant step towards defect density comparable to interfaces of silicon will benefit all III-V market areas. For example, in electronics and photonics, the leakage and dark currents of transistors and photodiodes can be massively reduced," the project leader, Johnny Dahl explains.

"The new technology can also enable many new III-V applications, such as III-V digital electronics. The high density of defects in III-V/oxide interfaces has been a major hurdle preventing the commercialisation of III-V digital electronics, but that problem has been now solved", he continues. The group thinks the new interface technology will be suitable for consumer electronics, fibre optics, telecommunications, digital electronics and even solar cells.

"The timing is just right to bring forth our new interface solutions. III-V materials have consolidated their importance in modern electronics and the technology has matured. The threshold to introduce our solutions to production lines is low and we believe that within two years the first products incorporating our technology will be available to consumers," says Dahl. The new project will last until June 2017 and it is partly funded by Tekes, the Finnish Funding Agency for Innovation.

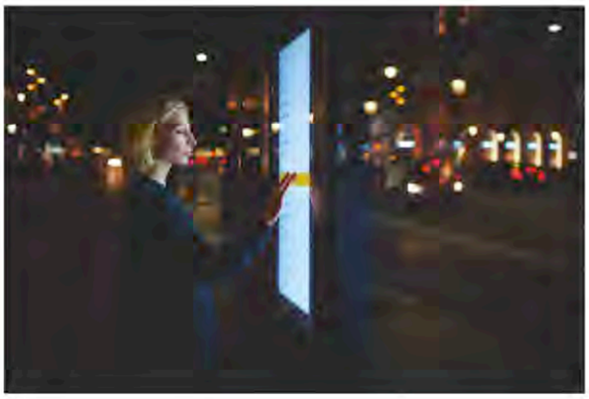
LED video technology gaining strength, says HIS

TOTAL UNIT shipments for all pixel-pitch categories in the direct-view LED video market recorded a 15.6 percent year over year increase in 2015, says IHS.

However, total revenue for 2015 only improved by 1.2 percent compared to the previous year, due to a dramatic price decline across all pixel-pitch categories.

Unit shipments in the direct-view LED video category are forecast to increase steadily at a compound annual growth rate (CAGR) of 16 percent from 2016 through 2020, according to IHS Inc.

"Application trends for the LED video industry differ slightly from other technologies, with little or no installations in corporate and education signage, which tend to rely instead on front projectors and LCD displays," said Sanju Khatri, director of digital signage and professional displays for IHS Technology. "The top applications for LED video are retail, outdoor sports and public spaces. There is a growing trend in indoor applications, particularly in public spaces, retail, control room and corporate signage."



The direct-view LED video market ended 2015 with a 366 percent increase year over year for sub-1.99 mm and a 129 percent increase year over year in 2 mm to 4.99 mm pixel pitch LED video displays, the two fastest growing categories of display resolution. Most of the growth in these resolutions can be attributed to recent technological developments in fine pixel-pitch direct-view LED displays, according to the latest IHS Digital Signage and Professional Displays Market Tracker.

Albeit slower than 2015, robust growth in these two categories is expected to continue in 2016, with an 84.8 percent rise in shipments expected for sub-1.99mm and 77.1 percent for 2 mm to 4.99mm pixel-pitch LED video displays.IHS expects the rate of advancement towards finer pixel pitch to slow significantly in the short term, due to the size limitations of current LED packaging. At the moment the narrowest pixel-pitch LED video display is Leyard's 0.7 mm product, launched in September 2015.

The price difference between sub-1 mm and 1.2 mm to 1.9 mm pixel-pitch displays is almost two times greater; hence, 1 mm pixel pitch LED video displays are rarely installed in a video wall configuration. Unilumin, Aoto, Leyard and other major brands are positioning sub-1 mm pixel-pitch LED video displays as a large format display for retail stores, control rooms, conference rooms, airports and other indoor applications.

In the longer-term, the industry is migrating to chip on board (COB) packaging instead of the traditional surface mount device (SMD), specifically for fine pixel-pitch LED video displays. "The use of COB allows for a much higher packing density of LEDs, enabling compact arrays of LEDs that are more heat efficient, cost effective, longer lasting and reliable," Khatri said. "The LED video display market can look forward to this transition as the production of COB LEDs ramps up."

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Compound Photonics shows off tiny laser-based imaging device

COMPOUND PHOTONICS, a technology company with manufacturing sites in the UK and USA, has released what it claims is the world's smallest native 4K imaging device. Measuring only 14 mm diagonally and featuring pixels smaller than 3μm, the device is based on the company's red, green and blue semiconductor lasers.

"Compound Photonics is the biggest and most capable photonics and projector manufacturer that you have most likely never heard of," declared Tim Anderson, the company's VP of product management in his presentation at the Display Summit China 2016 held in Yixing this week.

"We are the company that has succeeded in introducing the world to RGB solid state laser based technology, making it finally possible to manufacture a 3,000 lumen lamp-less native 4K projector that rivals the performance delivered by today's solid state displays." According to Anderson, the use of RGB laser technology eliminates lamps, creates a huge new colour gamut to work with, and enables balancing the colour output of each colour channel to achieve a perfect white point. What's more, Anderson asserted, Compound Photonics has invested significant engineering resources to reduce the cost of RGB lasers and speckle.

"Projector customers around the world want to be able to project a huge image in full daylight and still have an outstanding image," Anderson said. "Our engineers have developed specific algorithms that use an expanded colour gamut made possible by RGB laser technology. These algorithms combat ambient light and dramatically improve colour contrast."

Anderson said that Compound Photonics offered capabilities ranging from tiny, bright, full HD laser light engines for mobile devices, an embedded 1080P projector that is less than two cubic centimetres in size, IR and green lasers, head-up car displays, near-eye augmented reality, and gesture recognition.

The company owns a GaAs wafer fab in Newton Aycliffe, UK and it also has a semiconductor processing facility in Phoenix, Arizona where it manufactures liquid crystal on silicon displays and optics systems for its laser projection light engines.

Swedish start-up Ascatron raises €4 million

ASCATRON, a spin-out from the Swedish R&D institute Acreo, has completed A-round financing for the final development of its SiC power semiconductors for high voltage applications. The total of €4 million is shared between €3 million in equity capital, and €1 million in an innovation grant. The investors are from Italy and China, including the four venture capital investors Quadrivio, Como Venture, Rise Leader Investment and InteBridge Technology, together with the equipment producer LPE. The grant comes from the European Institute of Innovation and Technology (EIT) through KIC InnoEnergy. KIC supports innovation projects in the field of sustainable energy.

"We have started to implement our advanced material technology in a production equipment for SiC epitaxy", says Adolf Schöner, CTO of Ascatron. "The next step is to optimise our device design and outsource the remaining manufacturing of the chip to a foundry with capacity for volume production". "Our investors have a good mix of understanding both the advanced material technology needed for high performance SiC power devices, and how to address volume markets for semiconductors", says Christian Vieider, CEO of Ascatron.

"40 percent of the market for power electronic components is in China, and there is a lot of interest in SiC for energy saving". Target applications are process industry, datacentre, traction, wind power and grid transformers.

IRT Nanoelec integrates III-V laser on silicon

NANOELEC RESEARCH TECHNOLOGICAL INSTITUTE (IRT) in Grenoble, France – an R&D consortium headed by CEA-Leti – has announced the first co-integration of a III-V/silicon laser and silicon Mach-Zehnder modulator demonstrating 25 Gbps transmission on a single channel. This transmission rate usually is achieved using an external source, over a 10 km single-mode fibre (SMF).

"Jointly obtained by STMicroelectronics and Leti in the frame of the IRT Nanoelec cooperation, these results – especially fabricating the laser directly on silicon – demonstrate IRT Nanoelec's worldwide leadership in III/V-on-silicon integration to achieve high-data-rate fiber-optic modules," says project manager Stéphane Bernabé. "IRT Nanoelec and its partners on this project – Leti, STMicroelectronics, Samtec and Mentor Graphics – are paving the way to integrating this technology in next-generation transceivers for optical data links," he adds. To achieve the recent results, silicon photonics circuits integrating the modulator were processed first on a 200 mm silicon-on-insulator (SOI) wafer, although 300 mm wafers also could be used in the near future.

Then, a 2-inch wafer of III-V material was directly bonded on the wafer. In the third step, the hybrid wafer was processed using conventional semiconductor and/or MEMS process steps to produce an integrated modulator-and-laser transmitter.

Imec and Solliance present semi-transparent perovskite modules

NANOELECTRONICS research centre Imec, partner in Solliance, has presented a semi-transparent perovskite PV-module, achieving power conversion efficiencies up to 12 percent.

Solliance is a partnership of R&D organisations from the Netherlands, Belgium and Germany working in thin film photovoltaic solar energy. The technology would enable semi-transparent PV-windows, which are a key towards Zero-Energy Buildings. Moreover, combining these semitransparent perovskite modules with silicon solar cells, an unprecedented 20.2 percent in power conversion efficiency for a perovskite/silicon stacked solar module was achieved.

Stand-alone perovskite solar modules feature excellent power conversion efficiencies and can be made with simple fabrication technologies, such as coating and printing. Perovskites can also be used on flexible (plastic films or metal foils) as well as rigid (glass, metal) carriers. Properties of the solar cells can be varied by tuning the composition of the material components to adjust colour and transparency. The semi-transparent perovskite modules of Imec realised by scalable coating techniques showed efficiencies of 12 percent on sizes as large as 4 cm^2 and 10 percent on sizes as large as 16cm^2, a world-best achievement in this domain. The combination of perovskite solar modules on top of silicon solar modules bears the exciting potential of achieving power conversion efficiencies greater than 30 percent, thereby surpassing the efficiencies of the best single junction silicon solar cells, according to the copmay.

Imec's novel stacked module concept features a highly transparent perovskite solar module stacked on top of interdigitated back contacted (IBC) silicon solar cells. All devices had the same area and the semi-transparent perovskite top module shows a 70 percent transmission of light towards the crystalline silicon solar cell.

A power conversion efficiency of 20.2 percent was reached for the resulting stacked perovskite/silicon solar module of relevant sizes of 4 cm^2. Moreover, a power conversion efficiency of 17.2 percent was achieved for larger areas of up to 16cm^2, employing a silicon bottom solar module of four interconnected IBC cells, also representing a record result for this size. Tom Aernouts, thin film PV technology manager at Imec commented: "We are proud about these results as they show we have excellent control over the performance as well as the upscaling capabilities of this technology. Our future work will continue in increasing module sizes and optimizing the perovskite solar cell technology."

Ulrich Paetzold, researcher at the Thin Film PV group at Imec added: "With a mm-size perovskite solar cell stacked on our IBC solar cell even efficiency as high as 22 percent has been obtained. But advancement of the perovskite/silicon stacked solar module technology relies on demonstrators of realistic sizes."

Crystal IS adds high power UV-C LEDs

CRYSTAL IS, a US-based manufacturer of ultraviolet C-band (UV-C) LEDs, has announced a new commercial product line targeting higher power applications for disinfection of water, air and surfaces using 280 nm to 100 nm LED light. Klaran, Crystal IS's first generation disinfection product line, offers germicidal output powers from 15 mW to 30 mW. It is said to be uniquely suited for use in healthcare, lab water and consumer product applications where health and human safety is of primary importance. Use cases demonstrating the need for high powered UV-C LEDs include healthcare, lab water and consumer products.

According to the US Centres for Disease and Control (CDC), Hospital Acquired Infections (HAIs) impact one in 25 patients in the US each year. The Affordable Care Act (ACA) and the Centres for Medicare and Medicaid Services (CMS) report improved patient outcomes, shorter stays and fewer repeat visits linked to healthier environments that incorporate UV-C technology in addition to approved standard surface wipe protocols.

Point-of-Use lab water purifiers now make up 75 percent of an approximately 480 million dollar global market. UV-C LEDs can be integrated into these systems for Type I, II and III water purification, as defined by the American Society for Testing and Materials (ASTM). Global headlines highlight the need for safe and reliable drinking water and with that, the UV-C water purifier market is expected to almost double in size over the next five years from $9.16 billion to $17.85 billion dollars in 2020. In addition to the US, this growth is attributed to China and India where industrialization and a rising urban population is putting a strain on drinking water resources. Crystal IS says Klaran extends its value to manufacturers who need optimised, high output germicidal power for maximum disinfection rates; smaller footprints; rugged design for mobile use; and a non-hazardous, mercury-free solution with no fragile quartz tubes.

"For Crystal IS, developing a reliable disinfection product has been one of the company's primary strategic goals," said Larry Felton, CEO of Crystal IS. "Building on the successes of our commercialised Optan product line, we are pleased to now offer our high performing Klaran UVC LEDs for disinfection."

All eyes on **Allos**

As Allos Semiconductors celebrates epiwafer success with an industry leader, CEO Bukhard Slischka talks to Rebecca Pool about how his company can get customers ready for market faster than ever before

THIS APRIL, Germany-based Allos Semiconductors revealed it had transferred its GaN-on-silicon power semiconductor epiwafer technology to a 'major international industry player' in less than twelve weeks.

Remaining tight-lipped on which of its customers this is, Allos claims this move will kick-start GaN-on-silicon power semiconductor production for that company, so it can compete with industry front-runners that have already spent years and millions of dollars doing just this.

As chief executive Burkhard Slischka tells *Compound Semiconductor*: "Our philosophy is that our customers' engineers are very involved from day one, so after twelve weeks the process is established on their MOCVD reactor and staff possess ownership of the technology. At the same time, we guarantee wafer level specifications that are the best class in the world," he adds.

Allos Semiconductors' history is deeply rooted in Azzurro's pioneering GaN-on-silicon developments. The Germany-based epiwafer vendor had spent more than a decade developing and selling engineered on-silicon epiwafers for LED and power electronics applications that were supplied to Osram and Epistar, and more.

Operations ceased in early 2014, but six months later, former Azzurro employees unveiled fabless Allos Semiconductors, having bought all intangible assets including the technology, IP and patents. Setting out to license its IP while transferring the technology to customers' reactors, Allos soon revealed it was working with long-time partner, Epistar.

Less than six months later, Allos' 150 mm and 200 mm processes were transferred to the Taiwan-based LED chip manufacturer.

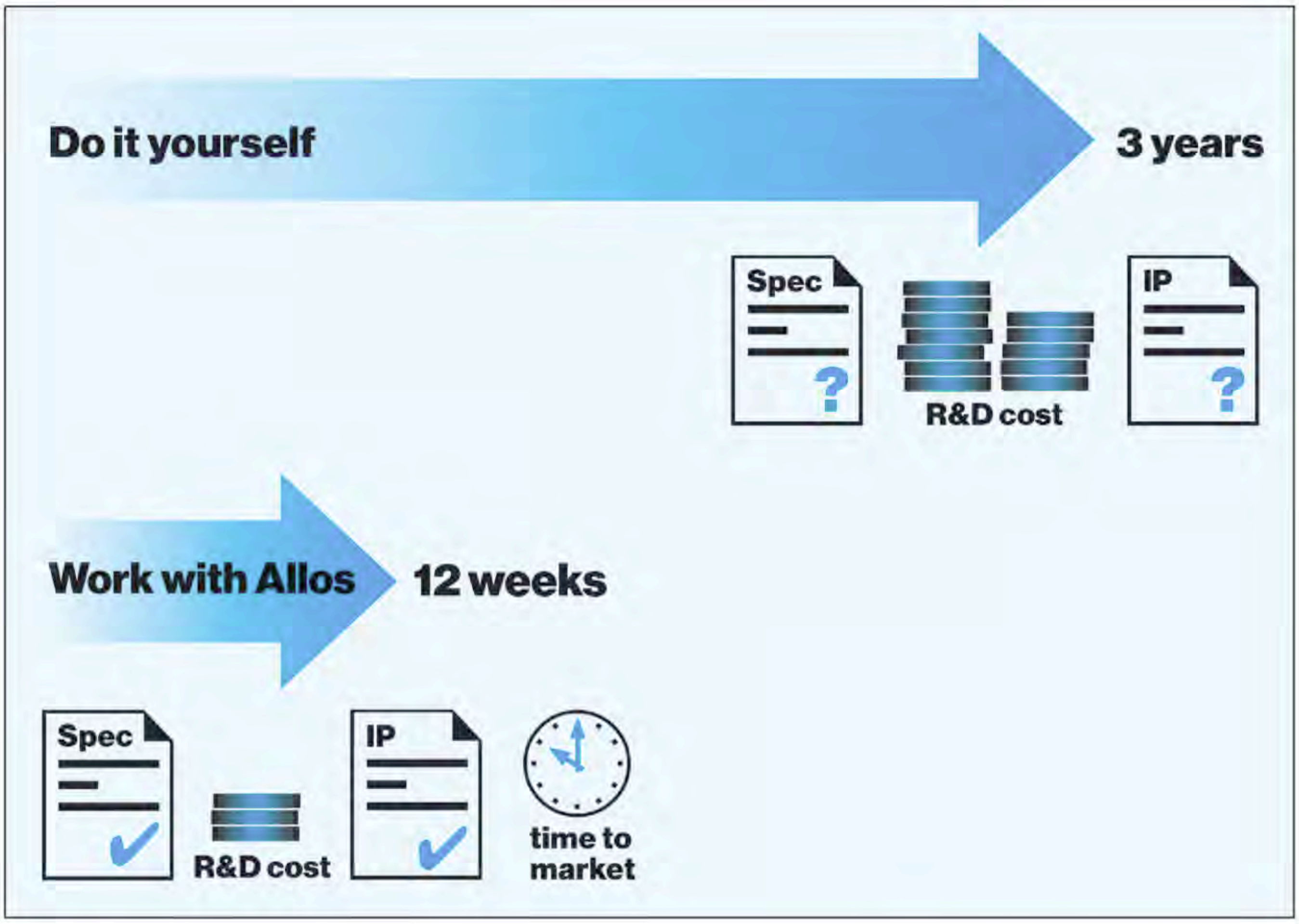
These results coincided with Epistar signing a global cross-licensing agreement with Cree, covering LED chip patents.

According to Slischka, Allos has continued to invest in research and development. "Technology-wise we have come a long way, and we now provide fundamentally improved product generation," he highlights.

"Compared to results at Azzurro, we have, for example, enhanced uniformity, much better electrical performance, as well as further improved crystal quality and bow control," he adds.

And while also promising good yields and fast growth times, Allos claims that the production-cost per wafer area is on par with that for today's GaN-on-sapphire LED wafers.

"To fully assess the impact on device performance, a company may need to wait months for the device processing and characterisation to be completed. But with the right set-up, customers can cut this feedback cycle time to less than two weeks"



Ready for market

As well as product quality and cost, Slischka believes manufacturability is key. "You may be able to grow layers with a high breakdown voltage but this is worthless if you, say, have problems with wafer breakage."

"Without the correct strain engineering between the GaN and silicon substrate, it is extremely difficult to get good yield. So for us, manufacturability is about balancing all the properties you need throughout the entire manufacturing process to get low cost devices," he explains.

According to the chief executive, Allos offers a process that will meet the required wafer parameters, yields and costs. "There is no point in achieving certain hero values for, say, breakdown voltage if the wafers are then prohibitively expensive," he adds.

Once licensing and technology transfer are in place, Allos can also offer what it calls 'development of customised solutions'. In it latest project, Allos will continue to work with its current, unnamed customer to get devices ready for market.

"Companies such as International Rectifier and Transphorm started developing GaN-on-silicon many years ago and have products in the market," he says.

"We can help a company, which is not necessarily within the top tier group of its industry, to catch up quickly and have world-class results."

And as the chief executive highlights, these companies need to act fast. "You really need to have fast device feedback cycles as this is typically a bottle-neck. During development, we can complete several epi-development runs a day and work on the epiwafer performance each time," he says.

"To fully assess the impact on device performance, a company may need to wait months for the device processing and characterisation to be completed. But with the right set-up, customers can cut this feedback cycle time to less than two weeks."

"This is the deal for the customer in the end," he adds. "You could probably do this yourself. But why would you when by working with us you get results much faster, at a much lower cost and with a lot less risk."

Extreme GaN

Cobham has joined forces with RFHIC to drive GaN radar forward. But this is only the beginning, learns Rebecca Pool

THANKS TO ITS HIGH VOLTAGE, high power, high frequency performance, and a decade of military development, the mighty GaN transistor has become the front-runner in power amplifier applications including radar, electronic warfare and more.

Silicon-based amplifiers struggle to operate at the higher frequencies of 4 GHz, while the GaAs devices just don't produce the peak power levels demanded by most pulsed applications. And although the manufacturers of vacuum electronic devices for even higher-frequency applications have been developing ever-smaller travelling wave tubes to stave off the competition, GaN is making in-roads to 4 GHz and beyond.

These developments in pulsed RF power device markets have not been lost on GaN device and system manufacturers alike. From Wolfspeed, Microsemi and Qorvo to BAESystems, Raytheon and more, myriad GaN-based components and circuits have been delivered. And in the last few weeks UK-based defence and aerospace systems manufacturer, Cobham, joined forces with RFHIC, Korea, a designer and manufacturer of RF and microwave components, to muscle in on the action.

GaN development

Radar frequencies are divided into different categories; L-band and S-band radars operate at 1 to 2 GHz and 2 to 4 GHz frequencies, respectively. Meanwhile C-band and X-band radars cover the 4 to 8 GHz and 8 to 12 GHz frequency ranges.

To date, many GaN applications have targeted S-band radar. Indeed, in a solid-state transmitter development programme dubbed 'SOLSTx', Cobham recently unveiled a 35 kW prototype S-band GaN transmitter for air traffic control and weather radar applications.

Now, working with RFHIC, Cobham intends to soon deliver a 175 kW solid-state transmitter prototype for long range radar surveillance, based on the 35 kW power amplifier modules. And the next step will be to develop 175 kW modules to form the building blocks of systems that provide multi-megawatts of power for meatier defence applications.

As Ralph Marrone, product line director for SOLSTx says: "RFHIC is a major commercial telecoms GaN provider with strengths in high power amplification. Part of our system for SOLSTx requires high power amplifiers so RFHIC brings strong commercial and competitive knowledge."

And Cobham means business. While GaN is the undisputed champion of performance for power amplification applications, hefty materials and processing costs have stymied industry adoption. Increasing production volumes is critical to shaving costs, and as Marrone points out: "[RFHIC] understands volume manufacturing."

"They actually have one of the highest volume capabilities for power amplification manufacture that I have ever seen," he says. "And this will be key to solid-state amplification."

RFHIC has been working with GaN for more than a decade, forging a strategic partnership with a GaN foundry service provider in 2004 and then joining forces with Cree in 2008 to develop GaN-on-SiC products.

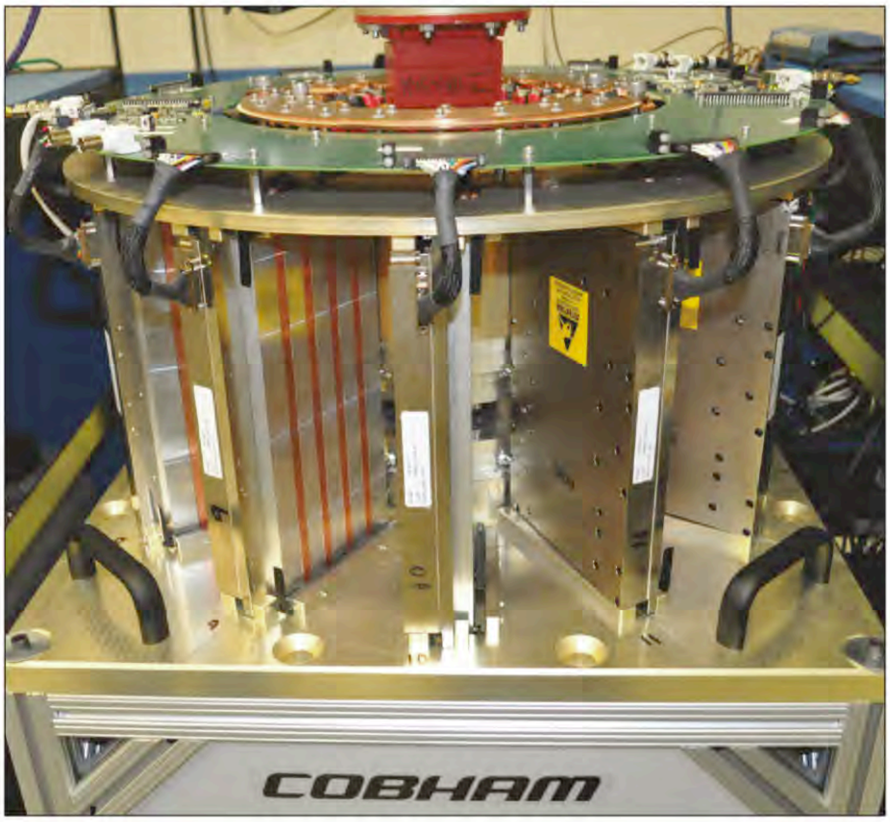
Delivering a host of GaN-based amplifiers and modules, the company now has links with several other foundries and remains close to Cree's company, Wolfspeed.

"It is publicly known that RFHIC packages for Cree, now Wolfspeed, in various locations and supplies most of these devices back to the company which are then supplied commercially," says Marrone. "So our development with RFHIC [involves] GaN-on-SiC, but this doesn't mean we are limited to [this technology]; other suppliers are working with GaN-on-diamond and GaN-on-silicon."

"We are 'technology agnostic' and will find the best match depending on customer requirements and applications," he adds. "The choice also depends on frequency and at low frequencies we may use silicon LDMOS but at the S-, C- and X-band, GaN is the technology of choice at this time."

Time to failure

What about the industry incumbent? Today's radar transmitters use a host of vacuum electronics devices including travelling wave tubes, magnetrons and klystrons. Indeed, recent figures from DARPA indicate more than 200,000 vacuum electronic devices are now in service in the Department of Defense alone, powering critical communications and radar systems.



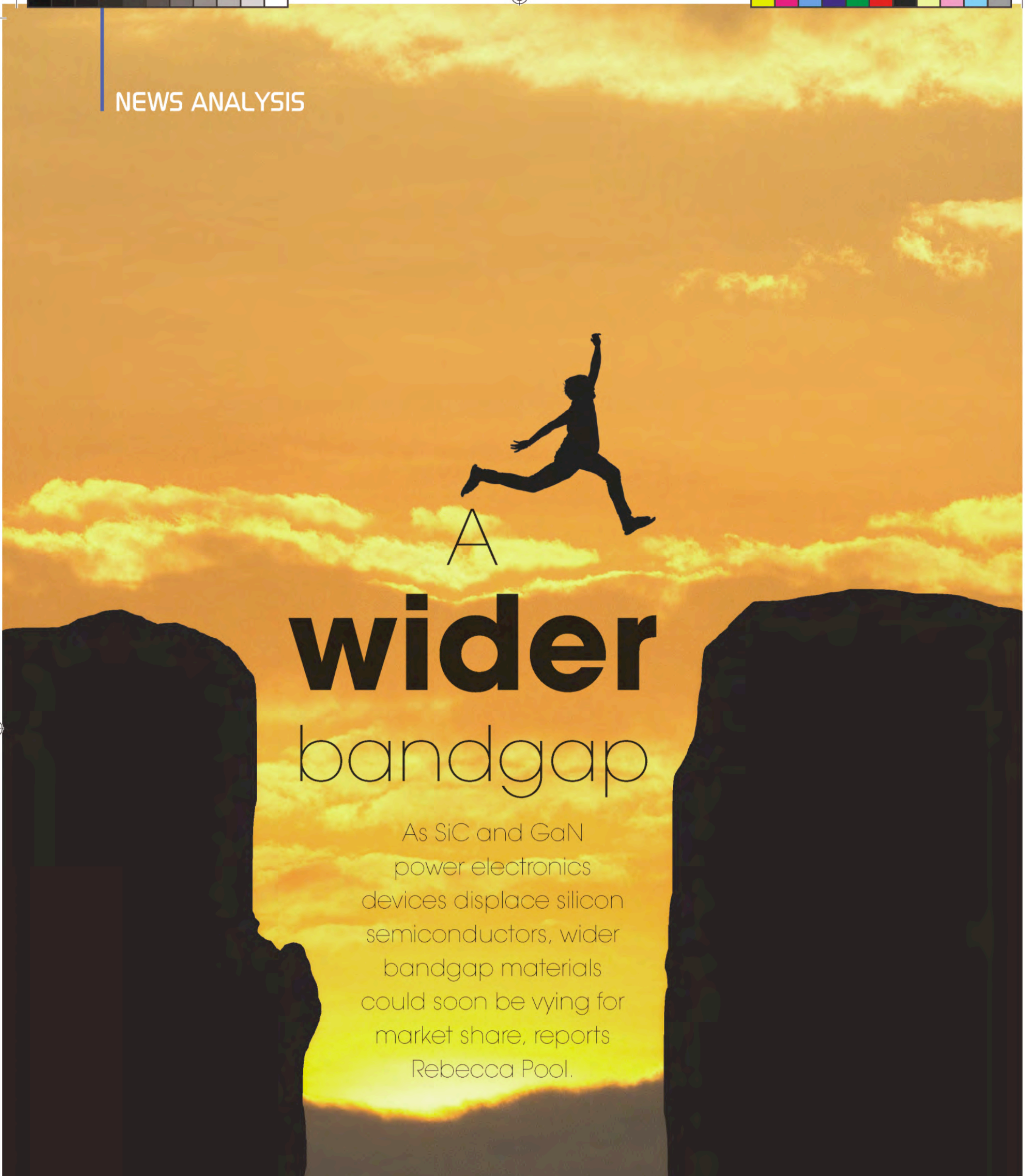
But according to Marrone, these devices have high operating costs, demand very high-voltage power supplies and crucially, can be beaten on reliability. As he points out, the latest 35 kW solid-state transmitter prototype delivers a significant increase in mean-time before failure (MTBF), compared to the travelling wave tube.

"This [metric] is very application specific but you might get up to a ten times increase in reliability here," says Marrone. "People always ask how do you prove reliability, but I think with GaN devices in the last ten years, reliability, with a high MTBF, has been proven."

The product director also points out how industry players can be concerned about TWT replacement, saying: "There is a strong installed base in vacuum tube electronics and [customers] want to understand the swap; can we fit our systems into the package they need at the right price point?"

"We're always going to get questions about future technology, but solid-state GaN is going to offer higher reliability and lower overall cost-of-ownership," he adds.

What's more, Cobham is setting its sights on taking its solid -state devices to ever-higher frequencies. Key applications for its SOLSTx products, operating in S- and C-bands, are going to be air traffic control and land and marine long-range surveillance, but the future will hold more. "We are focusing on the S- and C-bands right now but that doesn't mean we won't look at higher frequencies," says Marrone. "We have product road maps that look across all the bands, all the way up to the X-band."



A **wider** bandgap

As SiC and GaN power electronics devices displace silicon semiconductors, wider bandgap materials could soon be vying for market share, reports Rebecca Pool.

A RECENT ANALYST REPORT from France-based Yole Développement takes a look at the wide bandgap materials currently available for power electronics applications.

As expected SiC and GaN feature heavily, but report author and compound semiconductor market and technology analyst, Hong Lin, also scrutinises larger bandgap materials that promise even higher power device performance.

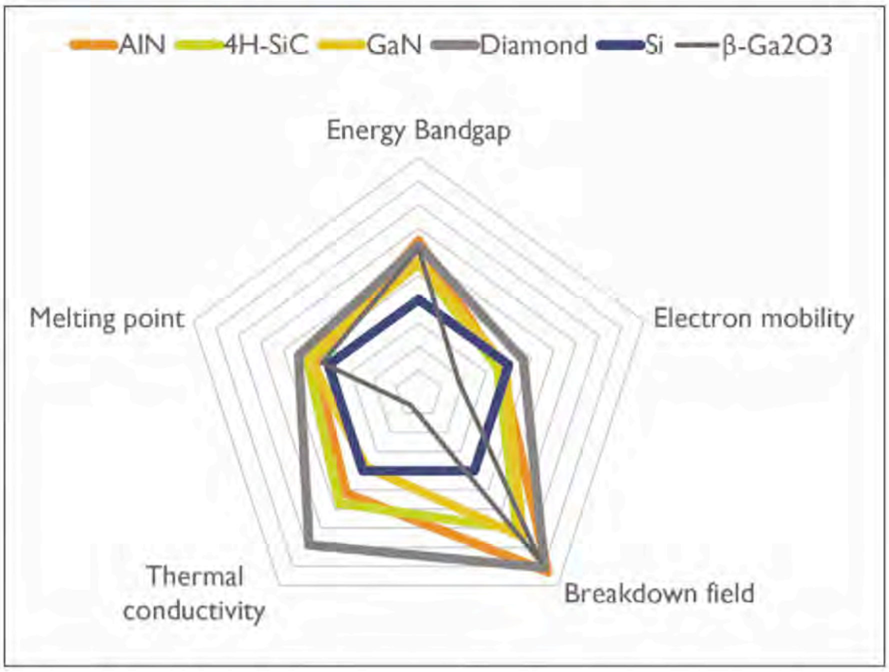
"In the beginning, [industry players] said silicon carbide would never ever happen, and today we have commercial devices," she tells *Compound Semiconductor*. "Materials such as gallium oxide and aluminium nitride are at very early stages of development but given time there could be new opportunities for new materials," she adds.

Thanks to its high bandgap and doping possibilities at room temperature, development of gallium oxide for power electronics applications is under way.

Japan-based public research and development body, New Energy and Industrial Technology Development Organisation, is driving progress, part-funding a next-generation power electronics project called *Research and development of Fundamental Technologies of Gallium Oxide Power Devices*.

Key partners include a cohort of Tokyo-based firms including power conversion business, Tamura, analog IC design and manufacturer, New Japan Radio, and optoelectronics developer, Koha, alongside the National Institute of Information and Communication Technology and the Tokyo University of Agriculture and Technology.

Crucially, as part of the project, researchers have developed and demonstrated the first ever Ga_2O_3 MOSFETs on single-crystal Ga_2O_3 substrates, claiming excellent device characteristics.



Besides GaN and SiC, other materials have even larger band gaps and can potentially increase the performance of power devices even more. Note that in this chart, the difference between two adjacent pentagons represents the doubling/halving of a material property.

High on-stage drain current, large off-state breakdown voltage, extremely low leakage current and high on/off drain current ratios have been demonstrated, opening the door to power devices with lower losses during switching operations. Indeed, researchers are confident performance will surpass that of silicon, SiC and GaN-based devices.

As Lin highlights, cheap, large single crystal Ga_2O_3 wafers can be mass manufactured via melt-growth in the same way as sapphire substrates are produced, also holding promise for low-cost, high-volume power device manufacture.

"In terms of materials development, this technology is quite impressive," she says. "Two-inch commercial single-crystal wafers are commercially available while six-inch wafers have also been grown."

But while cheap, native single-crystal substrates are a massive draw for future power device manufacture, Ga_2O_3 has a relatively low thermal conductivity, raising challenges for heat extraction in power devices.

"Device designers will be working on this and there are many ways to extract heat, such as thinning wafers to reduce the thermal resistance," she highlights. "This problem can be resolved, but it still needs more research and development."

"We have proof-of-concept devices but development is at a very early stage; we need many years yet to get to a final product," she adds.

Power electronics progress

At the same time, suppliers of AlN-based UV LEDs are now diversifying activities and targeting power electronics markets, following weak demand. According to Lin, key players here include Crystal IS and HexaTech, both from the US, as well as Germany-based CrystAL-N.

"Aluminium nitride has been traditionally used in UVc LEDs but market growth has not been so fast, so companies have been thinking of ways to use [the technology] for power electronics," she says. "It has a very, very high bandgap, so high performance devices [are possible]."

Indeed, just last year, researchers from HexaTech and North Carolina State University, US, alongside Japan-based colleagues at Tokuyama, Fuji Electric and the Tokyo University of Agriculture and Technology unveiled the first vertical Schottky barrier diodes, on AlN substrates. Unlike gallium oxide, AlN has a high thermal conductivity, alleviating heat dissipation problems at high power densities, but device challenges still exist. In recent years, work has been on-going at HexaTech to develop novel doping schemes for high-voltage power devices. However, as Lin asserts: "Doping this material is going to be the main challenge."

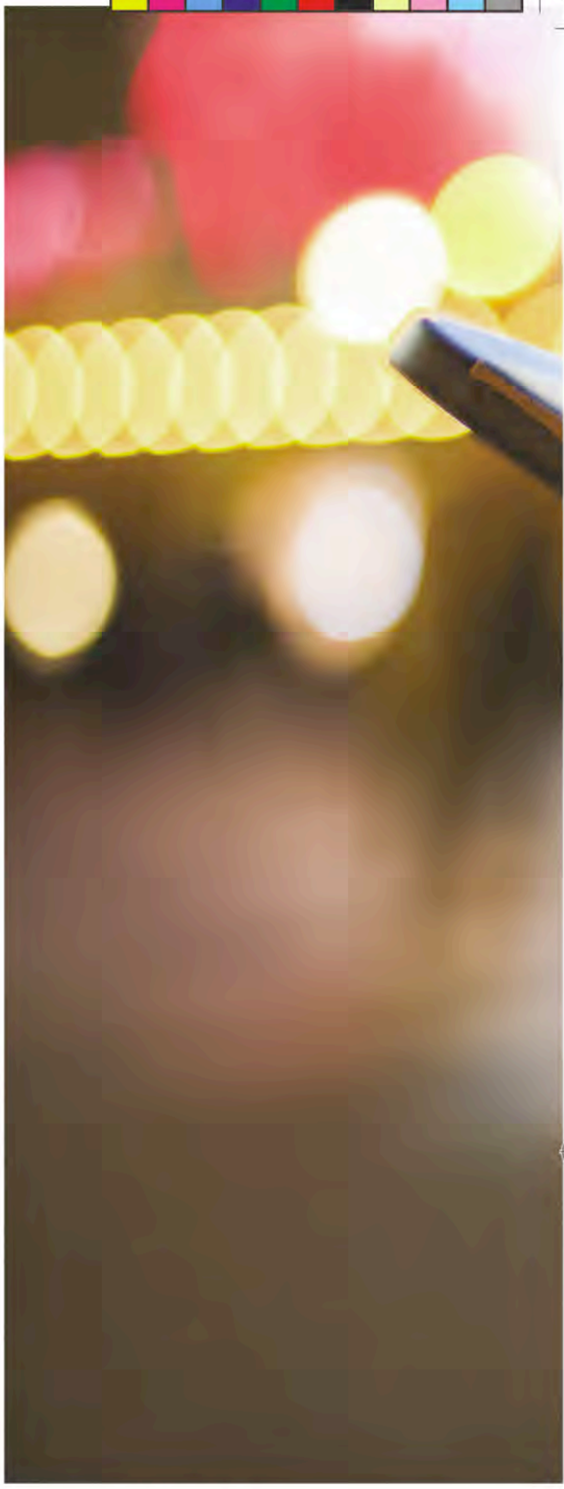
What's more, AlN wafers aren't cheap. Production is still at low volumes and with no real applications yet driving demand, costs are likely to remain relatively high.

"Like gallium oxide, devices are only at a proof-of-concept stage right now, and researchers are in the process of improving device performance," says the Yole analyst.

"We saw the first SiC diodes in the year 2000 and it has taken fifteen years to establish commercial devices," she says. "Researchers must be able to prove they can make good performance devices and then, if industry players find commercially-available devices don't quite work for an application, we will see many opportunities for these new materials."

GaAs: Safe for now

Technavio analyst, Sunil Singh, provides insight to the future of GaAs in the complex communications landscape.
Rebecca Pool reports



AS RISING SALES of smartphones worldwide fuel demand for GaAs power amplifiers, device vendors are jostling for more and more market share. GaAs semiconductors are already the incumbent and state-of-the-art technology in cellular handsets that use at least one GaAs-based power amplifier, and industry can expect more of the same in the coming years.

In his recent report *Global GaAs devices market 2016 to 2020* Technavio analyst, Sunil Kumar Singh, points out the leading players and highlights those that he believes have an edge.

"All vendors in this market are focusing on cellular communications due to the deployment of 3G, 4G and LTE networks and the trend towards 5G," he says.

"Global wafer capacity for GaAs devices is increasing with every company operating at, at least, an 85 percent production rate," he adds. "So competition is intense but Skyworks and Qorvo are the key vendors and cover a substantial amount of market share."

According to Singh, right now, Skyworks can produce around ten million chips a day using proprietary processes. And while its key market driver is data traffic, the company also has a huge product portfolio from amplifiers and attenuators to power management devices and voltage regulators covering defence, aerospace, automotive markets and more.

Meanwhile, the merger of RFMD and TriQuint Semiconductor sees Qorvo also delivering a vast product portfolio of GaAs-based devices serving mobile device, network infrastructure as well as aerospace and defence markets.

But, as Singh highlights, the company's recent acquisition of GreenPeak Technologies, a developer of CMOS wireless controller chips for the Internet of Things markets, signals more change is afoot. With GreenPark in tow, Qorvo could diversify into CMOS technology, joining the ranks of Skyworks, Avago Technologies – now a Broadcom company – and other competitors. Indeed, Skyworks, claiming proficiency in both technologies, promotes GaAs for its linearity and its power efficiency and CMOS for its easy integration, low cost and low power consumption. And, with more industry players owning each competing technologies, convergence becomes a real possibility.

"I'm not saying this will happen. But could we see GreenPeak CMOS chips equipped with broadband GaAs power amplifiers?" asks Singh.

"In this case, GreenPeak is a fabless company, so Qorvo may have to first develop a foundry for CMOS chips which could take time," he adds. "But in the near future, [the company] could be looking at technology convergence here."

Convergence aside, according to Singh, Avago Technologies, recently merged with Broadcom, is the other key player in the GaAs device market space.

And at the same time, Advanced Wireless Semiconductor, Anadigics, M/A-COM and Analog Devices, having acquired Hittite Microwave, all provide stiff competition.

"Analog Devices has such a strong financial background I can now see it becoming one of the top competitors for Skyworks and Qorvo," he highlights. "At the same time, M/A-COM sells directly to companies without third party sales channels and if it can deliver the volumes in accordance with current market demand I definitely see it taking more market share in the future."

CMOS threat?

Without a doubt, cheaper silicon CMOS power amplifiers provide the prime threat for GaAs devices in this market. And thanks to developments such as envelope tracking, the performance gap between the two technologies has narrowed. Still, Singh is adamant GaAs is safe for now.

"If CMOS was to rapidly increase in RF front end modules, the vendors operating in this space would struggle with [the existing] manufacturing capacity to mass produce these CMOS devices," he says. "But when it comes to GaAs devices, vendors such as Qorvo, WIN Semiconductor and Anadigics do have the capacity [to ramp up production], which is a huge advantage." At the same time, other power amplifier technologies are gathering market momentum. For example, Skyworks, has revealed plans to use SiGe power amplifier technologies in RF front end modules to boost power and efficiency in future wireless communications devices. Still, Singh believes GaAs devices will remain ahead of up and coming power amplifier technologies based on GaN-on-SiC as well as SiGe for now.

"GaAs can be directly substituted with these emerging technologies, but this isn't happening in the near future, at least until 2020," he says. "Device manufacturers will be considering, for example, form factors, load requirements, matching and filtering... and GaAs devices are ahead of the game here, compared to any other technology."

Refining chip manufacturing with wafer carrier monitoring

Mapping a carrier's emissivity and temperature profile exposes microcracks and emissivity variations that can directly impact thin-film deposition and device performance

BY CARRIE ANDRE AND DARRYL BARLETT FROM K-SPACE ASSOCIATES

A KEY PROCESS in the manufacture of most compound semiconductor chips is epiwafer growth. Engineers with expertise in this area are highly valued because they can ensure high yields, develop new devices quickly, and help diagnose faults within the reactor. Their skills are not limited to knowing the best growth rates and temperatures for depositing various alloys, but extend to understanding how to treat the hardware to obtain the best run-to-run and tool-to-tool repeatability.

If these engineers are responsible for producing epiwafers in an MOCVD reactor, they will have had to also devise an approach for minimizing variations associated with wafer carriers. Also known as platens or susceptors, these hardware components, which accommodate substrates during the deposition process, are typically baked in an oven after every growth run for many hours – and sometimes for several days.

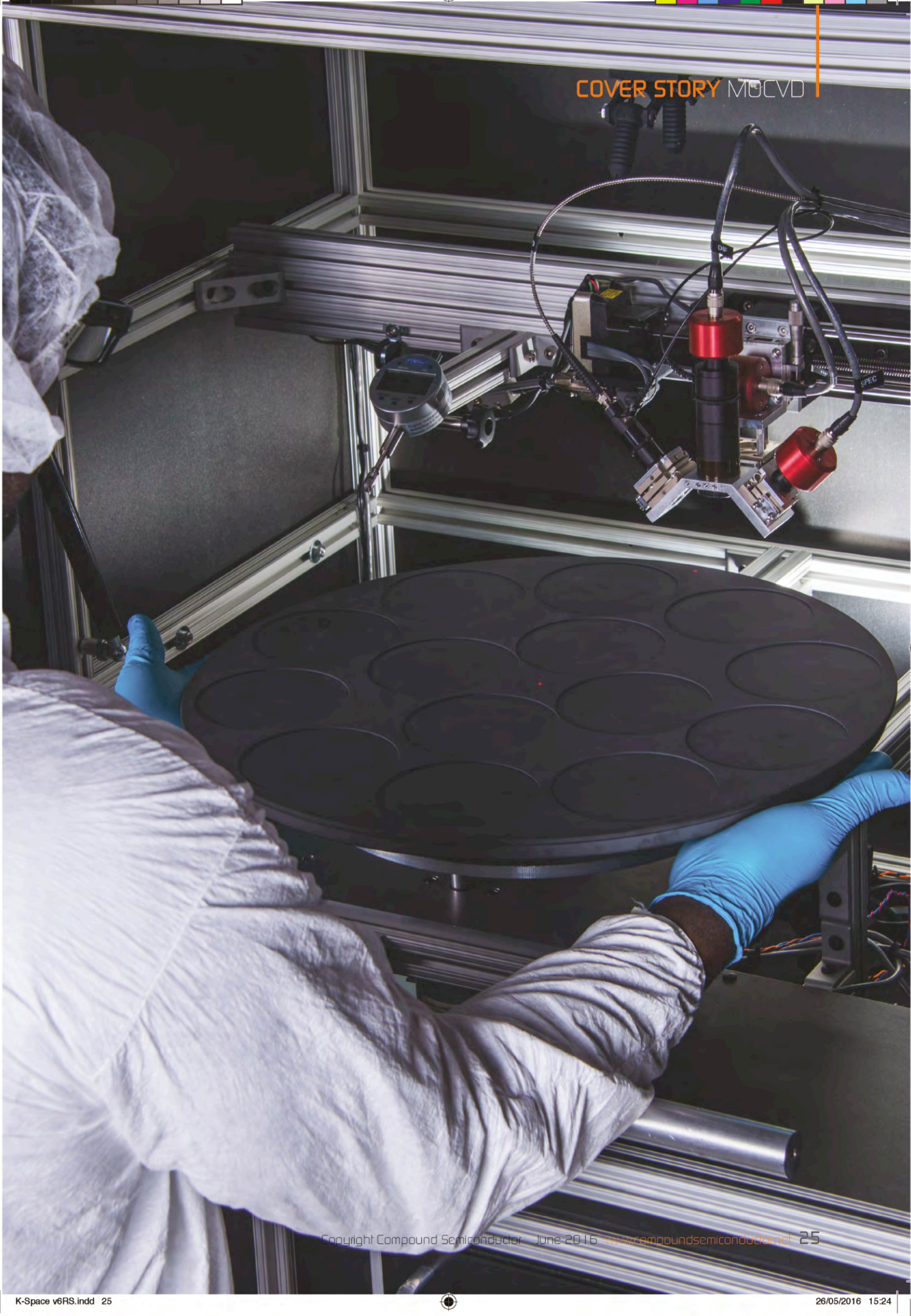
Figure 1. The kSA Emissometer, with its lid open, measuring the emissivity of a loaded Veeco K465i carrier.

The aim of this bake is to remove deposited material from the carrier, and rid it of any contamination. Ideally, the carrier is cleaned so that its emissivity – that is, its emission of infrared energy that heats the substrate to the required growth temperature – is returned to its original value. By doing this, the same recipe can be used from one run to the next to produce layers with the same thickness and composition.

While this may sound easy, in practice it is not. Multiple growth runs and subsequent bakes change the uniformity of carrier emissivity. And complicating matters further, the MOCVD chipmakers do not have a quantitative method for monitoring these carrier changes. Process engineers in many MOCVD fabs are forced to accept the changes in emissivity, and account for them by making small adjustments to the temperature set point, based on the growth history for a particular carrier. Although this helps, it can only address changes in the average emissivity, and it cannot compensate for any non-uniformities that may arise.

Another tough call for any MOCVD process engineer is to determine when it is no longer appropriate to use a carrier. One way to do this is to visually inspect a carrier and discard it if it contains significant defects or blemishes. Alternatively, the wafer carrier can be retired after the material grown on it exceeds a certain limit.

Unfortunately, both options are heavily flawed. Downsides include wasted growth runs, yield reduction, significant reactor downtime due to catastrophic carrier failure, and a very limited provision of the quality control data needed for improving the process for determining end-of-life.



These issues can be illustrated by considering the SiC growth process. When a carrier is coated with this material, microcracks can appear in the film that eventually cause the carrier to be unusable. These cracks are typically invisible to the naked eye, and result from a small mismatch between the coefficient of thermal expansion of the wide bandgap SiC semiconductor and that of graphite, which is the bulk material of the carrier. The cracks arise due to frequent, large-scale temperature swings during the MOCVD deposition process as well as extreme baking conditions.

The cracks in the SiC coating are not there when the carrier has just been introduced, but start to appear when the thickness of the film exceeds around 100 μm. These imperfections are incredibly detrimental, because the exposed graphite promotes carbon doping, and the microcracks significantly change surface emissivity and can ultimately cause implosion of the carrier inside the reactor. It is of little surprise, then, that many wafer carriers are retired after completing a set number of growth runs. But if engineers err too far on the side of caution, the carrier may be laid to rest too soon. The crux of the issue is that the 'real' lifetime of a particular carrier tends to be a mystery.

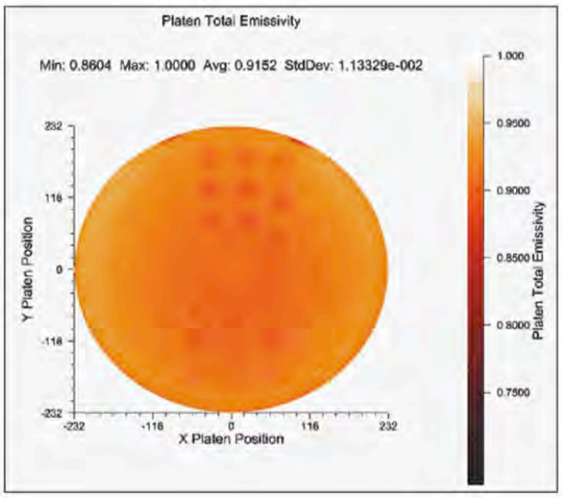


Figure 2. An emissivity map produced by the kSA Emissometer. The darker areas are the wafer pockets in the wafer carrier.

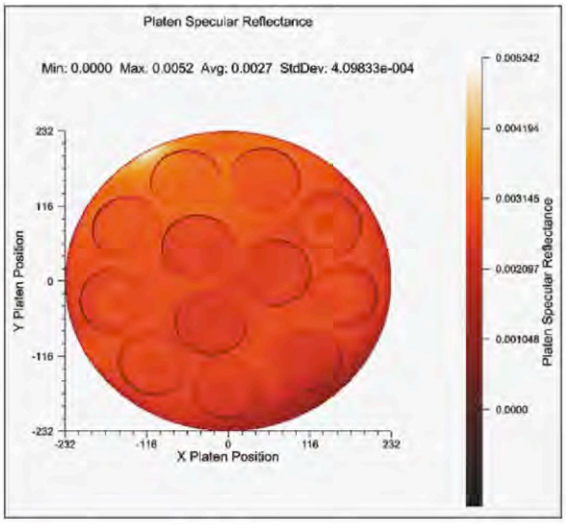


Figure 3. A specular reflectance map produced by the kSA Emissometer uncovers pocket machining marks in the MOCVD carrier.

Carrier inspection

To offer some insight into this crucial issue, our team from k-Space Associates of Dexter, MI, has developed an *ex-situ* instrument for measuring carrier emissivity (see Figure 1). The kSA Emissometer measures, over the entire carrier, absolute diffuse and specular reflectance. Summing together both of these reveals the total emissivity over the entire carrier.

Our tool can provide emissivity maps with a spatial resolution of 0.5 mm. This level of fidelity exposes non-uniform pocket emissivities, which can result from partial loading of the carrier during process development. This is the case for the carrier mapped in Figure 2, where pockets loaded with wafers were consequently protected from MOCVD deposition. The upshot is surface properties in those areas that were far closer to those of the original, new carrier.

When a wafer carrier is properly baked, the main contributor to total emissivity is the diffuse reflectance component. Meanwhile, the specular component is expected to remain at or close to zero over the entire surface. But when there is residual MOCVD deposition on the carrier, the situation is markedly different, with spikes appearing in the specular reflectance signal.

Specular reflection is also capable of exposing other forms of imperfection, such as the pin-pointing of small irregularities on the carrier surface. Our tool, for example, can uncover machining marks underlying the SiC coating (see Figure 3).

Another feature of our instrument is its capability to average total emissivity over certain radii – this can correspond to the location of optical pyrometers (such as RealTemp, EpiTT, and our own kSA ICE instrument). Armed with this insight, engineers can fine-tune the temperature set points for a production run with a particular carrier. This approach yields more accurate results than the 'estimation' methodologies widely employed today.

To underline the capability of *ex-situ* emissivity characterization, we have proven the strong correlation between the carrier emissivity and the actual carrier temperature in an MOCVD reactor. This has been accomplished by comparing carrier emissivity mapping, using the kSA Emissometer, with carrier temperature mapping using the kSA ScanningPyro (the latter is shown in Figure 4).

This study began with the selection, by a chip manufacturer, of an in-production carrier. We visually inspected this (see Figure 5 for a photograph of its central portion), before scanning it with a kSA Emissometer. The emissometer unveiled microcracks that are not visible to the naked eye. They produce a different emissivity, and should result in temperature non-uniformity on the heated carrier (see Figure 6 (a)).

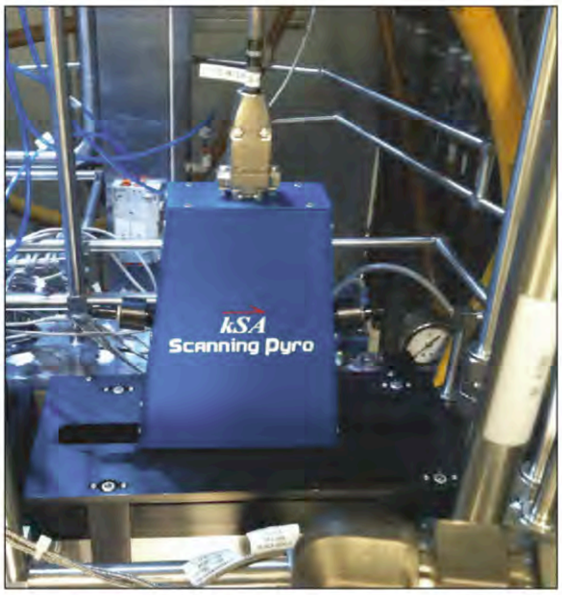


Figure 4. The kSA Scanning Pyro, in use on a Veeco K465i MOCVD reactor.

Figure 5. A photograph of an in-production wafer carrier used in trials conducted by k-Space Associates. This image shows what the human eye and the digital camera can – and cannot – see during inspection of a carrier. Microcracks are present on the carrier, but are not unveiled in this image.

We loaded this in-production carrier into a Veeco K465i, and heated the reactor to a temperature of 1000°C, according to a pyrometer in the middle of the chamber. Further inspection of the carrier came from our *in-situ* ScanningPyro tool – it is a dual-detector pyrometer with full scanning capability that can yield full carrier temperature maps in a single scan, and ultimately determine the temperature uniformity of the carrier.

Microcracks are also exposed in the temperature maps produced by our *in-situ* ScanningPyro (see Figure 6 (b)). In addition to this imperfection, the mapping shows that the centre of the carrier is by far its coolest part. This is expected, due to the cooler spindle beneath the centre of the carrier.

Our study underlines how our emissometer complements the scanning pyrometer. What's more, it shows how our emissometer – which opens the door to a scientifically based, quantitative approach to wafer carrier characterization in the production environment – is well positioned to become an indispensable tool for a variety of tasks. It can be used to determine the quality of a carrier bake after a deposition run, and ultimately eliminate guesswork from making a 'go-no-go' decision on the suitability of a particular carrier for the next production run. It can also deliver an accurate value for surface emissivity, aiding temperature set-point adjustments for a particular wafer carrier following a bake. And our emissometer can also: uncover microcracks, evaluate their severity, and help an engineer to decide when to retire a wafer carrier at the end of its useful lifetime; qualify wafer carrier vendors, via examination of the emissivity uniformity over the carrier, and within the batch of carriers; provide incoming quality control of the new wafer carriers; and prevent wasted MOCVD growth runs.

In short, the kSA Emissometer is a highly capable tool that enables engineers to drive up throughput and yield by offering unique insights into the condition of the wafer carrier.

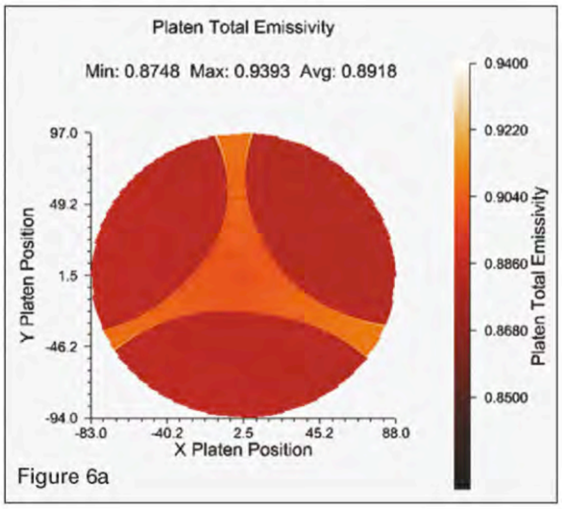


Figure 6a

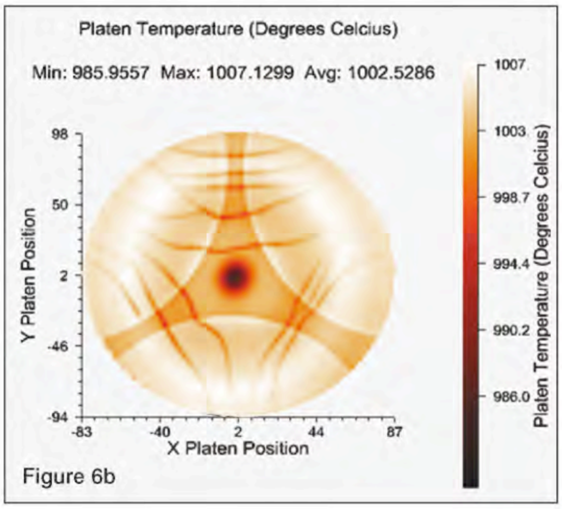


Figure 6b

Figure 6. (a) The kSA Emissometer unveils microcracks when generating a map of the total emissivity of a Veeco k465i wafer carrier (b) The microcracks are also seen in a map produced by the kSA Scanning Pyro *in-situ* instrument.

Shares: go go Oclaro

While the majority of CS shares head south, Oclaro's are bucking the trend and soaring

BY RICHARD STEVENSON

SOME of the biggest names in the technology sector are grabbing the headlines for the wrong reasons. Apple has attracted media attention for a drop in sales, leading pundits to question whether its golden years are over, while IBM is making waves by shedding workers in the US. Given these troubles, it is of no surprise that the share price of both companies is also struggling, with Apple's having fallen by nearly a third over the last 12 months and IBM's by almost one-fifth.

This pair is by no mean alone in having a tough time on the stock exchange. The technology-rich NASDAQ has fallen by several percent during the last year, while the share prices of many firms within the compound semiconductor industry have fared far worse. Take,

for example, the heavyweight quartet of Cree, Aixtron, Skyworks and Qorvo, which have all fallen in valuation by more than 20 percent in the twelve months leading up to the end of April 2015.

However, a canny – or lucky – investor in shares of companies within our industry could still have made a very tidy profit in the last year. To get their best return, they would have invested in Oclaro, which has had a share price that has rocketed by more than 160 percent. And they could still be very pleased with themselves if they had bought shares in JDSU-spin out Lumentum – its valuation has climbed by 30 percent since its launch in August 2015.

It is not the first time that Oclaro has topped our share price leader board. It was also the leader in 2014, when company CEO Greg Dougherty took radical steps to make the company profitable. Back then he slashed the workforce from 3000 to 1500 and streamlined operations, halving the number of sites from 20 to 10.

Fast-forward to today and it is clear that Dougherty's actions are working. In the two most recent fiscal quarters the company reported a profit of $2.5 million. And in the current quarter, ending on 2 July, it expects earnings of $7 million to $11 million on sales ranging from $115 million to $123 million.

Since Oclaro started its turn around, its share price has steadily increased, and it is now trading at its highest point since summer 2011 (although it is still far, far lower than the heady days of the dot.com boom). Driving these gains is an improved product portfolio, particularly for 100 G components with relatively high profit margins. For these products, sales for the most recent quarter were up 18 percent sequentially, and almost double those of the equivalent quarter of the previous year.

Speaking to investors on 3 May, 2016, in an earnings call following the release of third fiscal quarter results, Dougherty revealed that in addition to the success of 100G products, Oclaro's sales growth was being driven by an incredibly strong demand from China. "We are well positioned with all four of the major network equipment manufacturers in the region," claimed Dougherty, who added that Oclaro has had unanticipated demand for 10G parts.

Encouraging for the company CEO and his colleagues, demand from China shows no sign of abating. Strong growth is on the cards well into 2017 – demand for 100G is believed to be for a widely publicized backbone in metro networks, while shipments of 10G products are set to serve metro networks and aid access aggregation.

There are also other factors behind Olcaro's success. Revenue is increasing for lithium niobate modulators and narrow line-width lasers for coherent transmission. What's more, there is an increase in sales of the company's CFP line of transponder modules and transceivers, and its QSFP28 transceivers, which are said to benefit from the company's vertical integration model and its industry leading lasers.

To further increase sales, Oclaro is investing in the development of new products. They include what is claimed to be the industry's first 400G CFP8 PAM4 transceiver targeting primarily core routing applications, and a single-channel 400G lithium niobate modulator, which several customers are evaluating for field use.

Oclaro's share price has climbed steadily during the last year, and is now at its highest point since summer 2016.

Another highlight is the qualification of 25G DFB lasers for use in non-hermetic environments. "The significance here," said Dougherty, "is that we've demonstrated that our chips can reliably enable lower-cost packaging for data centre applications, by allowing use of cheaper materials and piece parts of optical sub assemblies."

Oclaro's ramp in production has even led to capacity constraints, according to Dougherty: "Our growth in Q4 will not be gated by demand, but will be limited by what we are able to ship." The company is currently production-constrained on the QSFP28, and recently allocated a significant amount of capital spending to grow its capacity. For most 100G products and tuneable 10G offerings, capacity is "very tight".

Lumentum's momentum

The only other company enjoying a double-digit rise in share price during the last 12 months has been Lumentum, the JDSU spin-out that acquired

With revenue on the up, Lumentum's share price is heading north.

the parent company's optical components and subsystems for telecommunications and data centre applications, along with its portfolio of high-power fibre lasers and its scientific laser and three-dimensional sensing technologies.

Lumentum's shares launched at $17 on 4 August, 2015, and initially headed north, to spike at just over $23. But by October they had plummeted to a low of $14, before climbing since then to now trade at around $25.

The company did not get off to an easy start. A week after launching on the stock exchange, company CEO Alan Lowe admitted during a call to discuss first fiscal quarter 2016 projections that sales of fibre lasers had dipped – although they were expected to recover – and revealed that there had been a now-resolved component problem directly related to the industrial fibre laser. The JDSU spin-out was also suffering from weak demand in the semiconductor equipment sector, where its lasers are used for PCB drilling, and wafer scribe and dice applications.

By the time the company reported its results for its first fiscal quarter on 3 November the share price had already began its steady climb from its nadir, and encouraging results led to further gains. Sales for the three months leading up to 26 September were $212.6 million, up by $3.7 million sequentially, and net loss was down to $0.4 million from $15.4 million.

Since then the company has increased its revenue quarter-by-quarter to hit $230.4 million for the third fiscal quarter 2016. Results for this period were discussed in a quarterly earnings call on 4 May, 2016, where Lowe described the demands for the company's products as strong and increasing.

This demand stems from upgrades and expansions by network and data centre operators in response to the need to increase capacity, connectivity and efficiency to accommodate the rapid growth in cloud computing, video streaming, mobile and other high-bandwidth applications.

According to Lowe, the only way to meet these demands is to deploy advanced optical communication technologies, such as 100G products. "Lumentum is a leader in these enabling technologies," claimed Lowe, "and our investments in new products position us well for these trends. Increasingly, network and data centre operators around the world are critically dependent upon our products."

Like Oclaro, Lumentum is benefiting from strong and growing demand from China. But there is also significant opportunity in North America, where metro deployments are poised to ramp as Lumentum's customers start to transition from field trials to full-scale deployment. "Hyperscale data centre operators continue to plan major 100G upgrades," enthused Lowe, "and we expect roll out to begin in the second half of the calendar year."

Lowe admitted that the company is struggling to fulfil some of its orders: "Despite investing in additional manufacturing capacity, we continue to have challenges in meeting some of our customers' increasing demand." To address this, Lumentum is increasing investments in capital equipment in order to expand capacity and meet the rapidly growing demand from customers, particularly for 100G and ROADM products. In the fourth quarter, the company plans to spend $25 million to $30 million on capital equipment.

The lion's share of Lumentum's sales comes from the telecom sector. It was worth just over $150 million in the most recent fiscal quarter, an increase of 2 percent sequentially. However, datacom revenue is growing far faster, with a quarter-over-quarter growth of 30 percent propelling sales to $45.5 million. Within this, revenue for 100 G products shot up by 140 percent in the latest quarter, to now contribute 40 percent of all revenue for Lumentum's datacom business. Total sales are tipped to increase, with Lumentum offering revenue guidance of $232 million to $242 million for the fourth fiscal quarter 2016. Operating margin should be between 8.5 percent and 10 percent, leading to earnings of $18.6 million to $22.1 million.

Third on the leader board is substrate maker AXT. It has had a significant jump in valuation in the last few days, so is already well positioned for a top spot next year. On 2 May it reported first fiscal quarter 2016 results. Sales and income exceeded guidance, with the company making a tiny profit on revenue of $18.7 million.

For JDSU spin-out Lumentum, quarterly datacom sales increased by 30 percent sequentially.

Commenting on the results, CEO Morris Young remarked that AXT's InP revenue was the highest it had been for several years. "Our manufacturing team continues to work on efficiency and yield improvement, and these efforts, along with our product mix, helped improve our gross margin in the quarter."

Plunging the depths

Footing the table for the second year in succession is sapphire producer Rubicon. Over that time frame its share price has sunk from just over $7 to around 60 cents. Rubicon's struggles result from a weak

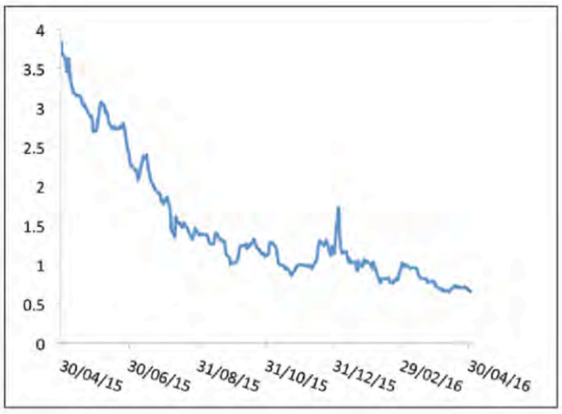
Compound Semiconductor share price leaderboard

Rank	Company	Ticker	Share value, April 30, 2015 ($)	Share value, April 29, 2016 ($)2	% appreciation	Change in Rank
1	Oclaro	OCLR	1.92	5.05	163.0	+13
2	Lumentum**	LITE	18.60	25.30	36.0	n/a
3	AXT	AXTI	2.38	2.57	8.0	+7
4	Emcore	EMKR	5.43	5.70	5.0	+1
5	IPG Photonics	IPGP	88.58	86.67	-2.2	-2
6	NASDAQ composite	IXIC	4,941.42	4,775.36	-3.4	-2
7	IQE (London)	IQE	0.33*	0.29*	-11.1	-1
8	Finisar	FNSR	20.33	16.46	-19.0	+4
9	Riber (Paris)	RIB	1.35*	1.09*	-19.6	+5
10	Cree	CREE	31.68	24.51	-22.6	+6
11	Aixtron (Frankfurt)	AIX	6.76*	4.99*	-26.2	+4
12	Skyworks	SWKS	92.25	66.82	-27.6	-11
13	Qorvo	QRVO	65.91	45.03	-31.7	-4
14	Infinera	INFN	18.80	11.89	-36.8	-12
15	Veeco	VECO	29.51	18.41	-37.6	-4
16	Rubicon	RBCN	3.84	0.68	-82.3	+1

* Converted to dollars using the exchange rates on 30 April of 1 EURO = 1.145 USD and 1 GBP = 1.463 USD

** Company started trading on 4 August, 2015. Only considered change in valuation from then.

Rubicon's share price has tumbled, due to lack of demand in the LED substrate market.



Rubicon's share price has tumbled, due to lack of demand in the LED substrate market.

sapphire market with excess capacity. And recently, according to company CEO, Bill Weissman, these issues have been exacerbated by fluctuations in inventory levels, which have created additional downward pricing pressure.

Although it might appear that the Illinois sapphire-maker is in dire straits – sales are still heading south, with the most recently reported quarterly revenue of $2.5 million down $2.9 million sequentially – the company is by no means dead and buried. It has products that promise to make a big impact in tomorrow's LED market, and it is pursuing opportunities for sapphire in other sectors.

The company is hopeful that its patterned sapphire substrates (PSS) can revitalise its business. "For PSS, we believe we have a competitive advantage in being able to produce PSS wafers in a vertically integrated process starting from powder aluminium oxide, particularly in larger diameters," said Weissman to investors in late February, during an earnings conference call to discuss results for the fourth fiscal quarter of 2015. He believes that many of his rivals don't have this capability, making them more vulnerable to disruptions. "[Vertical integration] was a significant factor in our qualification at an important six-inch PSS customer and we believe it will become increasingly important to other LED chip manufacturers over time."

Rubicon is increasing the size of its sapphire products to try and tap into opportunities in the aerospace, semiconductor, defence and industrial markets.

Qualifying customers for PSS can take a long time, but this can be beneficial, as it fosters an intimate, loyal relationship. However, even with this benefit, pricing for 6-inch PSS is weak, due to the low demand for 6-inch wafers. So, to make the best of a bad situation, Rubicon is striving to cut costs by introducing new consumables and refining its processes.

The weak pricing in the sapphire market stems from the unfulfilled promise of using this as a replacement for cover glass in mobile phones. It is unclear if this situation will change, but interest in this area has helped to spur development of sapphire for other applications where tough, transparent materials could prove very useful.

Rubicon's optical business is pursing these opportunities, and developing sapphire with dimensions of up to more than 500 mm for aerospace, semiconductor, defence and industrial markets. By the end of this year it aims to be producing 16-inch Kyropoulos boules for semiconductor and defence applications. Other companies can grow crystals of comparable size but Weissman believes that most of these rivals cannot meet the quality of the requirements.

Rubicon is also working on a government-funded project to produce windows of sapphire up to 2 inches thick, and as large as 18 inches by 36 inches. Weissman claims that there is significant customer interest in these massive windows, and argues that this US programme will position Rubicon to be the dominant supplier of large-area sapphire optical products within the next one-to-two years.

The sapphire maker clearly has a long way to go to turn around its fortunes. But as all investors know, when a company is struggling, significant gains in share price can result from reporting a relative modest, but better, balance sheet. Rubicon should also take heart from the fortunes of Oclaro, which footed the share price leader board in 2012 and 2013, but has topped it in 2014 and this year, by not doing anything spectacular, but simply heading in the right direction.

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PICs: Options for lighting up the chip

To produce the best PIC, is it better to take an InP laser and unite it with a silicon photonic chip, or make many components in InP, before uniting with silicon?

RICHARD STEVENSON INVESTIGATES

THE PHRASE 'silicon photonics' has its good and bad points. It's undeniably catchy, giving the impression that silicon foundries can churn out chips operating close to the speed of light; but it also causes confusion, because it suggests that a silicon chip can generate, route and detect light.

As all those that work with photonic integrated circuits (PICs) know, the latter is not actually true: a silicon laser is still a distant dream, because this material is an incredibly inefficient light emitter. So, to create a photonic chip today, the laser is made from compound semiconductor materials. In fact, it is possible to build the entire photonic chip from this material system. It is an approach that can deliver great commercial success, as shown by Infinera. However, it is not the only option, with one common alternative being the integration of the III-V laser with a silicon chip.

At the inaugural PIC International Conference, two differing views were offered on the pros and cons of different approaches for equipping a photonic chip with a light source.

Speaking at the session entitled *Where should the laser go?,* Shinki Matsuo from NTT Photonics Laboratories outlined a cost-effective approach for incorporating InP-based buried heterostructure lasers on silicon substrates; while Fang Wu from ArtIC Photonics championed the production of an InP circuit that is subsequently united with silicon. Matsuo, a Senior Distinguished Researcher at the NTT Device Technology Laboratories, gave a talk describing the development of a pair of devices: a distributed feedback (DFB) laser on SiO_2-on-silicon for datacom applications, and a novel photonic laser for use in computer communication. In both cases, the laser had a high modulation efficiency that resulted from the high degree of optical confinement.

The spokesman for NTT began his presentation by highlighting two findings from a Cisco study of datacentre traffic. This piece of market research determined that more than three-quarters of datacentre traffic is directed internally, and global data centre traffic is increasing at a double-digit rate.

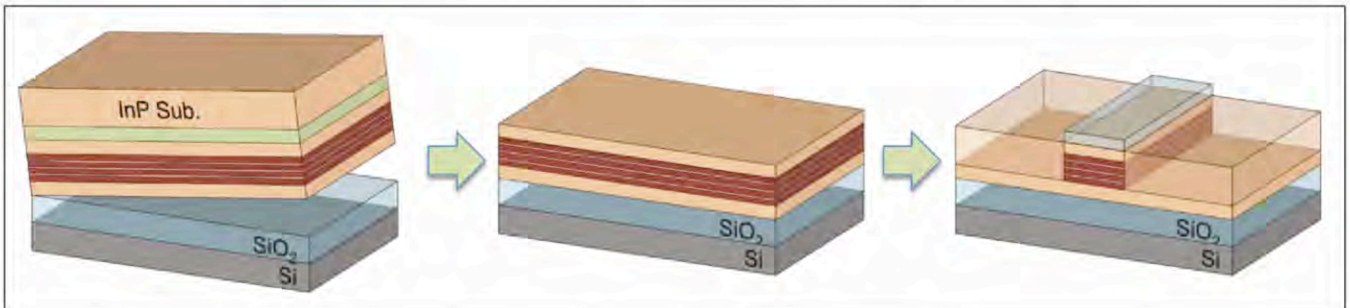

Figure 1. Engineers at NTT perform wafer bonding prior to the formation of a buried heterostructure. This approach simplifies device alignment.

For the data-centre application, today's workhorse is the VCSEL. It is used in links of about 1 m to 100 m or more, because it combines low cost with a very low power consumption. However, it may not be suitable in future, because it could struggle to cope with increases in traffic.

Matsuo believes that the increase in data traffic will be accommodated by the introduction of wavelength-division multiplexing technology in these short links. "The VCSEL is challenging, because it is difficult to control the single-mode lasing and the wavelength," argues Matsuo. He points out that the DFB laser might be better suited to this application, because it is easy to control the lasing wavelength of this source, which is well-established, given its use in telecom networks.

One of the weaknesses of the traditional DFB laser is its power consumption – it is much higher than that of a VCSEL. But this flaw has been overcome by NTT's lasers, thanks to the use of a membrane architecture. Another attractive attribute of these lasers is their low cost, which results from production with silicon fabrication technologies.

The low power consumption of the lasers stems from an architecture that ensures a high degree of optical confinement. Many developers of InP-on-silicon lasers – including teams at the University of California, Santa Barbara, Ghent, and Leti – employ a vertical *pin* junction and a III-V layer typically 3 μm-thick. This leads to an optical confinement factor ranging from 3-9 percent. In comparison, the NTT laser has an optical confinement factor of around 50 percent, thanks to a lateral *pin* junction that incorporates a III-V layer that is just 250 nm-thick.

Wafer bonding unites the lasers with the silicon substrates. As large SiO_2-on-silicon substrates are used, several InP wafers are bonded to them. If the bonding is carried out after the fabrication of the buried heterostructure, fine alignment is required in the bonding process. So, to avoid this issue, wafers are bonded before forming the buried heterostructure (see Figure 1).

To create the lateral injection lasers, after the buried heterostructure has been defined, silicon ion implantation defines the *n*-type region and the *p*-type region is formed via zinc diffusion (see Figure 2). "We slightly etch the InP layer to increased the coupling coefficient to the grating," explains Matsuo.

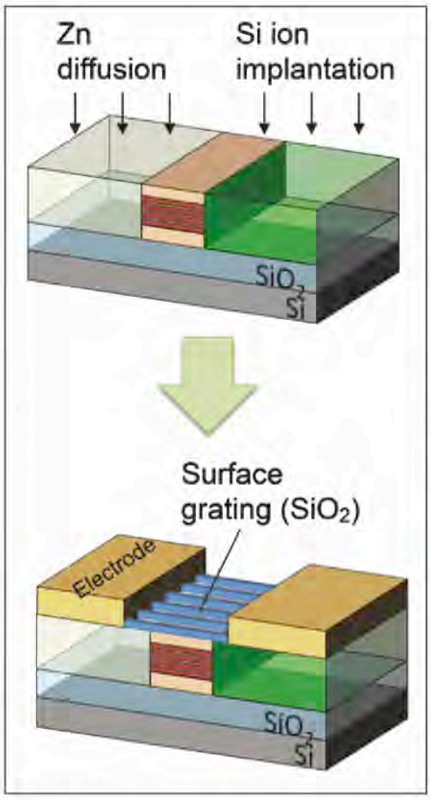

Figure 2. Using a lateral geometry enables the team from NTT to have a high degree of optical confinement for their lasers. This leads to an increase in efficiency.

The lasers that result operate at up to 100 °C, have a maximum output power of 0.93 mW at 25 °C, and produce a peak wall-plug efficiency of 9.7 percent. Driven at 25 °C with a 25.8 Gbit/s non-return-to-zero signal, their key figure-of-merit is 171 fJ/bit.

Recently, NTT's engineers have improved upon this by combining their DFB laser with a distributed Bragg reflector and a spot-size convertor. It is based on a 300 μm laser taper, which reduces in width from 1.5 μm to 0.1 μm. Although the taper introduces a loss – it is calculated to be 1.7 dB – the device delivers 131 fJ/bit when driven with a 25.8 Gbit/s non-return-to-zero signal.

Matsuo claimed that a far lower figure of 7 fJ/bit is required for "computercom" applications. "So we employ photonic crystal cavities."

Photonic crystal lasers may be made by forming holes in a slab of InGaAsP. But this quaternary has its downsides, including a low thermal conductivity and a lack of carrier confinement. These weaknesses make it challenging to realise room-temperature, CW operation. Although increasing the Q-factor and reducing the active volume helps, lasers still suffer from a low output power and a low modulation speed.

To address this, Matsuo and co-workers have developed an InP-based device that they describe as a LEAP laser – that is short for a λ-scale, embedded-active-region photonic crystal laser. Selecting InP, rather than InGaAsP, produces several benefits: it provides a hike in thermal conductivity from 4.2 W m^{-1} K^{-1} to 69 W m^{-1} K^{-1}; it enables effective carrier confinement; and it simplifies integration with input and output waveguides.

The team's electrically driven LEAP laser on an InP substrate operated with an energy cost of just 4.4 fJ/bit when hooked-up to a 10 Gbit/s non-return-to-zero signal. Replicating these results on a silicon substrate has been challenging, with the Q-factor increasing, leading to a hike in threshold current from 4.8 μA to 57 μA. "Now we are modifying cavity design," revealed Matsuo.

InP and silicon: Pros and cons

Wu, Co-founder and Chief Technology Officer of the Canadian start-up ArtIC Photonics, has also considered various material systems. In her talk, she compared the strengths and weaknesses of InP and silicon: "It's not clear cut, which is why there is a debate."

According to her, the merits of InP include its strong optical and optoelectronic functionality, which must be weighed against relatively high power consumption for electronic devices made with this III-V. She argues that InP can be used in foundries, but there are compromises: "It either has too complicated a foundry process, or it can be designed to a high-volume foundry, but design flexibility is restricted."

Silicon, meanwhile, is let down by its optoelectronic capabilities, but can form superior passive circuits, and is compatible with CMOS fabrication. "So clearly we need to have both material systems combined to meet the challenge," reasoned Wu.

One option is to bring the InP laser onto the silicon substrate to create a hybrid photonics chip with an optical interface. While this addresses concerns related to emitting and receiving light, it creates issues at the edge of the network that are related to the pluggable interface. "That's a big problem," says Wu. "It does not address the foundry compatibility."

A more traditional approach, which is pursued by ArtIC, is to begin by forming all the monolithic optoelectronic functions in InP. In the case of the Ottawa start-up, the InP wafer is then flipped over and attached to another made from silicon (see Figure 3).

The starting point for this is the growth and processing of the InP epiwafer. It features "base epitaxy", a collection of layers near the substrate that are used to form coupling waveguides and passive waveguides. Active devices are grown on top, using either selective-area growth or growth-etch-regrowth. Connecting devices by waveguides avoids the need for careful alignment, and ensures design flexibility.

Wu says that by adopting this approach, ArtIC can realise a continuous, uninterrupted process flow from beginning to end. By using standard semiconductor etch and protection steps, and a metallisation process, PICs can be produced with short process times under a smooth production flow.

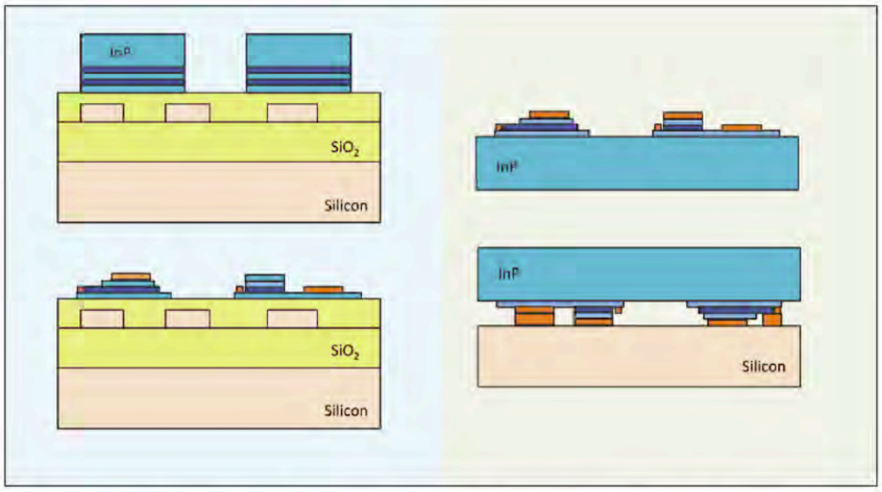

Figure 3. Forming lasers on silicon substrates (left) is not a foundry-compatible process. If the devices are defined on the InP substrates first (left), which is the approach that is pursued by the Ottawa start-up ArtIC, chip production can be outsourced to a foundry.

One of the major benefits of taking this particular approach is that it allows PICs to be produced in electronic foundries that churn out RFIC chips. "It helps reduce development costs, and more importantly, it is a manufacturing-ready process," enthused Wu.

She went on to outline some of the "true" building blocks that can be connected in different ways. They include a single-mode laser with a surface-etched grating that can operate at up to 10 Gbit/s; an electro-optic modulator that can deliver switching at up to 40 GHz; and a spot-size converter with a loss of less than 10 percent over the 1.49 μm - 1.63 μm spectral range.

Engineers at ArtIC have also designed Echelle gratings for wavelength division multiplexing. They can provide a channel spacing ranging from 100 GHz to 20 nm.

"The noise floor is below -35 dB," explained Wu, who also detailed a coherent receiver, featuring 14 integrated components.

Like NTT, the Canadian outfit is targeting the short reach data com markets with its PIC technology. However, it believes that low-cost, high-volume manufacture will allow its technology to also serve the medium-reach access market, which requires links of 10-20 km, and the longer reach metro market that involves data transfer over distances of around 40 km.

It will be interesting to see how PICs made with ArtIC's technology, and those made using NTT's, impact the market in the coming years. Discussions of the successes that they have, and that of their rivals, is sure to be one of the talking points of PIC International in 2017 and beyond.

"One option is to bring the InP laser onto the silicon substrate to create a hybrid photonics chip with an optical interface. While this addresses concerns related to emitting and receiving light, it creates issues at the edge of the network that are related to the pluggable interface"

Delivering multi-band detection with heterogeneous arrays

Transfer printing of silicon onto InGaAs creates a multi-band detector for visible and infrared imaging

BY LAXMY MENON, HONGJUN YANG AND WEIDONG ZHOU FROM THE UNIVERSITY OF TEXAS AT ARLINGTON, MATTIAS HAMMAR FROM KTH, SWEDEN, AND ZHENQIANG MA FROM THE UNIVERSITY OF WISCONSIN-MADISON

IT'S RARE that one material system can tick all the boxes. So it can make sense to unite two or three. That's the case with triple-junction solar cells, and it is an option for next-generation ICs and photonic integrated circuits.

Uniting different materials is also a winning formula for imaging systems. Here, integrating materials with different bandgaps enables detection in several wavelength ranges. This holds the key to the construction of multi-band, multi-spectral imagers that can be used for remote sensing, industrial surveillance systems, bio photonics, automotive cameras, fluorescent imaging, spectrometers on a chip, LADAR, and free-space optical communications.

Recently, the greatest interest in this sector has been associated with the simultaneous acquisition of visible and infrared light. There are several ways to do this, and the three most popular options today are using colour filter arrays, external mechanical filters, and exploiting a material's depth-dependent absorption.

With the first of these three, the colour filter array, different colours are identified by placing an array of spectral filters over an imager sensor. The traditional approach has been to have 50 percent of the area covered by a green filter, and the remainder split equally between red and blue.

Recently, however, there has been a move to combine red, green, blue and panchromatic, the latter of which is sensitive to all. But there are downsides of this approach that stem from the high sensitivity of panchromatic pixels to visible wavelengths, and the high sensitivity of the red, green and blue cells to near-infrared wavelengths.

If the second option is applied – the use of mechanical filters – then the most

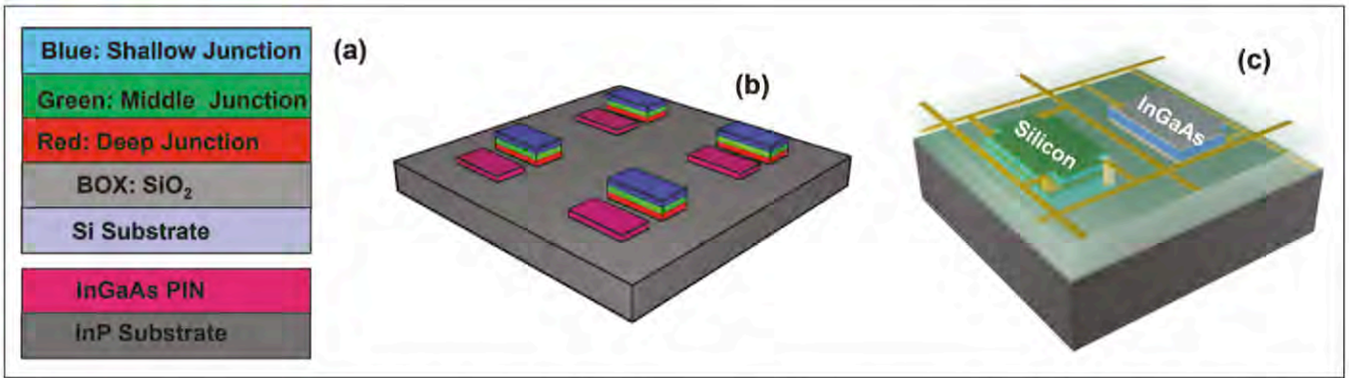

Figure 1. Crystalline nano-membrane-based stacked multi-colour, multi-band photodetector arrays: (a) Three-junction silicon-on-insulator wafer, optimized based on the penetration depth of blue, green and red wavelengths in silicon, and an InGaAs single junction wafer, before transfer; (b) silicon pixels transferred onto an InP substrate with precise alignment with an InGaAs pixel; (c) one pixel of multi-colour, multi-band membrane imager after device completion.

Wafer bonding	PDMS transfer printing	Epitaxial growth	PDMS transfer printing
Inability to scale to more than a few layers in the third dimension	Several membrane layers can be stacked on top of each other	Severe restrictions on the type and quality of materials that can be grown	It is possible to perform transfer printing on various materials with excellent repeatability
Incompatibility for use with structured or low temperature materials/ substrates	Transfer printing can be done on structured and textured surfaces	High temperatures are involved, which may damage underlying layers/circuitry	Transfer printing is done at low temperatures, which doesn't cause thermal degradation of the underlying layers
Challenging fabrication and alignment for the through wafer electrical interconnects	Layer to layer interconnects can be done by direct metallization on device structure		
Bowing and cracking occurs from mechanical strains due to the difference in thermal expansion of dissimilar materials	Processing occurs at low temperatures which avoids issues occurring due to difference in thermal expansion coefficients		
Demanding requirements for planar bonding surfaces	Transfer printing can be done easily on most surfaces		

Table 1. Comparison between polydimethylsiloxane (PDMS) printing, wafer bonding and epitaxial growth.

common approaches are to capture the same scene through two separate cameras simultaneously; or to use an IR blocking filter, or a visible blocking filter, to simultaneously take two images of the same scene. Unfortunately, both approaches require substantial post processing, such as image fusion. In addition, hardware is expensive, bulky and slow, whether filters are replaced mechanically or two cameras used. What's more, greater processing power is needed to analyse and compare two separate images.

For the third option, which involves exploiting the depth-dependent absorption property of a material, the leading technology is based on the vertically integrated photodiode structure. InGaAs and silicon is a common combination, with the quantum efficiency of InGaAs increased in the visible band through removal or thinning of the InP substrate.

Transfer printing

Our team at the University of Texas at Arlington is pursuing this type of approach. We are pioneering the use of a transfer printing technique to construct a multi-band detector based on silicon and InGaAs.

It is possible to build a multi-colour detector with just silicon, because photons with different energies have different absorption depths. The way to do this is to stack several *p-n* junctions on top of one another and exploit an absorption depth that varies by several orders of magnitude over the visible range. Merits of this approach include avoiding the inevitable transmission losses and colour aliasing effects, and having a resolution that is limited by colour-filter-based sensor arrays. There is a limit to what silicon can do, however. Its bandgap prevents detection at wavelengths beyond 1.1 μm, so we unite it with InGaAs, which is capable of detecting near IR wavelengths up to 1.68 μm.

Two widely used approaches for uniting different semiconductor materials are epitaxial growth and wafer bonding. Both have weaknesses: epitaxial growth, for example, cannot unite all materials and requires high temperatures, while wafer bonding is incompatible with some forms of semiconductor (see table 1 for a more detailed account of the limitations of both techniques).

We overcome all these shortcomings with a transfer printing process that has been widely used to create heterogeneously integrated devices. The process involves

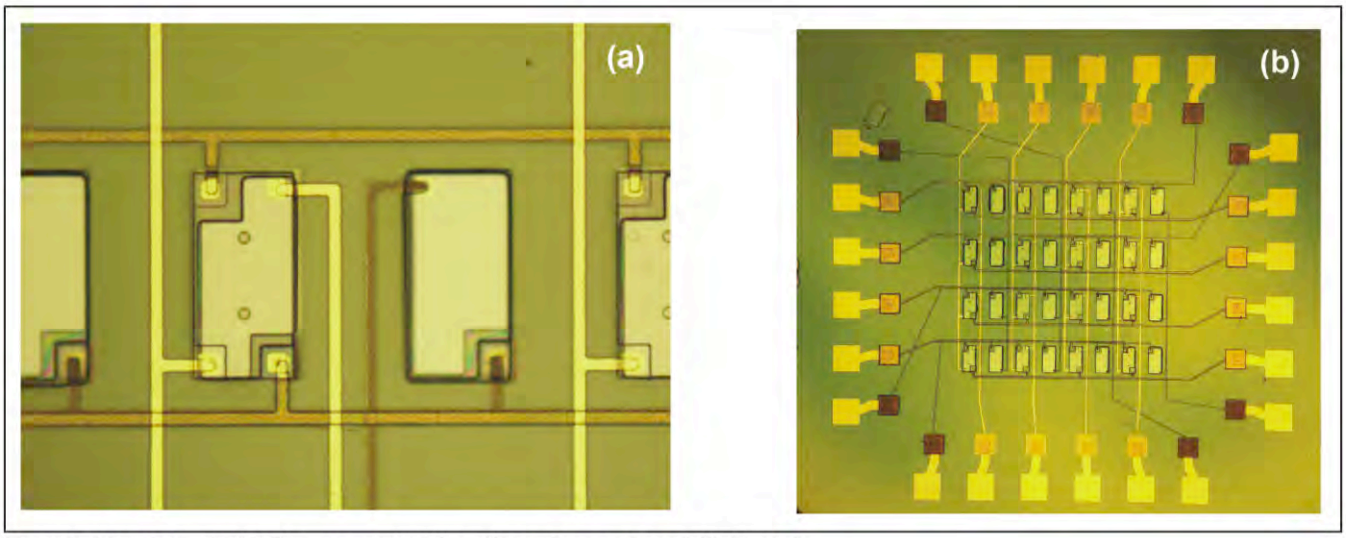

Figure 2. (a) a single pixel in the array, comprising of one silcon and one InGaAs photo-detector and (b) the entire 4x4 array.

a polydimethylsiloxane (PDMS) stamp that acts as the intermediate medium, transferring a membrane layer from the parent substrate to its new home. The great strength of this approach is that the highest performance material for a specific application can be transferred or integrated into unusual and challenging environments. Devices made by various groups include a membrane-reflector VCSEL, solar cells and an *n*-channel MOS inverter.

In our case, we form our heterogeneously integrated multi-band photodetector array by picking up silicon chiplets from a silicon-on-insulator platform with a PDMS stamp and transfer-printing them on to InGaAs photodetectors (see Figure 1).

The silicon chiplets have a vertical *n-p-n-p* structure, and are capable of detecting blue, green and red, thanks to the wavelength dependent absorption

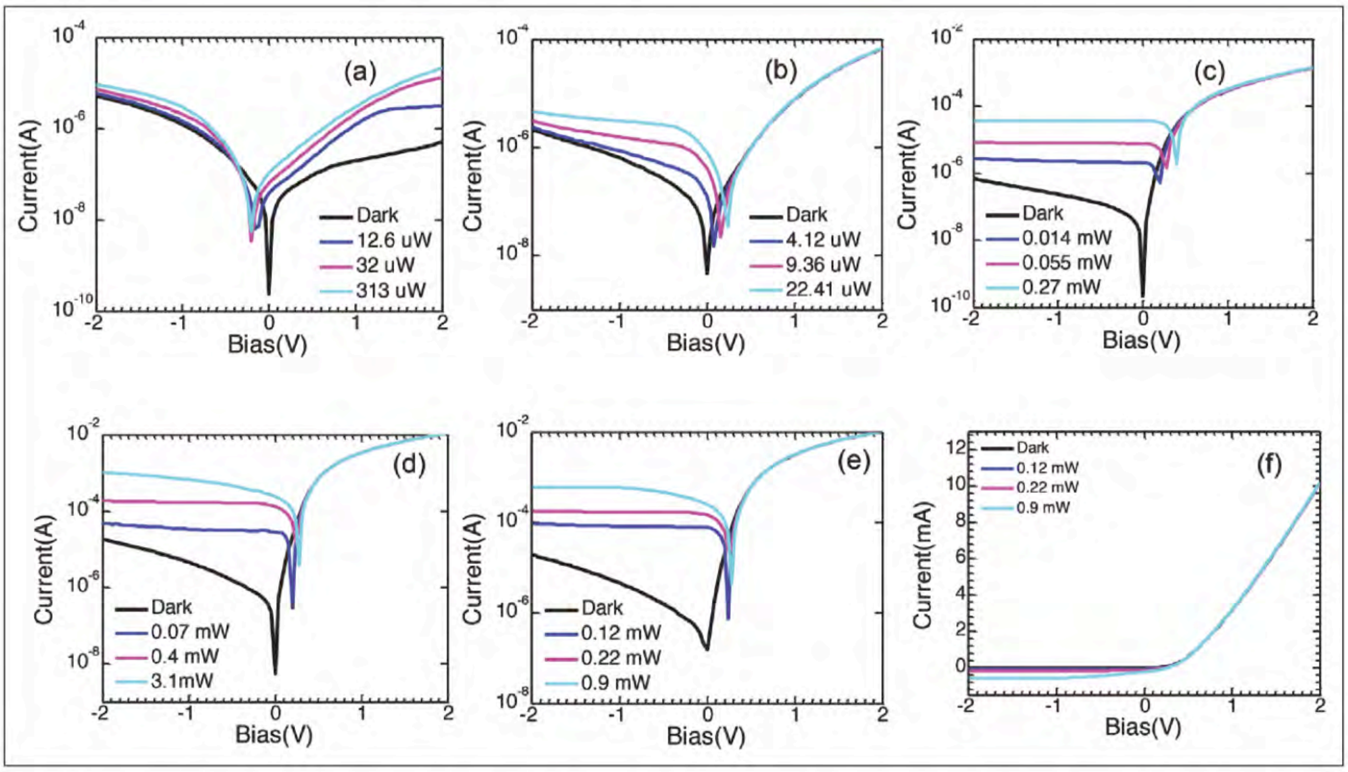

Figure 3. Measured current-voltage characteristics of blue, green and red junctions of silicon under illumination with (a) 405 nm (b) 532 nm (c) 632 nm, revealing responsivities of 0.09 A/W, 0.1 A/W, and 0.15 A/W, respectively. Measured responsivities in an InGaAs photodiode at 980 nm and 1550 nm are 0.5 A/W and 0.8 A/W.

property of silicon. Near infrared light is captured by the InGaAs detector, which has a *p-i-n* structure with a 2 μm intrinsic region. The transfer process must provide precise alignment, in order to ensure an alternately placed silicon and InGaAs photodetector array (see Figure 2).

With our approach, there is no need for mosaics, or for interpolation. What's more, by capturing visible and infrared radiation in a single shot, with the same resolution, we avoid complicated processing steps associated with the deposition of infrared blocking filters at the pixel level.

Proven success

Performing current-voltage measurements on our silicon and InGaAs devices verifies their good diode characteristics. We have also subjected these devices to different illumination wavelengths. The photoresponse of the devices show significant variation with incident intensity, indicating good responsivity (see Figure 4). This is encouraging, because responsivity is directly related to device efficiency.

If a multi-band detector is to offer good resolution during imaging, all its devices must deliver a uniform performance. When this occurs, colour images can be constructed by measuring the spectral responsivities for each junction and then performing post-imaging data processing.

Our development of multi-band detectors is in its infancy, with efforts beginning with a 4 by 4 array. With just 16 pixels, imaging an object is not possible.

So instead we have evaluated the performance of our detector by trying to recreate a column of pixels illuminated by a narrow slit, by imaging. In this process, we illuminate only one column of pixels through a narrow slit, while all other pixels remain dark. The photoresponse of all the pixels (all junctions) is measured in this condition, and by using the data obtained in post processing techniques, we can image the illuminated column of pixels. On the array, the pixels that are not illuminated by the light through the slit remain dark.

This experiment was successful, with the illuminated column – column 2 for the blue junction, and column 3 for green, red and infrared junctions – easily distinguished from the non-illuminated columns (see Figure 4). The non-uniformity in colour is due to a variation in the intensity of the light hitting specific junctions. This is promising, as it lays the foundation for imaging an object, or scenery during day or night.

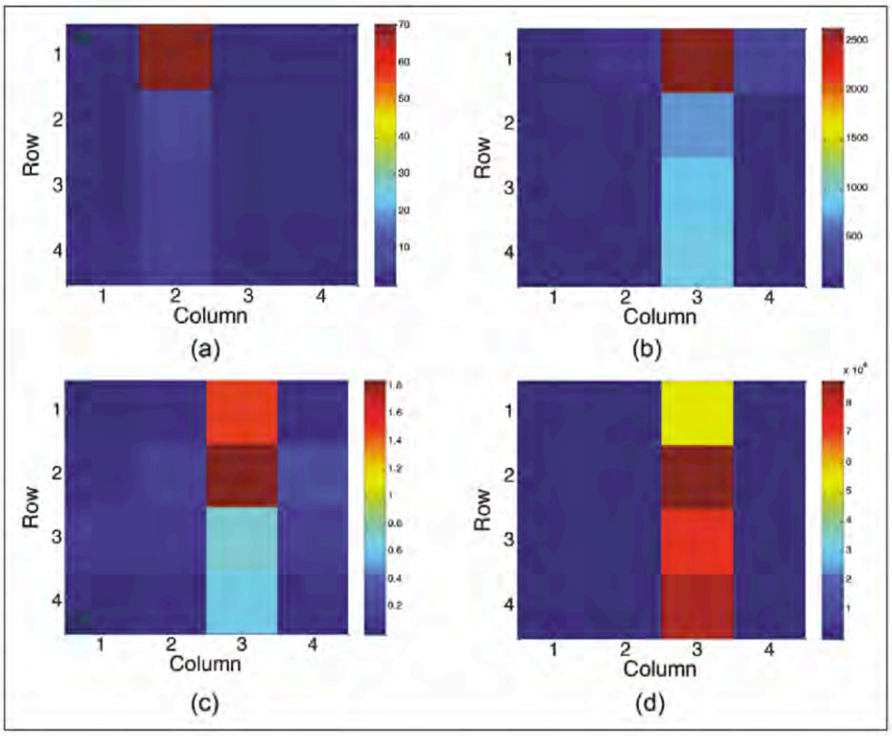

Figure 4. Reproduced images of the illuminated column in the 4×4 array formed by biasing the (a) blue junction; (b) green junction (c) red junction and the (d) infrared junction. The horizontal and vertical numbers in the figure indicate the row and column number of the array. Each square in the figures represents the difference between the measured photo current and dark current for that specific junction of the pixel. The scale bar on the right side of each figure shows the range of values in the square. Non-uniformity in colour is due to the variation of this diference between the various pixels, for that specific junction.

We have shown that by utilizing the inherent properties of silicon and InGaAs, and uniting them with an established PDMS transfer printing method that does not require any expensive equipment, it is possible to build a lightweight, cheap, heterogeneous detector array.

Other semiconductor materials could be used in this process, enabling the production of multi-band detectors covering other spectral ranges, and providing spectrally resolved sensing systems for other applications. We are already working on creating a GaN and silicon heterogeneously integrated light source/photodetector for bio-medical applications.

To enable our technology to serve even more applications, we are trying to build a detector on a flexible substrate, such as kapton or a shape-memory polymer. Additional goals are to increase the size of our arrays and their fill factor.

Further reading

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The superiority of single-wafer systems

Single-wafer MOCVD tools producing rapid changes in temperature are ideal for delivering high throughput while ensuring excellent levels of film uniformity

BY SHINICHI MITANI FROM NUFLARE

UNDERPINNING the long-term growth in global GaN LED revenue has been the penetration of this chip in an increasing number of 'killer applications'. Backlighting screens and keypads of mobile phones provided the first multi-billion dollar market for this device, and more recently sales have blossomed through the deployment of this chip in the backlighting units of larger screens, such as TVs and tablets, and in general lighting.

As LED revenue has increased, MOCVD growth has shifted to larger diameter formats. High-volume production began on 2-inch sapphire, but during the last decade or so, an increasing proportion of chips have been manufactured on 3-inch, 4-inch and 6-inch sapphire.

Recently, there has also been interest in alternatives to sapphire, including silicon. It is available in larger sizes, such as 200 mm and 300 mm, enabling even higher throughput at the die level. What's more, silicon has a superior thermal conductivity and 'processability' to sapphire. These merits have also driven interest in the growth of GaN-on-silicon heterostructures for electronic devices.

Makers of MOCVD tools have tended to respond to the trend of moving to larger wafers by increasing the capacity of their multi-wafer reactors. But there is another option. It is possible to mirror the path taken in the silicon industry, where an increase in wafer size from 100 mm to 150 mm prompted the majority of tools to switch from multi-wafer/batch tools to single-wafer variants.

At NuFlare Technology, Inc. of Yokohama, Japan, we advocate this approach. We began by developing a series of single-wafer epitaxial tools for silicon and SiC epitaxy, and we expanded our portfolio with the launch of tools for MOCVD growth of 200 mm GaN-on-silicon wafers. Single-wafer tools hold the upper hand over their multi-wafer siblings on several fronts, including the uniformity of the epitaxial film, the width of the process window, and material efficiency. In addition, it takes less time and expense to develop a device structure.

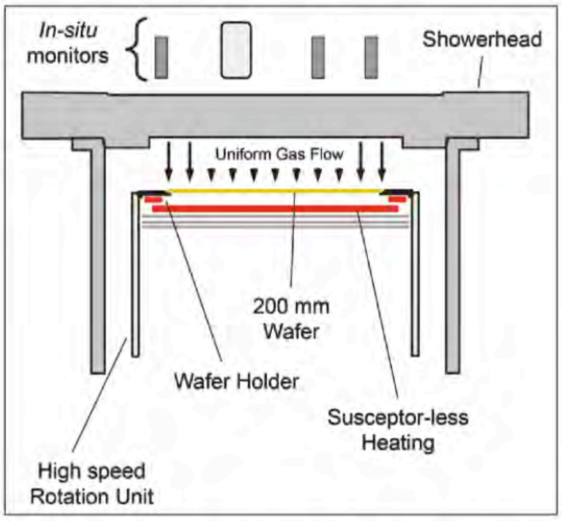


Figure 1. A cross-sectional view of an Epirevo MOCVD reactor.

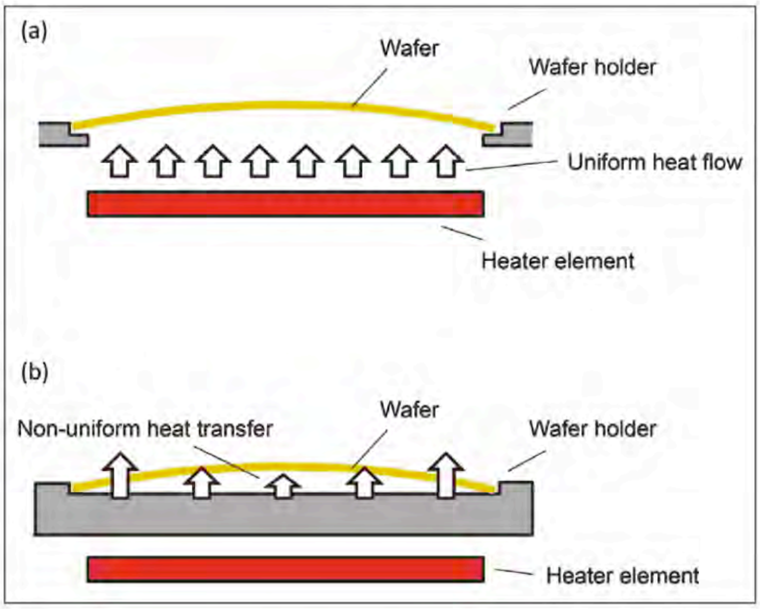


Figure 2. Heat transfer to a deformed wafer (a) in susceptor-less (direct) heating and (b) from a hot susceptor.

Although these strengths will appeal to GaN-on-silicon chipmakers, they may be reluctant to consider single-wafer tools. That might arise due to a belief that multi-wafer alternatives have lower hardware costs, because the expense associated with a gas-supply unit (gas panel) can be very high. However, we believe that this issue can be addressed by operating single-wafer reactors in parallel. This trims the hardware costs to those of a multi-wafer tool.

Another attractive attribute of the single-wafer tool is that it eliminates the need to adjust the growth process when scaling-up from a development reactor to a production machine.

The big challenge with a multi-reactor system assembled from single-wafer tools is that to guarantee high productivity, there must be a small difference in the growth characteristics of the various deposition chambers. In other words, the single-wafer reactors must deliver similar growth rates, compositions, doping profiles and so on.

Susceptor-less heating

We excel in this regard with our showerhead design. It features a unique rotation unit and an approach to wafer heating that is not based on heating of the susceptor (see Figure 1 for a diagram of our reactor).

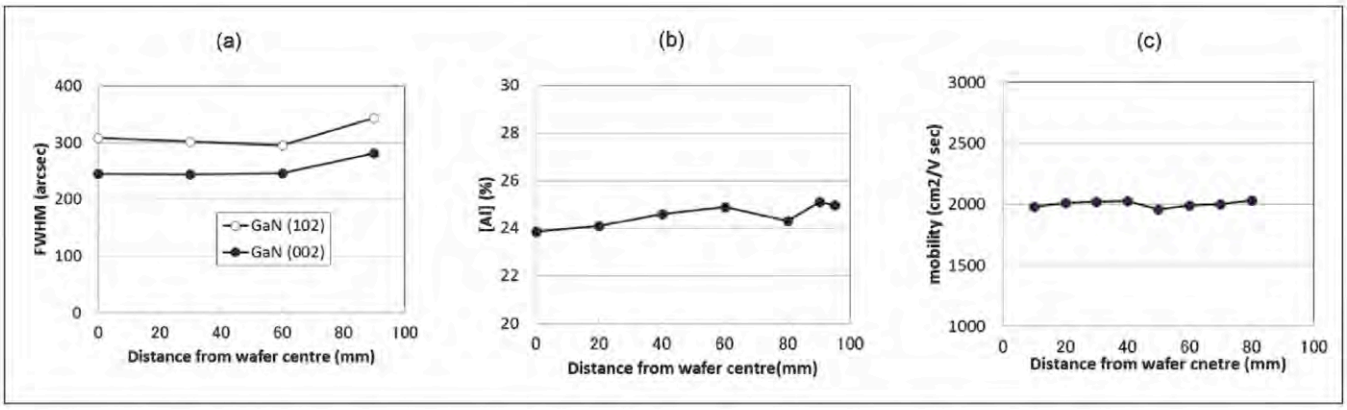


Figure 3. The Epirevo G8 is capable of highly uniform film growth. The capability is highlighted by: (a) Full-width half-maximum values of X-ray diffraction peaks of a GaN template on silicon, (b) the aluminium concentration of AlGaN, and (c), the carrier mobility of HEMT.

High in-wafer uniformity and material efficiency results from a uniform gas flow and a high-speed wafer rotation, achieved without using a centre-shaft (the typical rotation speed is 1500 rpm, and it can be faster). For growth of a GaN film on a 200 mm wafer, the standard thickness deviation is only 0.5 percent when applying an edge exclusion of 4 mm.

The wafer in our reactor sits on a ring-shaped wafer holder and is directly heated by a heater elements' radiation. Adopting this approach allows us to avoid one of the major weaknesses of the conventional approach to wafer heating – a variation in temperature caused by differences in the gap between the wafer and the susceptor, which is the source of heat. Regardless of the reactor geometry, when GaN is grown on a non-native substrate, the difference in thermal expansion between these two materials will cause the wafer to deform during growth. But in a reactor with a susceptor, variations are amplified by differences in temperature that result from differences in the distance between the susceptor and the wafer (see Figure 2).

By using susceptor-less heating, our single-wafer reactors do not suffer from a significant in-wafer temperature distribution. After optimising the heater arrangement, the temperature distribution across a wafer in one of our tools is approximately ± 1°C at 1100°C.

This incredibly high degree of temperature uniformity leads to a very small variation in the photoluminescence spectra across the wafer. For an InGaN/GaN multi-quantum well structure grown at 800°C, the standard deviation in photoluminescence peak wavelength is as small as 1 nm over a 200 mm wafer (average emission wavelength is 450 nm, and edge exclusion 4 mm). Judged another way, the 5 nm bin yield exceeds 95 percent.

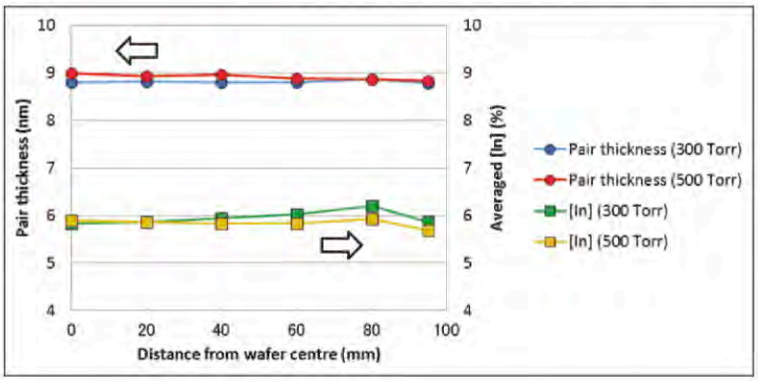
Excellent uniformity can also be seen in HEMT structures produced with our tool. This is evident in values across the wafer for: the full-width at half-maximum of X-ray diffraction peaks; the aluminium composition; and the carrier mobility (see Figure 3).

Our single-wafer reactor's wide process window is highlighted by measurements on multi-quantum well structures grown at 300 Torr and 500 Torr. At both pressures, indium composition and layer thicknesses are very similar.

Another merit of our approach to wafer heating is that it enables fast temperature ramping. This occurs because the heat capacity of the wafer is far less than that of the massive susceptor. Fast growth times result, which are not just due to a shortening of the time taken to ramp up the wafer prior to growth and to cool it down afterwards – there is also less time taken for temperature changes during MOCVD growth. This benefit frequently arises, because different layers are often grown at different temperatures, such as quantum wells and barriers in the active region.

One of the other features of our tool is the gas-phase etching of the wafer-holder. During GaN-on-silicon growth, GaN is also deposited on the reactor. Problems can follow, such as surface damage of the wafer, which results from melt-back etching of silicon by gallium droplets. However, we address these issues with our reactor: deposition of GaN is limited to the wafer-holder and avoided on the reactor wall, thanks to the well controlled gas-flow provided by on elaborately designed showerhead; and GaN that adheres to the wafer-holder is removed after every run to ensure repeatable GaN-on-silicon deposition. This cleaning process involves introducing etching gas

Figure 4. Radial distribution of the pair thickness, and the indium concentration, of multi-quantum wells grown at 300 Torr and 500 Torr.



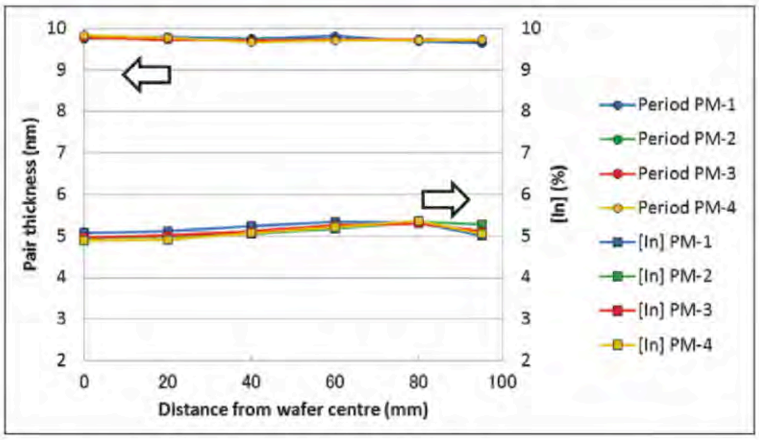


Figure 5. Radial distribution of the pair thickness, and the indium concentration, of multi-quantum wells of four wafers grown in different reactors in a run.

into the reactor and heating a dummy wafer on the wafer-holder. To minimise surface defects caused by manual loading, our tools employ cassette-to-cassette automatic loading of wafers. Note that this is a basic option on our tools.

Matching reactors

A high throughput is only possible when our reactors are used in parallel. To ensure a high yield, the set of reactors that are employed must be matched to one another.

The first step that we made towards this goal involved designing a gas supplying unit that delivers an equal amount of material to every reactor. One gas panel is used for the main raw materials. A master-slave, mass-flow controller gas distribution technology divides each material gas flow into an equal amount of subflows, which is fed to each reactor. Our second step for ensuring reactor-to-reactor consistency involves compensating for the small variations in film thickness and alloy composition between each deposition chamber. In the case of InGaN/GaN multi-quantum wells, success resulted from independent tuning of the growth parameters for each reactor (see Figure 5 for the results on four wafers grown in four different reactors).

With reactor-to-reactor consistency assured, process engineers can take advantage of the greater flexibility of a set of single-wafer reactors, rather than a multi-wafer tool. When developing devices, their needs can be satisfied with one reactor with one gas panel. Adding a second reactor and a gas panel for the new reactor to the existing system offers an easy route to higher throughput during the latter stages of development. For production, the system can then be upgraded to four reactors sharing a single gas panel (see Figure 6).

Having proven the capability of our tool for manufacturing LEDs and electronic devices, we are now evaluating its suitability for producing other classes of device.

To satisfy the demands of all of our customers, we must strive to continually improve the performance of our tool. Efforts in this direction include the development of new recipes, such as those for: the growth of InGaN/GaN multi-quantum wells at higher pressures, and the optimisation of buffer layers, doping profiles and device structures. We are also working to increase the time between maintenance, and offer a reactor for 300 mm wafers. The performance of the latter can only be confirmed through a joint development with our customers.

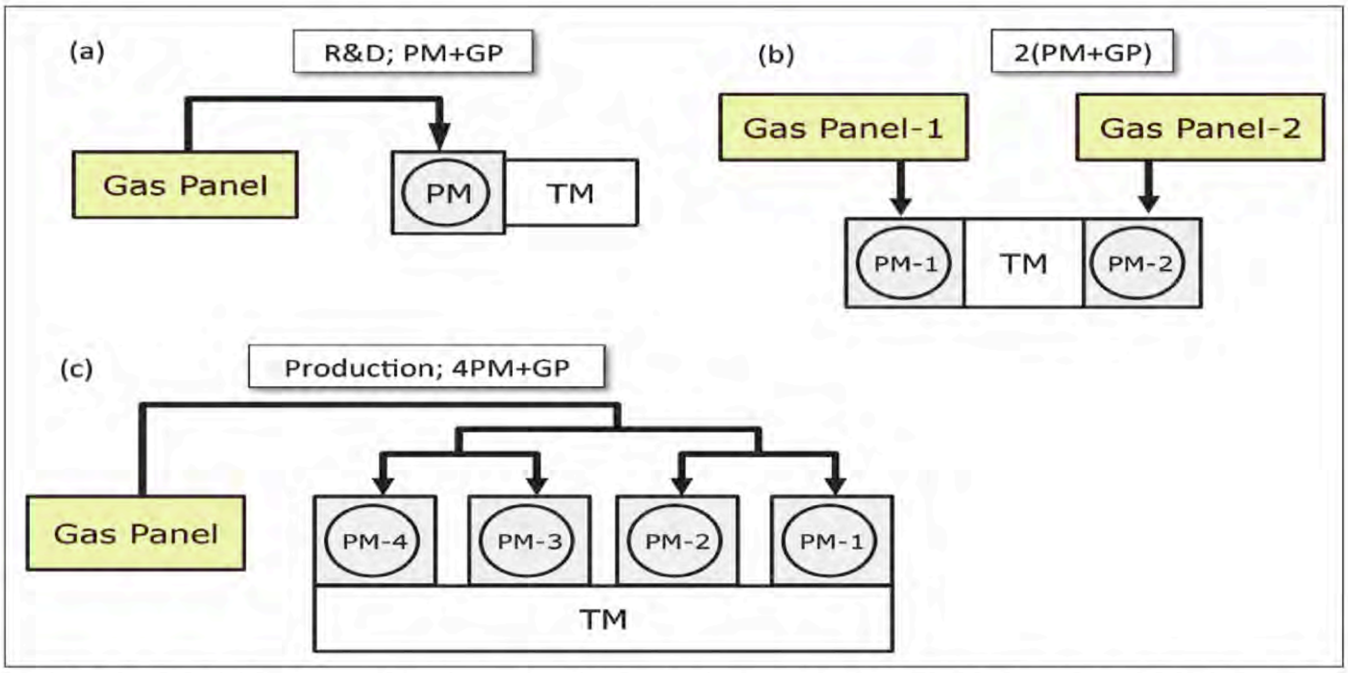


Figure 6. Examples of system configurations: (a) simple configuration of process module and gas panel (PM + GP); (b) independent, two simple systems of PM + GP with a transfer module (TM); and (c) 4 PMs + GP system for production.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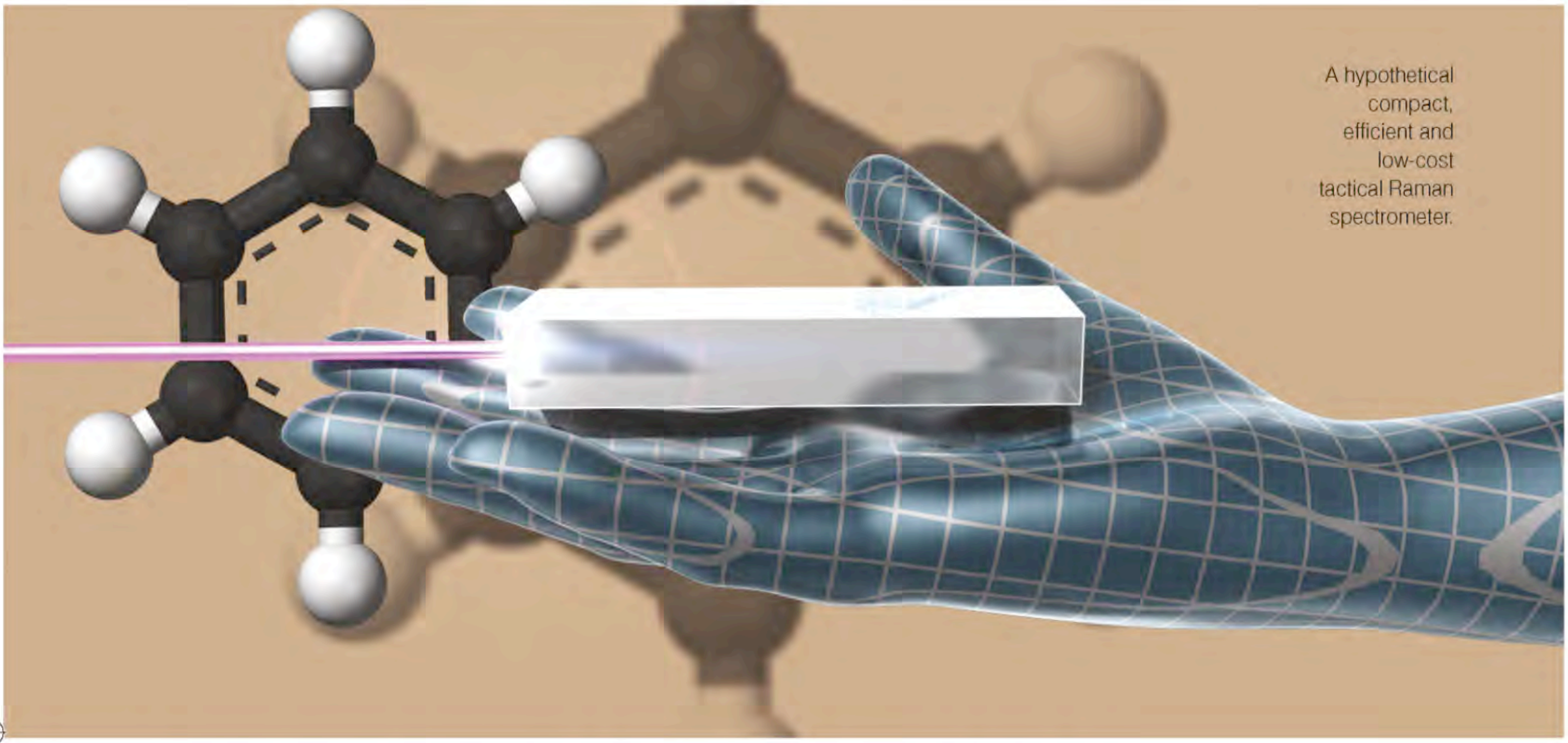


A hypothetical compact, efficient and low-cost tactical Raman spectrometer.

Sapphire substrates slash the cost of deep UV lasers

Optimised growth enables the first optically pumped, low-threshold deep UV lasers on sapphire

BY XIAOHANG LI FROM KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY (PREVIOUSLY WITH GEORGIA TECH), AND THEERADETCH DETCHPROHM AND RUSSELL DUPUIS FROM GEORGIA TECH

AMONG all the electromagnetic waves in the universe, the most relevant to us are those in the visible spectrum. It is the radiation at these wavelengths that enables us to see our surroundings and live, by breathing in oxygen generated by photosynthesis.

Just a short reduction in wavelength, however, and radiation may be far less welcome. In the deep UV, which corresponds to wavelengths of 280 nm or less, photons have higher energies and can interact with living cells, exciting electrons and disrupting critical chemical processes. This has led to mutation and cancer. Fortunately, however, UV light also has a good side. Highly energetic photons can be used to excite, engineer or break materials and chemical bonds in numerous applications.

One example of the positive use of UV light is as a source for enabling the identification of unknown biochemical substances. Radiation in this spectral range is ideal for this task, because all the functional groups are absorptive in the deep UV, compared to just a few in the visible. This makes for stronger signals that speed detection.

Using UV light to identify substances is not easy, however. Many applications cannot be taken out of the lab, because today's gas and solid-state deep UV lasers are bulky, complex, and costly.

To tackle this issue, DARPA has funded and led two consecutive programmes: Compact Mid-Ultraviolet Technology (CMUVT) and Laser UV Sources for Tactical, Efficient Raman (LUSTER). These programmes had a primary purpose of developing deep UV semiconductor diode lasers for efficient, low-cost, tactical Raman spectroscopy.

Benefits of a compact, deep UV laser are by no means limited to providing a source for Raman spectroscopy. This device could also aid non-line-of-sight (NLOS) communication, which is enabled by special characteristics of our atmosphere. In its upper region, ozone absorbs nearly all the sun's deep UV light. Consequently, light in this solar band is nearly non-existent on the earth's surface. The result is a low noise environment for the deep UV radiation, where photodetectors can reach a quantum-limited level of photon-counting detection.

Another appealing feature of the NLOS communication technology is that close to ground level, molecules and aerosols produce strong angle-independent scattering of deep UV light. This creates numerous communication paths from the source to the receiver, enabling the transfer of information even when line-of-sight obstacles are in the way – such as buildings in an urban city.

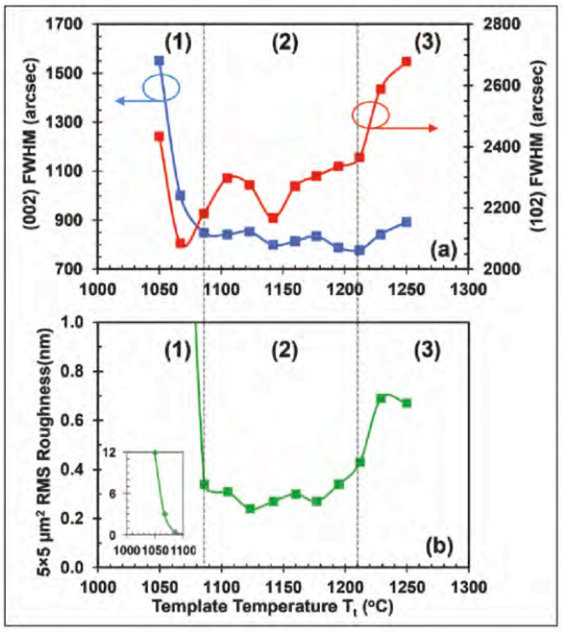


Figure 1. (a) The full-width half-maximum of peaks produced from X-ray diffraction ω-scans, and (b) root-mean-square roughness values from a 5 μm by 5 μm, atomic-force microscopy scan of AlN-on-sapphire templates formed at different growth temperatures.

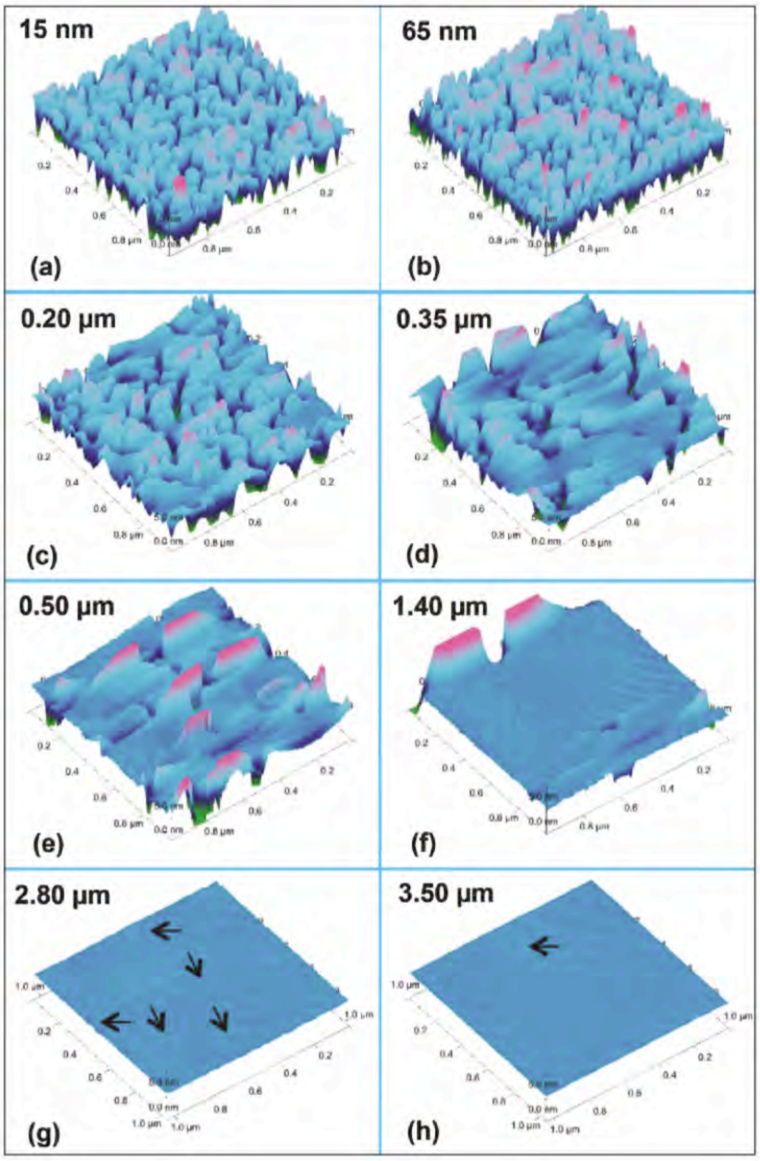


Figure 2. Atomic-force microscopy images showing surface morphology evolution of the three-layer AlN/sapphire structure as a function of total AlN layer thickness, shown in the upper left of each figure.

What's more, deep UV light from the source is absorbed moderately by the atmosphere. This limits the distance that information may be transmitted, making this communication technology ideal for tactical applications.

The most promising class of materials for making a compact, reliable, low-cost, and efficient deep UV semiconductor laser is the III-nitrides. Its attributes include high chemical and mechanical toughness and a very suitable range of bandgaps – the wavelength of the band edge can be as short as 200 nm.

Providing further motivation for the development of a deep UV III-nitride laser is the success of this

The development of deep UV lasers would aid non-line-of-sight communication, which could be fitted to robots used to destroy IEDs.

material system in blue LEDs and laser diodes. But replicating performance at shorter wavelengths is far from easy. As of today, the wall-plug efficiency of most commercial deep UV LEDs is still in the low single-digit range, and there is yet to be a demonstration of an accompanying laser diode.

One of the biggest challenges associated with developing a deep UV laser is that the highly mature, blue-emitting InGaN system is not up to the task, due to its smaller bandgap. Stretching emission from the blue to UV demands the addition of aluminium to GaN, and this increases the in-plane lattice mismatch between the III-nitride and the most common substrate, sapphire. Material quality degrades, with imperfections dragging down the quantum efficiency.

On top of this, it is difficult to design a deep UV laser diode. One challenge is to develop a structure that provides sufficient optical confinement. Judged in these terms AlGaN is not ideal, with changes in the aluminium content producing small variations in refractive index.

Another concern is that there is yet to be an experimental report of a switch in polarisation from the transverse-electric to the transverse-magnetic mode during the onset of stimulated emission. If the polarisation mode switches, this has a big impact on device design, because the transverse-magnetic mode leaks light deeper into the absorptive *p*-region, due to its broader beam profile.

Finally, *p*-doping in UV devices is far more tricky than its visible counterparts, because the activation energy of the magnesium acceptor is considerably higher in aluminium-rich AlGaN than it is in GaN. The upshot is an insufficient hole density in the active region that hampers stimulated emission.

Solving all these issues simultaneously is very challenging. Consequently, many research groups start by putting aside issues related to *p*-doping and focus on the rest. By taking this approach, their first goal is to produce optically pumped deep UV lasers, preferably with short wavelengths and low thresholds.

Pioneering this approach is a team from Kogakuin University. In 2004, this group reported the first deep UV III-nitride laser. Formed on a SiC substrate, this optically pumped, 241.5 nm laser has a very large threshold of 1200 kW/cm^2.

The next milestone in deep UV laser development came in 2011, when a partnership between Palo Alto Research Centre and the US Army Research Laboratory announced the demonstration of an optically pumped 267 nm laser with a threshold power density of just 126 kW/cm^2. One of the big differences between this laser and that produced at Kohgakuin University is the choice of substrate – it had been switched from SiC to bulk AlN. Reasons for preferring the latter include a low dislocation density – it is around 10^4 /cm^2 – and a similar lattice constant and thermal expansion coefficient to that of aluminium-rich AlGaN. Thanks to these merits, there is a low dislocation density in the AlGaN heterostructures. During the last few years, more groups have had success with AlN substrates. Low thresholds have been obtained by optical pumping while pushing the lasing wavelength ever shorter, to reach to 237 nm. These accomplishments have highlighted the AlN

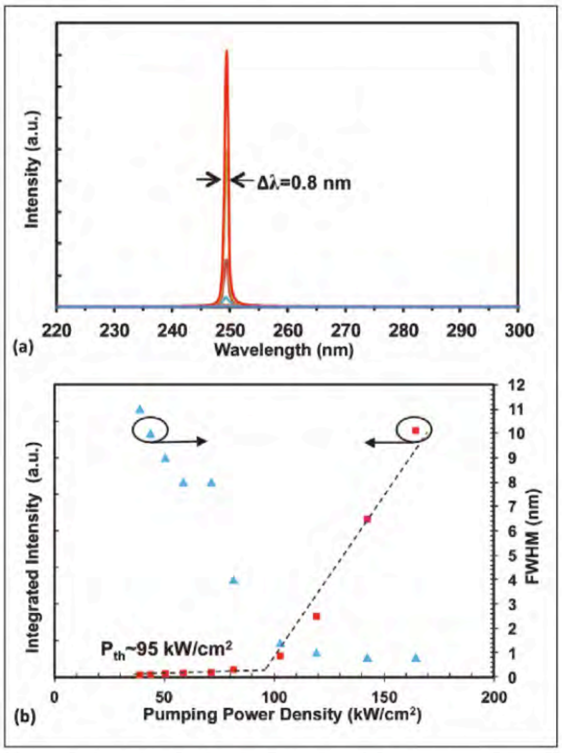


Figure 3. (a) Laser emission spectra and (b) spectral integrated intensity and linewidth of the 249 nm laser versus pumping power, using 193 nm excitation.

substrate as a technically promising platform for demonstrating and developing the deep UV laser diode.

However, there are issues associated with the AlN substrate. Supply is limited, costs are high, and it is only available in small sizes. What's more, the current manufacturing process for making it introduces carbon impurities, which is a hindrance for UV devices, because they absorb light in this spectral range.

What about the alternatives? SiC is not ideal, due to relatively high costs that hamper manufacture. Far cheaper is sapphire, but it is plagued by large lattice and thermal expansion mismatches with AlN. These differences can lead to dislocation densities of over 10^{10} /cm^2, unless special growth processes are adopted. And such a high level of imperfections is a major concern, because the internal quantum efficiency of a deep UV emitter is generally inversely proportional to the density of the dislocation-related, non-radiative recombination centres.

The crux of the matter, however, is this: Is a dislocation density as low as that of the AlN substrate essential for obtaining a high internal quantum efficiency and low-threshold lasing? Perhaps not. A detailed photoluminescence study by a partnership between Meijo University and Nagoya University has shown that despite a dislocation density of low 10^9 /cm^2, the internal quantum efficiency for aluminium-rich AlGaN multiple quantum wells can exceed 50 percent. Note that these samples were grown on an AlN-on-sapphire template.

This finding is encouraging, given that similar or lower dislocation densities for AlN-on-sapphire templates have been realized by a mainstream growth technique, MOCVD. A common approach with this deposition technology is epitaxial lateral overgrowth (ELO), where AlN layers are re-grown on patterned seeding AlN templates. However, this technique is costly, takes considerable time and leads to uneven surfaces. These issues stem from a process that involves lithography, etching and a re-growth process that attempts to form over the patterned templates a coalesced, flat layer that is several microns thick.

One common MOCVD modification is pulsed atomic layer epitaxy (PALE). Nitrogen and aluminium precursors are supplied in a pulsed mode, in a manner that allows aluminium atoms sufficient time to mobilize on the epitaxial surface. This approach is simple, but increases the growth time and thus the cost.

Some groups have united the two, combining ELO and PALE to accelerate coalescence over patterned templates. Additional attempts to improve material quality have involved growth temperatures exceeding 1200 °C, because this increases aluminium atom

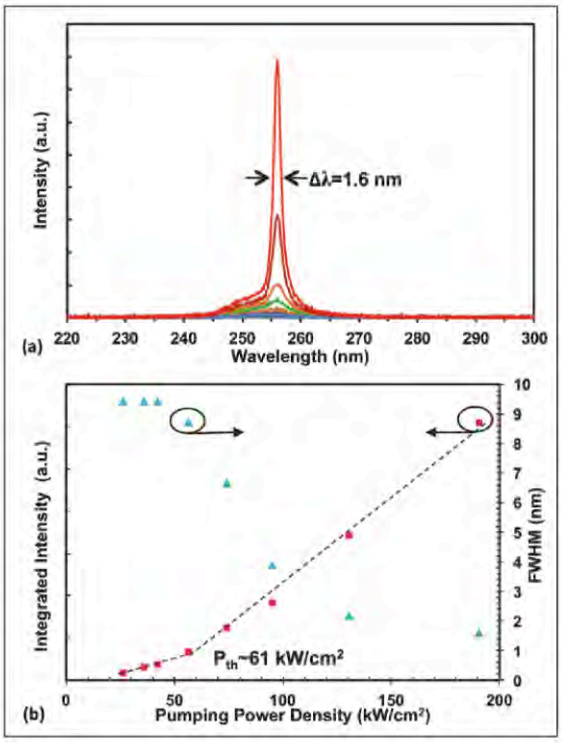


Figure 4. (a) Laser emission spectra and (b) spectral integrated intensity and linewidth versus pumping power densities of the 256 nm laser. Measuremnets taken at room-tempertaure, using 193 nm excitation.

mobility. This has been employed independently, and jointly with the ELO and PALE, to produce heterostructures with a low-dislocation density and a smooth surface. High-temperatures have their downsides, however. Reaching high temperatures requires a special reactor configuration, and these growth conditions can cause considerable thermal stress and cracks, due to the large thermal expansion mismatch.

Our goal at Georgia Tech has been to develop an MOCVD growth process for an AlN-on-sapphire template that is simple, efficient and yields a dislocation density of low 10^9 /cm^2. To trim costs and save time, we avoid the ELO and PALE technologies.

We were also keen to see if lower temperatures could be used for AlN growth. Experiments had previously been carried out at 1100-1500 °C by teams from Meijo University and Linköping University, using an incremental step of 100 °C. This step is too large, however, because it prevents an insight into the variation in material quality with small changes in temperature – and it ultimately fails to uncover the optimum temperature.

With our study, growth temperatures for the AlN template were varied from 1050 °C to 1250 °C using an incremental step of just 18 °C. This led to a very interesting discovery. At temperatures exceeding 1212 °C material quality deteriorates – the surface gets rougher, surface bunching begins, and the linewidth in the X-ray diffraction scan increases (see Figure 1). We also found that high-quality AlN templates can probably be produced with growth temperatures as low as 1100 °C.

Using this temperature, we optimised our growth conditions. We discovered that the best results came from a relatively simple template, formed from continuous growth of three layers: a 15 nm AlN buffer layer, a 50 nm AlN intermediate layer, and a 3400 nm AlN template layer. These were grown at 930 °C, 1130 °C, and 1100 °C, respectively, on a *c*-plane planar sapphire substrate. Encouragingly, deposition involved a relatively high growth rate of 2.30 μm/h, realised with a growth efficiency of 2200 μm/mol that indicates a low degree of parasitic reactions.

Scrutinising the template with conventional inspection techniques provided proof of good material quality. An atomic force microscopy scan over a 1 μm^2 area uncovered well-defined terraces and determined a root-mean-square roughness of just 0.07 nm (see Figure 2), while transmission electron microscopy revealed a total threading dislocation density of 2×10^9 /cm^2.

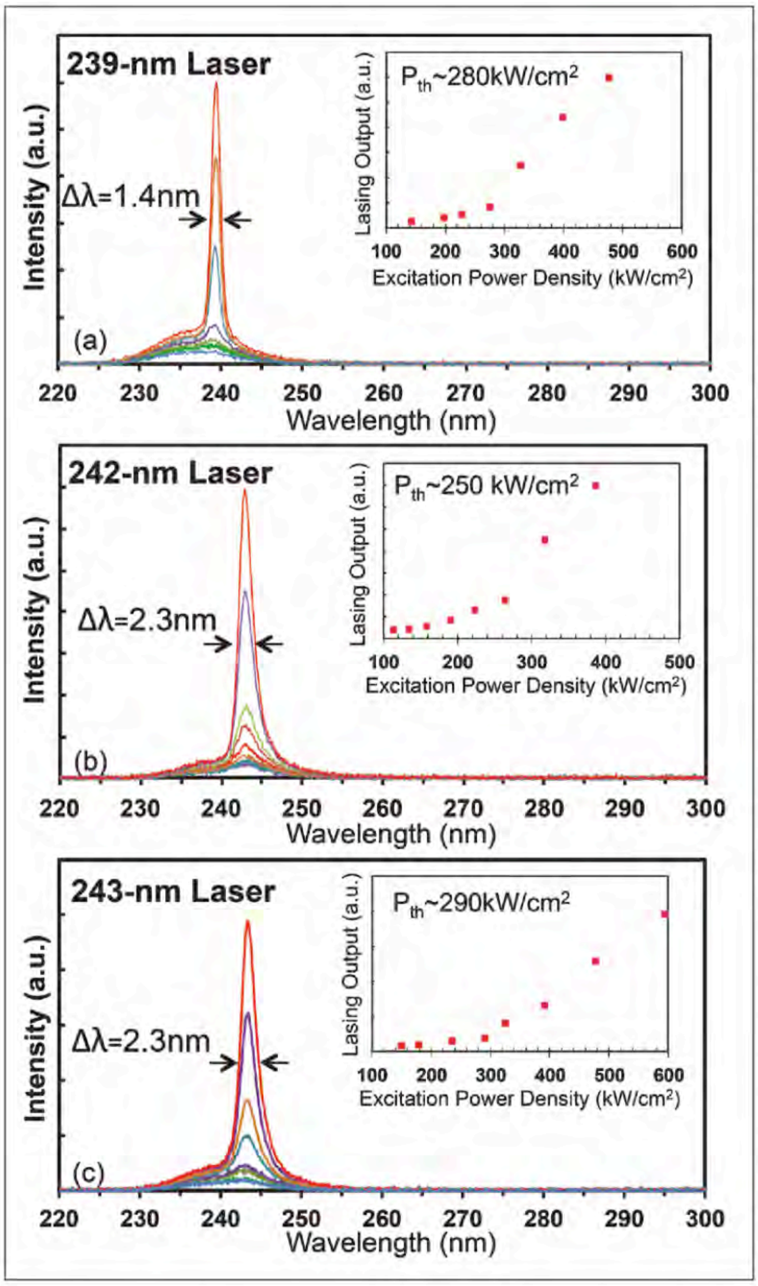


Figure 5. Emission spectra of the (a) 239 nm, (b) 242 nm, and (c) 243 nm lasers by power-dependent photoluminescence at room temperature. The insets show the respective light output intensity of stimulated emission as a function of excitation power density.

Equipped with these templates that have a dislocation density that we targeted, we grew pseudomorphic AlGaN heterostructures for an optical pumping experiment. They contained an AlGaN grading waveguide layer, five periods of AlGaN multi-quantum wells designed for laser emission at 250 nm, and an AlGaN cap for surface passivation. The composition and thickness of the AlGaN layers were optimized to enhance optical confinement and thus reduce threshold.

Following growth of the heterostructures, wafers were scribed, either by laser or hand, and cleaved into Fabry-Pérot laser bars. Laser scribing led to smoother facets. These chips were not given a high-reflectivity coating, and had a reflectance in the UV region of around 20 percent.

We formed a 249 nm laser using laser scribing that had a threshold of 95 kW/cm^2 (see Figure 3). We also produced a 256 nm laser, using hand scribing, that had a threshold 61 kW/cm^2 (see Figure 4). Both these thresholds are low values for this spectral range. The smoother facets resulting from laser scribing produced a higher slope efficiency and smaller linewidth. For both spectra, stimulated transverse-electric polarised emission dominated optical output.

To design high-performance, deep UV lasers operating at shorter wavelengths, it is imperative to know the spectral range where the dominant lasing mode switches from transverse magnetic to transverse electric. This transition is governed by the valence band structure of AlGaN. The transverse electric mode dominates when lasing results from a transition from the conduction band to a heavy hole band that sits at the top of the valence band. To reach shorter emission wavelengths, the aluminium content in AlGaN must increase, and this shifts the split-off hole band closer to the heavy hole band. The switch in lasing from the transverse-electric to the transverse-magnetic mode occurs when the topmost band changes from the heavy hole band to the split-off hole band. Note that we are the first group to report this switching of stimulated emission from the transverse-electric mode to the transverse-magnetic mode for lasers grown on the same type of substrate.

Our study shows that to ensure that the transverse-magnetic mode dominates lasing, lasers must emit at shorter wavelengths than those of our initial structures. One way to do this is to increase the aluminium composition in the active region, but this reduces optical confinement. So we prefer to decrease the composition contrast between the grading layer and active region. This diminishes the net interface polarization charge, increases the transition energy in the multi-quantum well, and drives emission to shorter wavelengths.

Efforts in this direction have led to a portfolio of lasers emitting at 243 nm and below. We have produced structures emitting at 239 nm, 242 nm, and 243 nm with laser thresholds of 280 kW/cm^2, 250 kW/cm^2 and 290 kW/cm^2, respectively (see Figure 5). All these lasers were scribed by hand, so they didn't have the smooth facets that ensure the narrow linewidth of our 249 nm laser. Nevertheless, thresholds are lower than those of lasers at similar wavelengths that were reported by other groups and are grown on bulk AlN substrates.

Our lasers operate as we intended, with spectra dominated by transverse-magnetic, polarized stimulated emission (see Figure 6 for details). When operating above threshold, the difference in peak wavelength between the two modes is negligible. This reveals a minimal energy separation between the heavy hole and split-off hole bands and those have crossed over in our lasers.

Although we have focused on the edge-emitting laser in our discussion in this feature, this is not the only UV laser that could serve many important applications. There is also the deep UV VCSEL, which promises high-speed modulation, good beam quality, and great control of the production process. Progress with this vertical emitter is lagging behind its edge-emitting cousin, but we have recently made some important progress, using optical pumping to demonstrate the onset of deep UV stimulated emission from the surface of AlGaN heterostructures grown on AlN-on-sapphire templates (see Figure 7). Key milestones ahead of us and our peers include the development of high-reflectivity, high-conductivity distributed Bragg reflectors that could lead to the fabrication of the first electrically injected deep UV VCSEL.

While that may be some way off, we are undeniably making good progress, by optimizing growth processes and improving material and structural quality. This has enabled us to demonstrate low-threshold deep UV lasers, the switching of laser emission from the transverse-electric to the transverse-magnetic mode, and report the first observation of the onset of surface stimulated emission from III-nitride heterostructures on a sapphire substrate (see Figure 7).

What is needed now is to address a number of technological barriers that are preventing the demonstration of a deep UV laser that operates via electrical injection, rather than optical pumping. The good news is that many teams are working on this goal, both in the US and in many institutions overseas. Hopefully these efforts will deliver a major breakthrough in *p*-doping of aluminium-rich AlGaN, as today this is a major barrier to electrically driven, deep UV lasers.

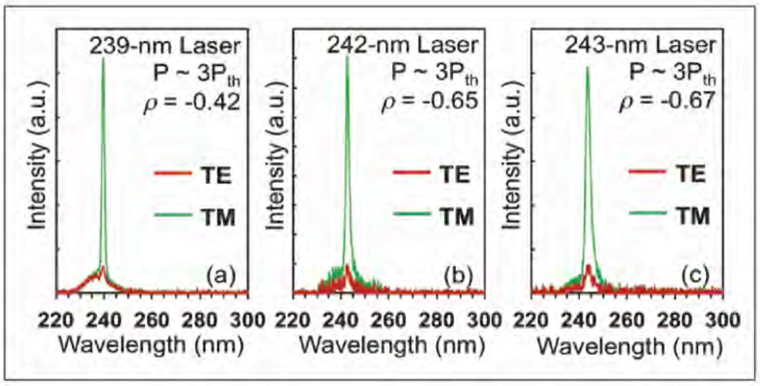


Figure 6. Transverse-electric-polarized and transverse-magnetic-polarized spectra of the (a) 239 nm, (b) 242 nm, and (c) 243 nm lasers above respective threshold, showing transverse magnetic-dominant stimulated emission. The polarization degree, defined as $\rho = (I_{TE} - I_{TM}) / (I_{TE} + I_{TM})$, was calculated wherein I_{TE} and I_{TM} represent the integrated spectral intensity of transverse-electric-polarized and transverse-magnetic-polarized emission, respectively. Note that the ρ values will be much closer to -1.0 if the peak intensity is used. This has been the case in some reports.

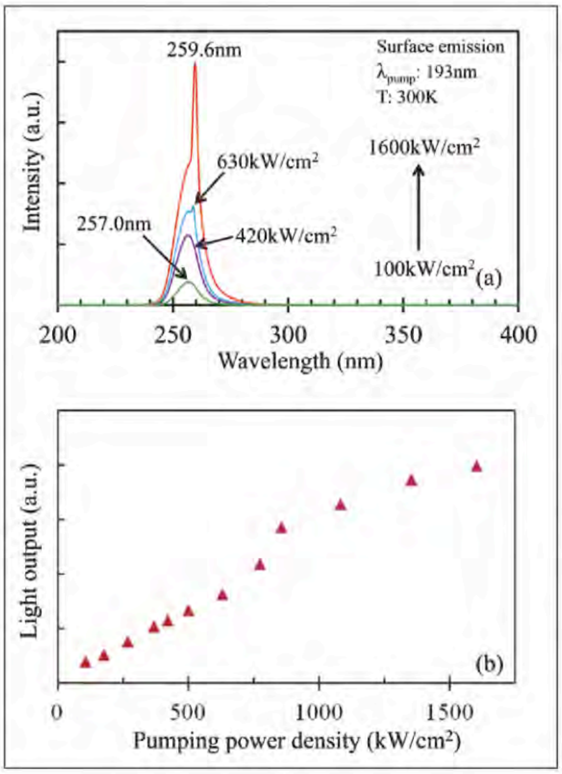
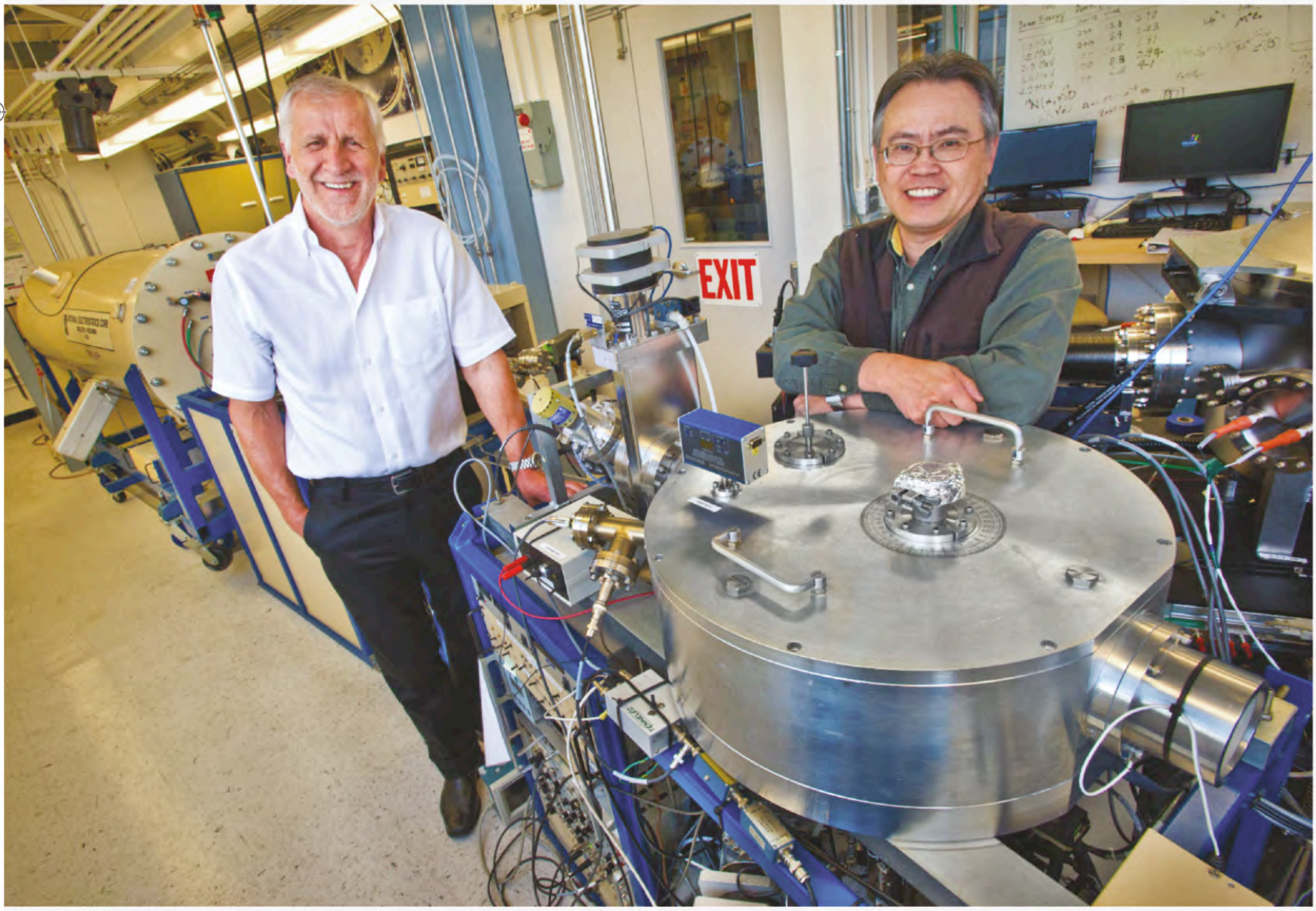


Figure 7. (a) Surface emission spectra under power-dependent optical pumping and (b) light output intensity of surface emission as a function of pumping power density.

Pursuing high-efficiency photovoltaics with novel alloys

By forming an intermediate band, dilute nitrides promise to propel single-junction solar cell efficiency to new highs

BY KIN MAN YU FROM THE CITY UNIVERSITY OF HONG KONG AND WLADEK WALUKIEWICZ FROM LAWRENCE BERKELEY NATIONAL LABORATORY



THROUGHOUT THE WORLD, governments are encouraging greater use of renewable energy in a bid to cut carbon dioxide emissions. This is helping to drive up the deployment of solar cells, the majority of which are made from silicon.

Although silicon currently offers the best bang-per-buck, it has major downsides, including an efficiency that is not that high – and has little room left for improvement. These weaknesses are a consequence of the incredibly wide range of solar photon energies. The sun's radiation extends from 0.4 eV in the mid infrared to 4 eV in the deep ultraviolet, and it is impossible for a single-junction cell to convert all of this energy efficiently. Photons with energy above the band gap must lose their excess energy to heat, while those below it will not be absorbed.

To increase power conversion efficiency, the solar spectrum has to be divided into parts that are absorbed by separate cells with different energy gaps. This is the basic premise of the multi-junction solar cell, which features junctions from different materials connected in series.

The most established class of multi-junction cell is based on group III-V compounds – and it may have a bottom cell made from germanium. This particular multi-junction cell is an established commercial technology, dominating power generation on satellites and generating megawatts of electricity on the ground, where it lies at the heart of solar concentrating systems. However, the chips are very expensive, due to the high cost of the materials and complexities associated with epitaxial growth.

A promising alternative – proposed more than 50 years ago by Martin Wolf, when he was working at the Hoffman Electronics Corporation in El Monte, California – is to use a single-junction device with multiple bands. This approach – that realises the same objective as using semiconductors with different gaps in multi-junctions cells – involves the introduction of a narrow band of partially occupied states in a semiconductor band gap. This modification to the single-junction cell facilitates transitions from the valence band to the conduction band through a sequential absorption of two lower-energy photons (see Figure 1 for a simplified band diagram). In a sense, the intermediate band plays the role of a stepping-stone, allowing sub-bandgap photons to excite electrons across the band gap.

These intermediate-band solar cells have the potential to deliver a massive hike in efficiency. Detailed balance calculations in 1997 by Antonio Luque and Antonio Marti from the Technical University of Madrid show that a power-conversion efficiency of 63 percent is possible when the intermediate band is ideally located. This value is far higher than the limit of what is possible for a two-junction tandem cell. What's more, if a junction can be made from a material with two bands of intermediate states, efficiency can reach almost 72 percent.

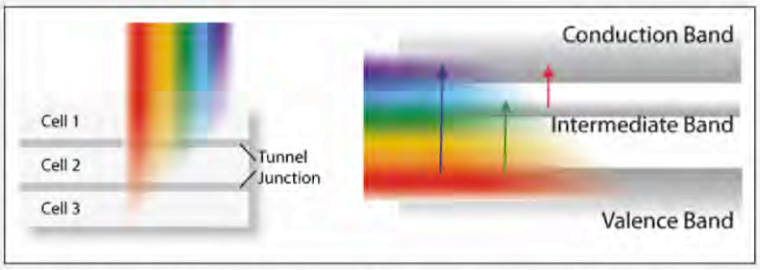


Figure 1. A simplified band diagram of a (left) multi-junction (MJ) and (right) an intermediate-band solar cell (IBSC). In a MJ cell, semiconductor materials with different bandgaps are stacked on top of each other with the material, with the largest gap on top. This allows absorption of a large fraction of the solar spectrum. In a IBSC, solar radiation can be absorbed by the valence band (VB) to either the intermediate (IB) or conduction band (CB), and at the same time by the IB to the CB.

Fulfilling this promise of very high efficiency has not been easy, due to difficulties in identifying a semiconductor with an appropriate band structure. One option is to turn to quantum confinement effects in semiconductor superlattices and quantum dots. This has produced some success. However, it is difficult to produce a device that incorporates enough low-dimensional semiconductor material to have an intermediate band with sufficient absorption, while managing the strain in the structure so that it does not impair material quality. If this degrades, optical quality also falls. What's more, there is limited scope to adjust the position of the intermediate band.

Highly mismatched alloys

Our partnership between the City University of Hong Kong and Lawrence Berkeley National Laboratory is pursuing a different approach, based on highly mismatch alloys. The new class of materials, discovered by our research group at Berkeley, are formed by alloying distinctly different semiconductors.

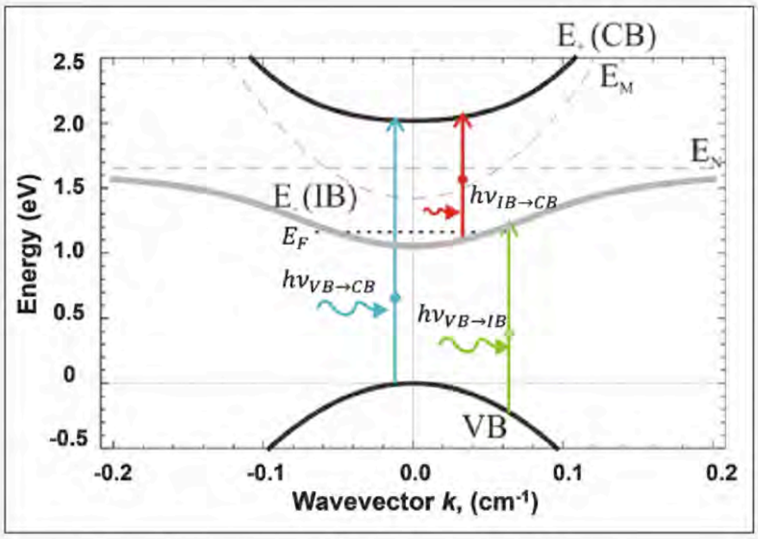


Figure 2. Energy band structure of $GaN_{0.024}As_{0.976}$ calculated using the band anti-crossing (BAC) model.

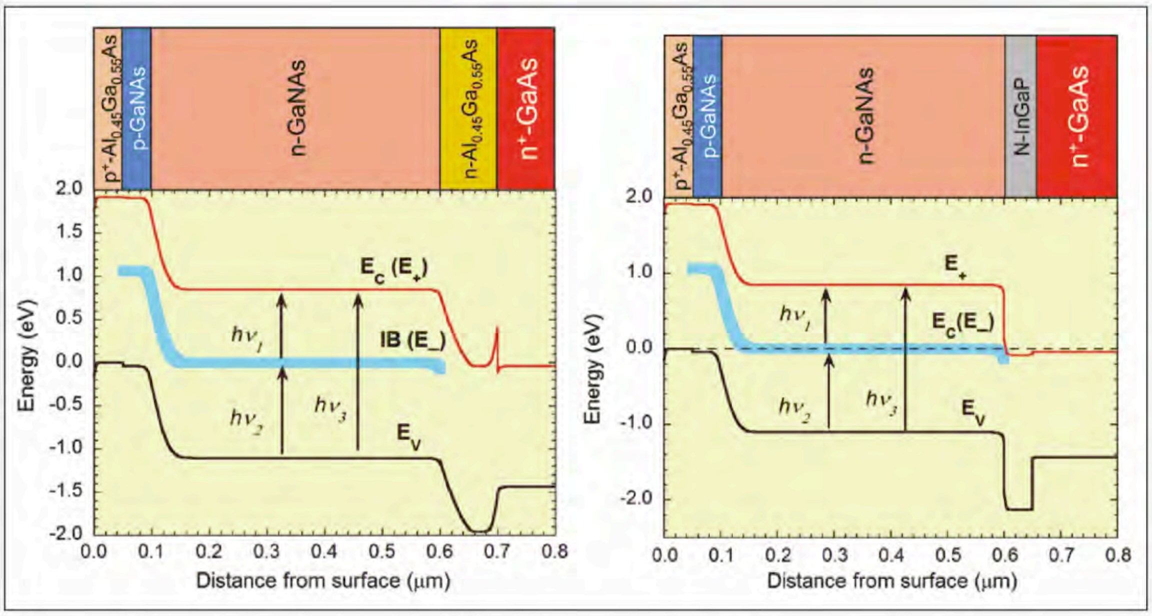


Figure 3. (a) The structure and band diagram of a blocked intermediate-band (BIB) device with the intermediate band (IB) disconnected from the contacts. Transitions generating electron-hole pairs utilizing the IB are denoted as $h\nu_1$ and $h\nu_2$. The transitions from the valence band (VB) to the conduction band (CB) are represented by $h\nu_3$. (b) The structure and the band diagram of a UIB device with the IB connected to the backside contact.

The two most prominent, extensively studied groups of highly mismatched alloys are dilute nitrides and dilute oxides. In the former, column V atoms in III-V compounds are partially replaced with nitrogen; and in the later, oxygen partially replaces column VI atoms in II-VI compounds.

We choose to focus on dilute nitrides. They command attention because the partial substitution of arsenic with nitrogen produces a drastically different band structure in the resulting GaN_xAs_{1-x}.

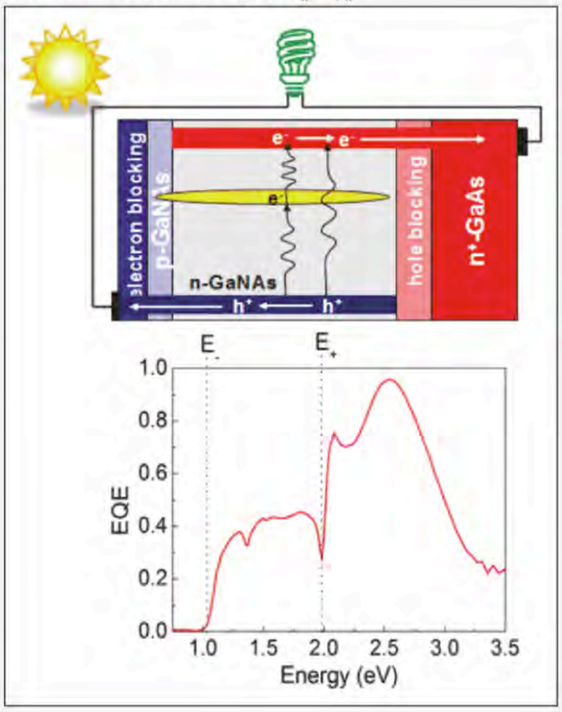


Figure 4. The structure of an intermediate-band solar cell structure with blocking layers, and the measured external quantum efficiency (EQE) of this device.

The band structure of this class of highly mismatched alloy is well described by the band anti-crossing model. For example, the bandstructure of $GaN_{0.024}As_{0.976}$ calculated using this model shows that replacement of arsenic with 2.4 percent of nitrogen results in a splitting of the conduction band into two subbands: a lower, relatively narrow band that is located at 1.1 eV above the valence band and forms an intermediate band; and an upper band, shifted 0.5 eV higher than the original conduction band of GaAs (see Figure 2 for the band diagram). This dilute nitride is ideal for making intermediate solar cells, because it has optical transitions for photon energies of 0.9 eV, 1.1 eV and 1.9 eV.

One of the key requirements for an intermediate band solar cell is electrical isolation of the intermediate band from the charge-collecting contacts. This condition ensures that the operational voltage is determined by the largest band gap.

To demonstrate the importance of this pre-requisite, we have produced a pair of devices by MOCVD. The first has a blocked intermediate band, created by incorporating AlGaAs blocking layers on the surface and substrate sides (see Figure 3 (a)). The control, which highlights the pitfall of failing to isolate the intermediate band from the charge collecting contacts, has the intermediate band connected to the substrate side of the device (see Figure 3 (b)).

Another essential ingredient for the intermediate band solar cell is that its intermediate band has to be partially filled with electrons. Taking this step increases the optical absorption of the low energy photons (0.9 eV -1.1 eV) that promote electrons from the intermediate band into the conduction band. We satisfy this requirement by doping the GaNAs absorber with tellurium. This produces an electron concentration in the intermediate band of 10^{16} to mid-$10^{17}/cm^3$.

We have measured the external quantum efficiency of our devices (see Figure 4). As we predicted, in the unblocked intermediate band control, the intermediate band takes on the role of the conduction band. This creates a device that acts as a single gap photovoltaic cell, with characteristics determined by the band gap of about 1.1 eV. At higher photon energies, photocurrent falls off rapidly. In stark contrast, in the blocked intermediate band device, the photocurrent clearly exhibits two thresholds. The first of these occurs at about 1.1 eV and corresponds to the transition from the valence band to the intermediate band; and the second, at 2 eV, is associated with optical excitation directly from the valence band to the conduction band. The origin of both these thresholds has been confirmed by photomodulated reflection spectroscopy.

With this particular device, the backside blocking layer prevents electron transport from the intermediate band to the back contact. So, when the cell is illuminated, electrons that accumulate in the intermediate band absorb another low-energy photon, and are then promoted to the conduction band, where they can be collected at the back contact. It is also possible to promote electrons directly from the valence band to the conduction band – this is the origin of the higher energy threshold at 2 eV.

In short, the results provided by the external quantum efficiency measurements are very encouraging. The blocked intermediate band device has all the essential features of the multi-band solar cell: the open-circuit voltage is determined by the largest band gap; and sub-band light can contribute to the photocurrent through sequential absorption of two photons.

One issue that can plague intermediate band solar cells based on highly mismatched alloys is a weak coupling of the three optical transitions between the valence, intermediate and conduction bands. To determine whether this is the case in our devices, we have measured the electroluminescence from our intermediate band solar cells (results are shown in Figure 5). We find that the blocked intermediate-band device produces two-colour electroluminescence under reverse and forward bias. This is great news, as it provides a clear demonstration of the presence of the two optical transitions necessary for properly operating an intermediate-band cell. As expected, forward biasing of the unblocked intermediate band structure produced a solitary electroluminescence peak, resulting from transitions between the intermediate band and the valence band.

Although our efforts have provided clear evidence of an operational, intermediate-band solar cell based on highly mismatched alloys, the devices need to get better. Improvements must include an increase in the optical coupling strength between the intermediate band and the conduction band, an increase in the lifetime and the diffusion length of electrons in the conduction band, and an optimisation of the doping in the absorber layers.

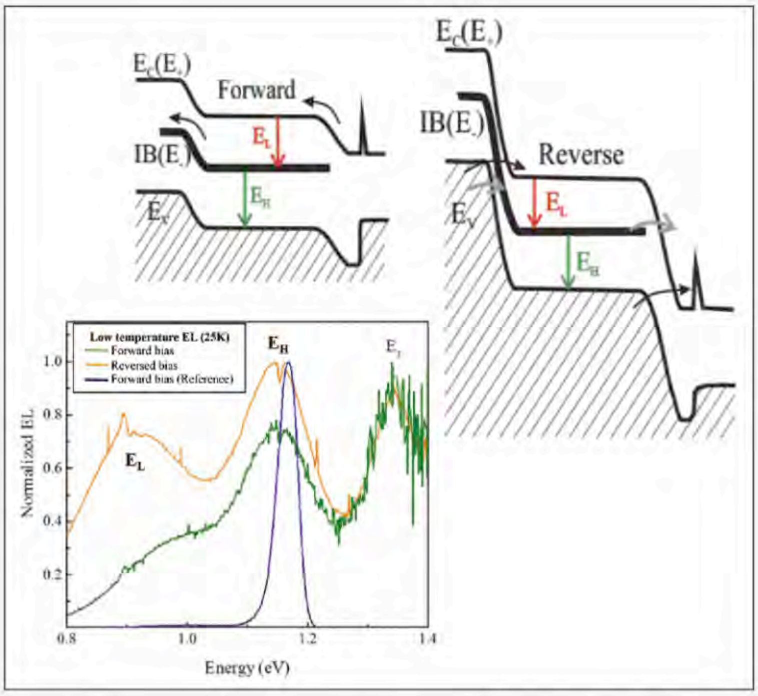


Figure 5. Electroluminescence spectra of the blocked intermediate band (BIB) structure as shown in Figure 3 (a) under forward (green) and reverse (yellow) bias. The electroluminescence of the reference unblocked intermediate band (UIB) structure is also shown (blue). The energy band diagram of the BIB structure under forward and reverse bias is also shown.

Gains in performance might require the introduction of new, highly mismatched alloys. This could be a new alloy composition of dilute nitrides that provides a better location of the intermediate band relative to the conduction band. Recently there has been progress in synthesis of new highly mismatched alloys, which may be more suitable for intermediate band solar cell applications. These include dilute II-VI oxides as well as GaAsP-based dilute III-V quaternary nitrides.

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Unravelling the nature of point defects in nitride LEDs

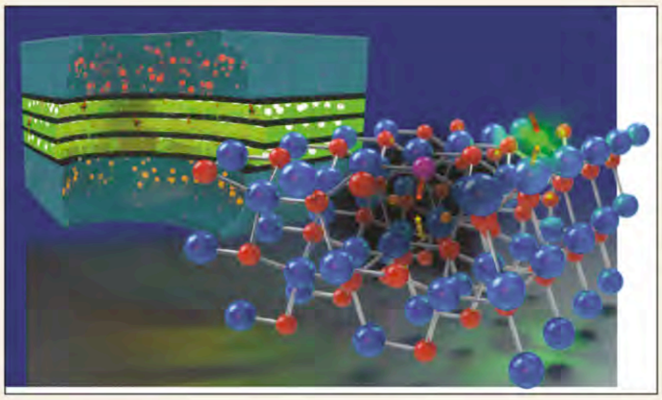
Calculations reveal that complexes based on gallium vacancies are making a significant contribution to non-radiative processes in LEDs

A partnership between researchers in the US and Lithuania has performed calculations that highlight the need to minimise point defects in LEDs.

This team of computational scientists have discovered that defects originating from gallium vacancies, which are complexed with oxygen and/or hydrogen, can cause a high Shockley-Read-Hall recombination rate. LED performance is impaired by this, because the Shockley-Read-Hall process is non-radiative, and thus limits LED efficiency.

Another insight provided by their work is that the Shockley-Read-Hall recombination rate for a given defect increases with indium content in the InGaN layer. This trend can account for the 'green-gap' – the decline in the external quantum efficiency as the indium content in the InGaN quantum well is increased to push emission from the blue to the green.

Spokesman for the computational scientists, Chris Van de Walle from the University of California, Santa Barbara (UCSB), explains that the "core defect" that causes Shockley-Read-Hall is the gallium vacancy. "But gallium vacancies have quite high formation energies, and are not likely to form by themselves."



Calculations have uncovered the microscopic origin of Shockley-Read-Hall in III-nitrides: gallium vacancies that are complexed with oxygen and/or hydrogen.

They can form, however, by combining with oxygen to create a complex with lower formation energy. So it is important to supress the incorporation of oxygen – above and beyond what is already routinely done – to produce highly efficient LEDs.

To calculate the non-radiative rates in InGaN alloys with various forms of gallium vacancy, the team used a formulism and code developed by team-member Audrius Alkauskas – he used to work at UCSB, but is now in Lithuania, jointly with the Centre for Physical Sciences and Technology in Vilnius and Kaunas University of Technology.

Producing reliable results hinges on providing the code with very accurate values for band structures and, for defects, appropriate formation energies and defects levels. For the latter the team employs the Vienna Ab initio Simulation Package, a widely used code for density-functional calculations.

The calculations show that complexes between gallium vacancies and two common, unintentional impurities that are present in a reactor – oxygen and hydrogen – have Shockley-Read-Hall recombination rates that can vary by six orders of magnitude, depending on InGaN composition (see Figure 1).

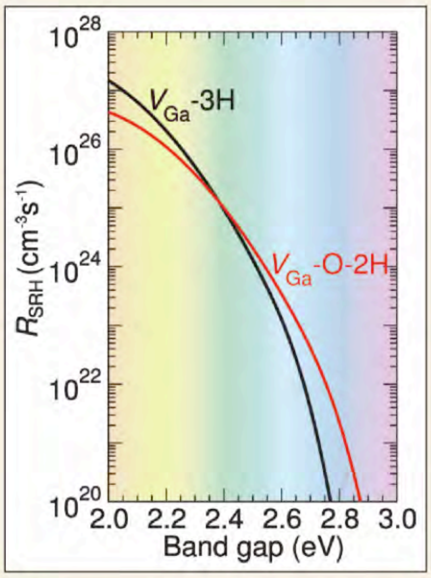


Figure 1. An increase in indium content leads to a tremendous hike in the Shockley-Read-Hall recombination rate, and can account for the green gap in InGaN LEDs.

"We did consider complexes between gallium vacancies and other impurities, such as silicon," says Van de Walle. However, they are unlikely to have a major impact because formation energies are higher, and it is less likely that the impurity is present in a significant concentration.

It is possible that defects that are not based on gallium vacancies could also influence the Shockley-Read-Hall recombination rate. However, determining whether that is the case would take substantial, additional effort and computer time.

"We do not claim to have performed an exhaustive search on all defects that could potentially be detrimental," explained Van de Walle. "But we thought it important to publish results on a set of defects that has so far emerged as a prime candidate."

One of the next goals for the team is to investigate whether other defects and impurities could make a significant contribution to Shockley-Read-Hall recombination in nitride LEDs.

C. Dreyer *et. al.* Appl. Phys. Lett. **108** 141101 (2016)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Superior solar blind detectors

Detector sensitivity hits a new high thanks to indium-surface-assisted, magnesium delta doping

A NOVEL doping technology has enabled scientists from Sun Yat-Sen University in China to set a new benchmark for solar-blind detectors.

Their avalanche photodiodes, which operate in the solar-blind spectral region that equates to wavelengths shorter than 290 nm, will aid development of devices for flame and biological agent detection, high-voltage corona inspection, space communication and missile warning.

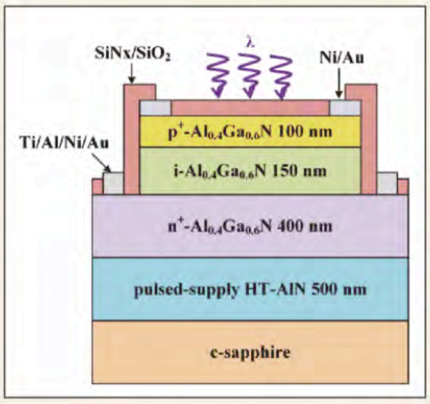
The team's avalanche photodiodes combine an external quantum efficiency of 52.7 percent at zero bias with an avalanche gain that exceeds 2 x 10^4 under high reverse bias. These two figures are very important, because the magnitude of their product governs the sensitivity of the detector.

"[Sensitivity] is important for all applications of photodetection, especially for the solar-blind UV detection, because in many application cases the UV signal is very weak," says team-member Hao Jiang.

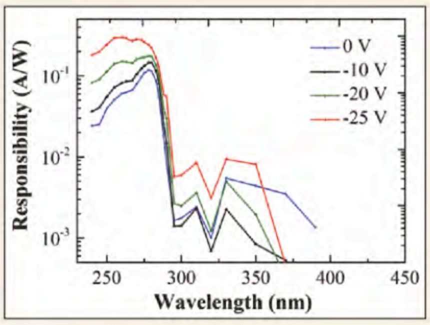
In 2014, researchers from Nanjing University reported a comparable avalanche gain of 2.1 x 10^4. However, the diameter of their photodiode was just 35 μm, compared with 100 μm for the device made by Jiang and co-workers. Commenting on this, Jiang remarked: "Considering that in general the larger the junction diameter of the avalanche photodiode, the worse the avalanche gain, it can be argued [our results] are record-breaking."

The key to the impressive performance of the team's avalanche photodiode is the indium-surface-assisted, magnesium delta-doping of aluminium-rich AlGaN.

Fabrication of solar-blind detectors requires the use of aluminium-rich AlGaN – compositions of at least $Al_{0.4}Ga_{0.6}N$ are needed for detection at such short wavelengths. But doping these ternaries is very tricky, due to: a low incorporation efficiency of acceptor dopants; a strong self-compensation effect, arising from the presence of donor-like native defects; and a magnesium acceptor activation energy that increases from 160 meV for GaN to 500 meV for AlN.



The avalanche photodiode, which has a 100 μm diameter circular aperture, is formed using MOCVD.



Increasing the reverse bias led to increased responsivity and external quantum efficiency, which climbed from 53 percent to 79 percent.

Jiang argues that their team's doping method addresses all these weaknesses. Incorporation of the magnesium dopant is enhanced through delta-doping with the indium surfactant, which also supresses self-compensation, while activation energy is reduced via self-formed composition modulation.

The researchers formed avalanche photodiodes on sapphire, using MOCVD to deposit an epitaxial stack (see Figure 1), and then defining a circular mesa with inductively coupled plasma etching.

To remove dry-etching-induced damage and smooth the surface, samples were dipped in boiling potassium hydroxide for 80s and then annealed under nitrogen gas for 1 minute at 750 °C.

After *n*-type and *p*-type contacts were added, the edges of the device were passivated by depositing a SiN/SiO_2 stack by plasma-enhanced CVD.

Electrical measurements revealed a dark current below 4 x 10^{-12} A for a reverse bias of less than -17 V.

Jiang and co-workers argue that this very low dark current results from a low density of screw dislocations, which are the primary leakage path in nitride semiconductors. The density of screw dislocations is 2.8 x 10^8 cm^{-2}, according to X-ray diffraction and inspection of a surface etched in potassium hydroxide.

Increasing the reverse bias beyond -20 V led to a hike in dark current. Under these operating conditions, the maximum electric field in the depletion region is estimated to be at least 1.49 MV/cm. That is enough to trigger impact ionisation, according to previous work by the team.

The researchers have measured the photoresponse of their devices at a range of bias voltages (see Figure 2), finding that responsivity increases from 114 mA/W at zero bias to 176.2 mA/W at -20 V.

"The next step [for our team] is to develop a low-dark-current AlGaN solar-blind avalanche photodiode with a multiplication gain higher than 10^5, aiming to achieve single-photon detection," reveals Jiang.

H. Wu *et. al.* Appl. Phys. Express **9** 052103 (2016)

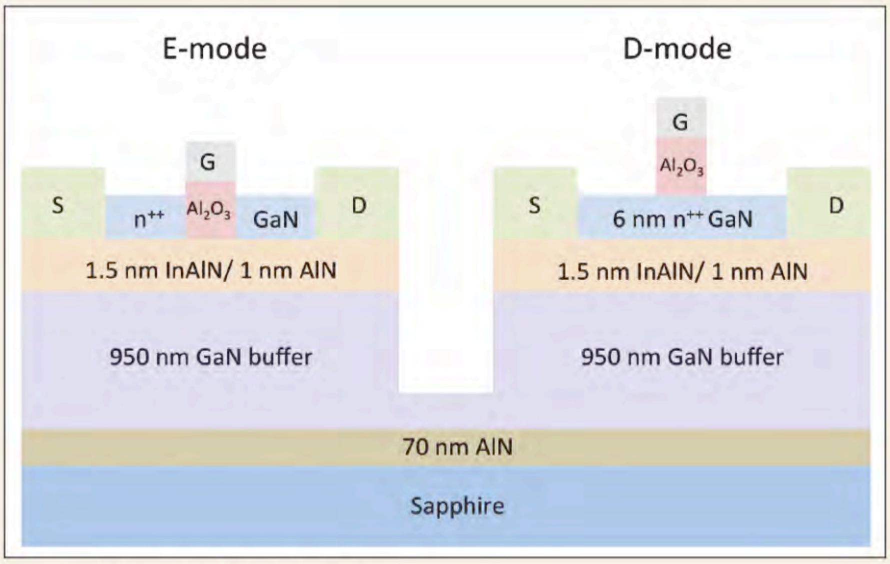
Simplifying mixed-signal circuits in GaN

Selective plasma etching integrates E-mode and D-mode HEMTs for mixed-signal electronics

EUROPEAN researchers have developed a relatively simple approach for making a logic invertor with E-mode and D-mode GaN HEMTs.

Led by Jan Kuzmik from the Institute of Electrical Engineering, Slovak Academy of Sciences, the team produced its invertor by starting with the same epistructure for both types of devices, and then selectively etching the heavily doped *n*-type GaN cap layer in the gate trenches of the E-mode HEMT.

The researchers' effort is an important step in the development of GaN electronics for high-performance digital and analogue circuits. This field is very promising, thanks to advances in the design of E-mode HEMTs, and increases in transistor speed that stem from a self-aligned approach.



Integrated E-mode and D-mode HEMTs

Creating fast mixed-signal circuits in GaN is not easy, however. Options employed by other groups are to turn to different epistructures for E-mode and D-mode devices, and to use a combination of a gate recess and an additional growth step for the Ohmic contacts.

Major merits of the approach of Kuzmik and co-workers are a single epistructure, and just one lithographic step for gate recessing, oxide deposition and metallisation.

What's more, their self-aligned approach eliminates the gate-space-charge extension towards the drain. This will allow faster devices by minimising the drain delay component.

Furthermore, unlike a two-step alignment process, no additional capacitance is introduced beyond the MOS gate footprint.

The challenge with the technology developed by Kuzmik and his colleagues is that the threshold voltage of the E-mode HEMT is governed by the gate recess. And determining the appropriate etching conditions is not as easy as it might first appear, because surface native oxides can inhibit the process.

So, to determine the etching selectivity between the cap and barrier layer, it is essential to account for any differences between the etch rate of the bare (oxidised) barrier and the capped variant.

To determine the appropriate etching conditions, the researchers investigated the impact of the plasma etching process on different areas of the E-mode HEMT.

Recessing of the gate involved inductive-coupled plasma, reactive-ion etching with a mixture of $SiCl_4$ and SiF_6 for between 2 minutes and 5 minutes, using a pressure of 2.7 Pa. Measurements on the processed material revealed a GaN etch rate of 6 nm per minute – implying an optimal etch time for the gate recess of 150 s to 210 s – and indicated good selectivity with respect to InAlN.

Electrical measurements on a 2-inch wafer revealed an average E-mode HEMT threshold voltage of 0.8 V, and a value of -2.6 V for the D-mode variant. The spread in both devices across a 2-inch wafer was ±0.5 V.

Both classes of transitor exhibited a peak drain current of 0.35 A mm^{-1}. This similarity is encouraging, suggesting that etching did not compromise current.

Kuzmik's team also measured the transconductance of both devices.

The E-mode HEMT peaked at 110 mS/mm, while the D-mode variant was lower, but flatter. These differences are attributed to the larger channel-to-gate distance in the D-mode HEMTs, and the additional conduction in its heavily doped *n*-type GaN layer.

Measurements on the direct-coupled HEMT logic invertor using a 2.5 V supply voltage determined noise margins for the logic '0' and '1' levels of 137 mV and 812 mV, respectively.

The researchers claim that the invertor can be improved by tuning the technology and applying appropriate scaling to transistor dimensions.

M. Blaho *et. al.* Semicond. Sci. Tech. **31** 065011 (2016)

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