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Mainstream development

III -V transistors on 200mm silicon

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Editor-in-Chief
David Ridsdale dr@angelbcl.co.uk
+44 (0)1923 690210

Consultant Editor
Richard Stevenson PhD
richardstevenson@angelbc.co.uk
+44 (0)1291 629640

News Editor
Dr. Su Westwater suwestwater@angelbc.co.uk

Director of SOLAR & IC Publishing
Jackie Cannon jc@angelbcl.co.uk
+44 (0)1923 690205

Account Managers
Shehzad Munshi sm@angelbcl.co.uk
+44 (0)1923 690215
Tommy Beazley tb@angelbcl.co.uk
+44 (0)1923 690222

USA Representatives
Brun Media
Tom Brun E: tbrun@brunmedia.com
Tel: 724 539-2404

Janice Jenkins E: jjenkins@brunmedia.com
Tel: 724-929-3550

Director of Logistics
Sharon Cowley sc@angelbcl.co.uk
+44 (0)1923 690200

Design & Production Manager
Mitchell Gaynor mg@angelbcl.co.uk
+44 (0)1923 690214

Circulation Director
Jan Smoothy js@angelbcl.co.uk
+44 (0)1923 690200

Subscriptions Manager
Debbie Higham dh@angelbcl.co.uk
+44 (0)1923 690220

Chief Operating Officer
Stephen Whitehurst stephen@angelbc.co.uk
+44 (0)2476 718970

Directors
Bill Dunlop Uprichard – CEO
Stephen Whitehurst – COO
Jan Smoothy – CFO
Haroon Malik, Jackie Cannon, Scott Adams, Sharon Cowley, Sukhi Bhadal

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

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

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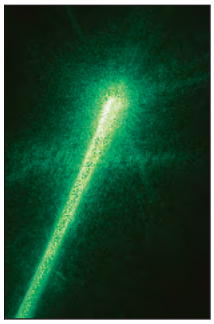
New planes bolster nitride laser credentials



Engineers with an entrepreneurial streak whoop with delight when they spot a technology with the potential to generate piles of cash. But they also know that it is going to take many years of hard graft if their dreams are to materialize into a game-changing product.

One of the most promising technologies that could be netting billions of dollars by the end of this decade is the nitride laser that is built on unconventional cuts of gallium nitride.

There are many benefits associated with turning to these semi-polar and non-polar planes: Reduction or even elimination of internal electric fields that hamper laser emission; the opportunity to increase the indium content in indium gallium nitride layers and propel emission further into the green; and greater design freedom, allowing engineers to invent architectures that are quicker and easier to make.

Unleashing the potential of this class of lasers began in 2007, when Rohm and the University of California, Santa Barbara (UCSB), independently unveiled violet lasers. Since then their performance and color range has increased to a level where it now eclipses that of its conventional cousins. This form of laser now holds the records for the highest continuous wave output power and wall plug efficiency for single mode blue lasers, and the lowest threshold currents and longest emission wavelengths for green nitride lasers (see this month's *Research Review* for details).

Record-breaking lab results don't guarantee commercial success, but the signs are looking good for the semi-polar and non-polar lasers. The UCSB spin-off Soraa has published reliability data that shows that these devices can go the distance, and engineers at this start-up and the Japanese semi-polar laser pioneer Sumitomo Electric Industries find that chip yields in the lab significantly exceed those of conventional equivalents.

Soraa is also sampling product. Future success will hinge on convincing potential customers that it is worth making the transition to both a new technology and a new company.

If Soraa and the other semi-polar and non-polar laser makers can fill their order books, they will then have the challenge of churning out chips with an acceptable profit margin.

To do this they need reasonably sized substrates. Much of the early work in the field was carried out on incredibly expensive pieces of gallium nitride no bigger than a fingernail, but times have changed. Sumitomo has recently unveiled 2-inch non-polar GaN, and Ammono plans to be launching 1-inch semi-polar and non-polar substrates this year. With a good foundation now to grow on, these laser pioneers should be in with a good chance of success.

Richard Stevenson PhD
Consultant Editor

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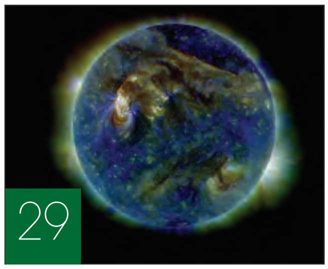
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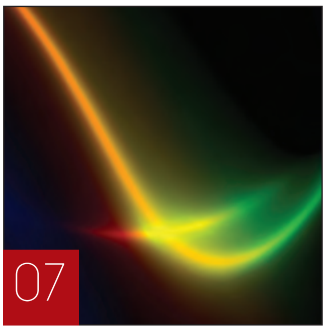
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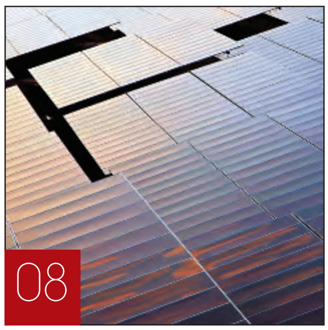
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Cree lights up Denny's restaurants

DENNY'S Corporation, one of America's largest full-service family restaurant chain, has chosen energy-efficient LED lights from Cree as the preferred lighting standard for all its new and remodelled stores across the United States. Cree's LR6 six-inch downlights are being specified in various applications, including dining areas and rest rooms in all newly constructed and converted facilities.

"We evaluated numerous LED light fixtures from a variety of manufacturers to ensure that we chose the best possible product and partner for this major lighting specification," explained Mitch Riese, corporate architect, senior manager of design & construction, Denny's. "With the Cree LR6 fixture, we found the best value for our money, helping us deliver warm light, while reducing energy consumption and maintenance requirements."

Pete LaBarre, a Denny's franchisee in Colorado Springs, Colo., is already seeing extensive savings since converting to LED lighting. LaBarre has installed more than

400 Cree LR6 downlights in the dining rooms of his five restaurants, a move that has saved him around $15,500 per year in energy costs alone. Impressed with the energy and maintenance savings from installing LR6 downlights in his dining rooms, LaBarre has decided to use the six-inch LED downlights in a variety of other applications. Currently he has replaced 500 fluorescent bulbs and tubes with 200 Cree LR6 fixtures, illuminating the perimeter of each restaurant.

"Our lights stay on all the time, so we did a watt comparison of what we had in place before the LR6 downlights," said LaBarre. "We found that we used 6,000 kilowatt hours less per month in the store that had the Cree fixtures versus the store that had the fluorescent lighting," he said.

Another early LED lighting devotee is Joey Terrell, a Denny's franchisee in Illinois. In 2009, Terrell opened his second restaurant in Joliet, a suburb of Chicago. Built according to Leadership in Energy and Environmental Design (LEED) Gold standards, the Joliet Denny's includes a combination of natural lighting and Cree LR6 LED downlights to reduce the restaurant's lighting load.

According to Terrell, this lighting design reduced utility costs by 83% and his electricity bill is now around $1,000 a month instead of the expected $2,100 a month based on the average costs for his location.

"Restaurants use 285% more utilities than the average commercial building," said Terrell. "The easiest way to reduce costs and improve energy-efficiency is to switch from traditional fluorescents to daylighting and LEDs, and that's what we did."

Roled Opto and FLS Light Up Pearl River in Guangzhou

FUTURE LIGHTING SOLUTIONS (FLS) has announced that it is illuminating the Pearl River in Guangzhou, with 700,000 Lumiled's LUXEON Rebel LEDs. The city of Guangzhou recently completed a project to illuminate the banks of the Pearl River as part of their welcome ceremony for the Asian Games and to celebrate the successful convening of the Games in Guangzhou. This project was an open tender called for by the Guangzhou Municipal Government, which was awarded to Roled Opto Electronics (Shanghai).

The project objectives were to create a green, energy efficient, environmentally friendly and high-tech Asian Games. The Guangzhou Municipal Government's requirements called for a professional LED manufacturer, with reliable pre and post sales support.

Roled Opto Electronics (Shanghai). was the main designer of the solution for this project. The deployment involved around 30,000 LED light fixtures and 700,000 LUXEON Rebel LEDs. China Construction Eighth Engineering Division (Guangzhou Subsidiary) was responsible for installation.

LUXEON Rebel LEDs were selected based on their luminous flux, color temperature, color index and reliability of the LEDs. With the help of Future Lighting Solutions (FLS) and the use of their Usable Light Tool (ULT), LEDs best suited for this project were selected. Roled also made use of QLED Thermal simulation software to optimize their heat dissipation system.

With the support of the Lighting Resource Centre (LRC), Roled was also able to test and evaluate optical lenses, and deployed National Semiconductors' buck regulator as part of the solution. FLS and Roled have always based their partnership on a philosophy of strategic co-operation. With assistance provided by FLS and their LRC, Roled Opto Electronics selected suitable LED models and optical lenses, which were able to resolve a number of issues related to lighting efficiency and light distribution.

They also had to keep in mind that the Guangzhou Municipal Government expected an ROI within 3 years, and hence devised a solution based on LED light fixtures as this technology delivers more than 60% savings in terms of energy consumption, and reduces CO_2 emissions by 80%. These factors greatly shorten time taken to actualize the return on investment. At the same time, FLS also provided significant support in terms of price, availability and supply continuity, which enabled Roled to complete the project according to schedule.

Wang Shiming, GM at Roled Opto Electronics' adds, "During the Guangzhou Asian Games, images along the banks of the Pearl River that were broadcast captured the essence of the dazzling skyline. In particular, images of the White Swan Hotel were displayed repeatedly during the opening ceremony, which effectively illustrated how the LUXEON Rebel LEDs were able to deliver based on the requirements of the business owner and the Guangzhou Municpal Government."

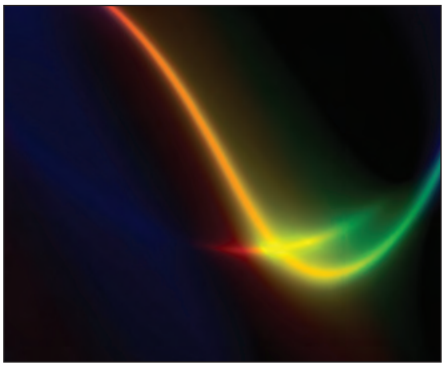
Opnext Releases First High Power IR Laser Device with Photo Monitor

OPNEXT, a global manufacturer of high power, low operating current red and infrared laser diodes, has introduced a 637nm, 120mW high power laser with a built-in monitor photo diode.

The company's HL63142DG red laser diode, which is designed for industrial and military applications, including military target acquisition, achieves optimal performance and output by enabling system designers to monitor the laser's performance and adjust output power in real time. Opnext customers are currently sampling the red laser diode for use in industrial and military applications. Using a unique and proprietary design, the HL63142DG built-in monitor photo diode allows a system designer to control the optical performance by monitoring the photo diode current and adjusting for temperature and power variants. Performance monitoring capabilities are essential for maintaining constant laser output power in construction systems and biomedical and other applications that experience changes in their operating environments.

The HL63142DG operates at a temperature range up to 50°C and 120mW in the 637nm wavelength band in a 5.6mm diameter to industry standard package.

"We expect to see initial demand for this high quality laser with built-in monitor photo diode to come from military target acquisition-type applications where precise laser control is an important performance parameter," said Tadayuki Kanno, President of Opnext's devices business unit. "The industry trend is moving toward producing laser diodes that are high power, while consuming less energy, and Opnext continues to innovate in bringing these key performance capabilities to market." Opnext offers one of the industry's most comprehensive portfolios of laser diodes, spanning from 635nm to 850nm, driven by more than 30 years of innovative laser heritage. Opnext high quality, reliable red and infrared laser diodes are proven to consume a low operating current, which extends battery life, while still maintaining the integrity of the laser diode power in a variety of applications such as gun sights, rangefinders, line leveling construction systems and biomedical applications.



RFMD PowerSmart Power Platforms Achieve 4G Performance

RF Micro Devices (RFMD), a designer and manufacturer of high-performance radio frequency components and compound semiconductor technologies, has achieved a major performance milestone related to its PowerSmart power platforms. RFMD's PowerSmart power platforms are a new product category reshaping the future of multimode, multi-band cellular RF architectures.

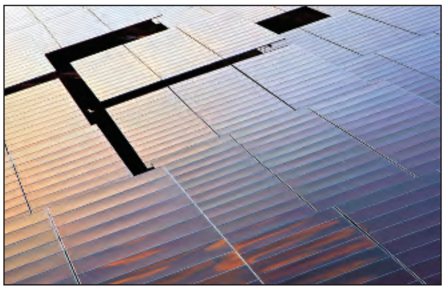
During independent product testing, the PowerSmart power platforms achieved HSPA+ 4G data upload speeds while drawing approximately 15% less current than competitive solutions. Product qualification tests, which are routinely performed to evaluate each new cellular product's front end, transceiver and baseband, are currently being conducted in support of a highly anticipated product family spanning multiple form factors, to be launched by a leading cellular device manufacturer beginning in the March, 2011, quarter. PowerSmart power platforms feature a revolutionary new RF Configurable Power Core that delivers multiband, multi-mode coverage of all communications modulation schemes, including GSM/GPRS, EDGE, EDGE Evolution, CDMA, 3G (TD-SCDMA or WCDMA) and 4G (HSPA+, LTE or WiMAX).

HSPA+ 4G devices are capable of maximum data upload speeds of 22 megabits per second (Mbps). Because the RF Configurable Power Core in PowerSmart is compliant with all current and known future 4G data standards (HSPA+, LTE QPSK, LTE 16QAM, and LTE 64QAM), RFMD anticipates subsequent smartphones featuring PowerSmart will support upload speeds significantly greater than 22 Mbps.

In addition to the RF Configurable Power Core, which performs all power amplification and power management functionality, RFMD's PowerSmart power platforms include all necessary switching and signal conditioning functionality in a compact reference design, providing smartphone manufacturers a single scalable source for the entire cellular front end.

BluGlass Commissions Rainbow to Process InGaN Solar Cells

BLUGLASS has commissioned the foundry services of related party Rainbow Optoelectronics Materials Shanghai to provide device fabrication and processing services for the purposes of creating a nitride solar cell prototype designed by BluGlass.



The arrangement enables BluGlass to outsource the processing of its Indium Gallium Nitride (InGaN) solar cell designs to an expert group-III nitride company without the need to invest in additional capital equipment during the research phase. BluGlass non executive director Alan Li is the general manager of Rainbow, a semiconductor device manufacturing company which provides nitride semiconductors (primarily LED displays) to more than 25 countries. InGaN solar cells, if successful, promise to be long lasting, relatively inexpensive and importantly, the most efficient ever created. BluGlass is developing solar cell structure designs and is now seeking to develop cell prototypes as part of its Climate Ready grant.

Research from Hong Kong demonstrates tunneling through the power barrier

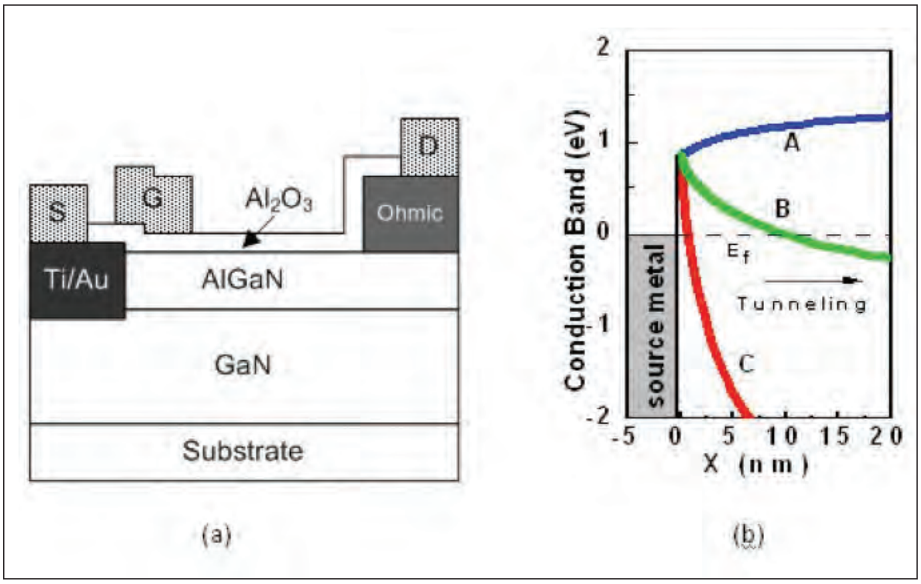


Fig. 1: (a) Schematic cross-section of an AlGaN/GaN tunnel junction FET. (b) The conduction band energy diagram of the tunnel junction FET at the source junction. The labels A-C represent different bias conditions. A: V_{GS} = -3 V, V_{DS} = 10V; B: V_{GS} = 0V, V_{DS} = 10V; C: V_{GS} = 3 V, V_{DS} = 10V. At zero gate bias, the tunnel barrier's thickness is ~10nm and does not allow significant tunnel current, leading to the normally-off operation.

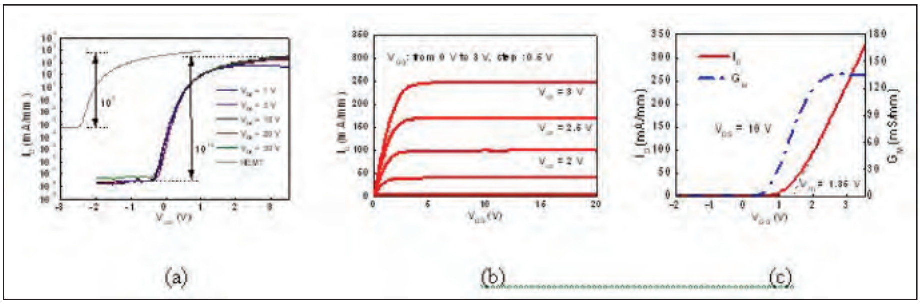


Fig. 2: (a) low off-state current and high ON/OFF ratio; (b) Ids-Vds characteristics; (c) transfer characteristics.

"THERE is a light at the end of the tunnel" is a phrase used by many looking for research results around the world. Now, Kevin Chen and his group at The Hong Kong University of Science and Technology add to this motto and declare there is also "Power at the end of the Tunnel".

The research group have recently shown that a wide bandgap Gallium Nitrate (GaN)-based power tunnel FET with normally off operation can be realised and achieved on widely available baseline AlGaN/GaN heterostructures.

The devices are claimed to offer record-low off-state leakage and record-high on/off current ratio at a high drain voltage. Advances in AlGaN/GaN HEMT technology have already shown that these devices are capable of beating silicon in terms of performance.

Two of the most challenging but also highly desirable features of GaN power devices are normally-off operation with positive threshold voltage and low off-state leakage current at a high drain voltage.

The GaN power tunnel FET, with its new current controlling scheme and a novel Schottky source configuration, delivers normally-off operation and low off-state leakage current simultaneously.

According to Chen, the new power tunnel FET features a metal-2DEG (two-dimensional electron gas) tunnel junction that is controlled by an overlapping gate electrode. Since the current turn-on/off is mainly controlled by the tunnel junction instead of the 2DEG channel, positive threshold corresponding to normally-off operation is realized on the as-grown normally-on epi-wafers.

This method of realizing normally-off operation is fundamentally different from the previous approaches that shift the threshold voltage of the 2DEG channel from negative to positive values.

Furthermore, since the Schottky junction at the source electrode is naturally reverse biased in the off-state, excellent leakage blocking and high I_{ON}/I_{OFF} ratio can be obtained, on an epitaxial wafer without the need for a sophisticated buffer layer.

At a source-drain voltage of 50 V, the drain leakage current is 10^{-11} A/mm and the on/off current ratio is 10^{10}. The off-state breakdown voltage of an AlGaN/GaN T-FET with a gate-drain spacing of 2 microns is 274 V, more than twice of that obtained in an AlGaN/GaN HEMT with the same gate-drain spacing.

This new power tunnel FET technology could provide a low-cost approach to obtaining normally-off operation and low leakage since it does not require sophisticated techniques such as gate recess, fluorine implantation or an AlGaN buffer layer.

However, the process must be optimised in order to improve the run-to-run reproducibility and uniformity, which is the next aim for the scientists.

The results of this research will be published in the paper "Normally-off AlGaN/GaN metal-2DEG tunnel-junction field effect transistors" by L. Yuan, H. Chen, and K. J. Chen, IEEE Electron Device Letters, vol. 32, No. 2, Feb. 2011.

Anadigics Joins Exclusive NASDAQ Global Select Market

ANADIGICS, a leading provider of semiconductor products in the rapidly growing broadband wireless and wireline communications space, has been chosen by the NASDAQ Stock Market to join its Global Select Market for companies satisfying the highest financial and liquidity qualifications.

Established in 2006, the NASDAQ Global Select Market was created as a separate market classification to drive greater recognition for world-class NASDAQ-listed companies that demonstrate a commitment to high standards and good governance. "We are honoured to receive this prestigious distinction from the NASDAQ Stock Market," said Mario Rivas, President and CEO. "Our company takes great pride in striving for excellence in all aspects of our business. So receiving this kind of recognition as one of NASDAQ's top companies is a tremendous point of validation for our efforts."

According to NASDAQ, qualifying for the Global Select Market is a mark of achievement, leadership and stature for the companies that are included, while also demonstrating a message of high standards to investors. Anadigics has been a publicly traded company on the NASDAQ Stock Market since 1995.

"We have enjoyed a long-term successful affiliation with the NASDAQ Stock Market and we're excited about this next phase of our relationship as one of the elite Global Select members of the market," said Thomas Shields, Chief Financial Officer.

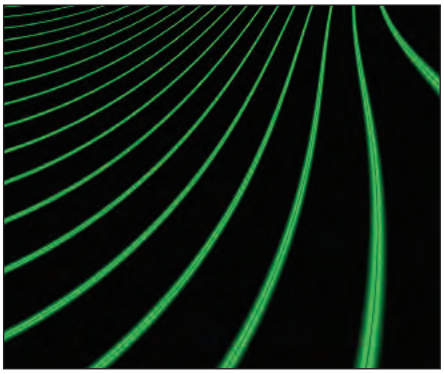
Soraa's green laser have minimal speckle

SORAA INC., a rapidly expanding clean-tech semiconductor company and a manufacturer of green and blue laser diodes, has demonstrated its latest green laser diodes (LDs), which are ideally suited for >20 lumenpico projectors.

The firm, formerly known as Kaai, Inc., says that these direct emitting green lasers have produced images which exhibit substantially reduced speckle compared to conventional green lasers based on second harmonic generation. The company displayed the green and blue LDs at its private suite at the Consumer Electronics Show in LasVegas Nevada January 6-9, 2011.

Soraa's green LDs output more than 75 milliwatt of continuous wave power in the 520-525nm range, are single spatial mode and multi spectral mode. The devices can be directly modulated at high speeds required for high resolution displays with minimal speckle.

The company says that LDs are well suited for all picoprojector display generating technologies including LCOS, scanning MEMS mirrors DLP, and other diffractive applications. Soraa's green LD devices complement the firm's previously announced blue 450nm LDs, which the company says already exhibit industry best efficiency and power.



Soraa's LDs are based on InGaN semiconductor technology and are fabricated on innovative nonpolar and semipolar GaN substrates. Soraa's direct diode green and blue lasers offer improvements in performance, size, weight, and cost over conventional gas or solid state lasers for consumer projection displays, defense pointers and illuminators, biomedical instrumentation and therapeutics, and industrial imaging applications.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ACID EXHAUST
DANGER

In order to become a successor to silicon CMOS technology, III-V transistors must be built on silicon substrates that are large enough to be processed by VLSI toolsets. Sematech has done just this by fabricating InGaAs MOSFETs on 200 mm silicon (100) using state-of-the-art silicon foundry tools. **Richard Stevenson investigates.**

Sematech builds III-V transistors on large silicon wafers

Back in the twentieth century, the route to making faster, cheaper silicon chips was clear-cut: simply reduce the size of the transistor. But if such an approach had been adopted in recent years, it would have failed to deliver the gains in performance needed to keep pace with Moore's Law.

To maintain the level of progress prescribed by that Law, foundries have modified the standard silicon MOSFET and introducing new, more exotic materials. One of these is HfO_2, which is used as the gate material. This replaces SiO_2, a dielectric that would now lead to unacceptable increase in leakage current with transistor scaling. Another change is the introduction of silicon germanium, which is used to strain the pMOS device and speed the passage of holes from source to drain.

The trend of incorporating a wider palette of materials is set to continue – the International Technology Roadmap for Semiconductors is advocating a move away from silicon transistors from 2015, when the 11 nm node will be rolled out. III-V MOSFETs are widely viewed as the most likely successors. However, despite their rich, long history of development, there is still a great deal to do before compound semiconductor transistors can be churned out in their millions at the world's leading foundries.

Development of III-V MOSFETs dates back to the 1960s. Then, just like now, the appeal of turning to this class of material stems from its very high electron mobility, which promises to lead to far faster chips. Finding a gate material that forms a high-quality interface with compound semiconductors has been one of the biggest obstacles to realizing such a device. SiO_2 was quickly discarded in favor of other silicon compounds, sulfur passivation techniques, gates made from Ga_2O_3 and Gd_2O_3 oxides, and more recently, atomic layer deposition of aluminum oxides. There has also been a switch from a GaAs channel to an InGaAs one that sports superior transport properties.

Nearly all of this work has involved a native substrate for III-V transistor development – reports of device fabrication on silicon substrates, the only material platform enabling a practical successor to silicon CMOS, have been few and far between. And almost all these efforts have used silicon substrates that are far too small to be processed by leading silicon foundries equipped with state of the art toolsets.

The one exception is an effort by Sematech, a US-based nonprofit consortium of major semiconductor and chip-manufacturing equipment makers that performs basic research on chipmaking. At the recent International Electron Devices Meeting, Sematech front-end process device engineer Richard Hill detailed the fabrication processes and device results of $In_{0.53}Ga_{0.47}As$ MOSFETs with varying gate lengths that were formed on 200 mm silicon wafers using state-of the-art manufacturing tools.

"Our devices have been manufactured using a VLSI toolset, with processes that could be carried out in any one of the big foundries or IDMs," says Hill. Turning to VLSI enables the fabrication of chips with very high levels of integration and a very small pitch, attributes that are impossible to realize using traditional III-V transistor manufacturing methods.

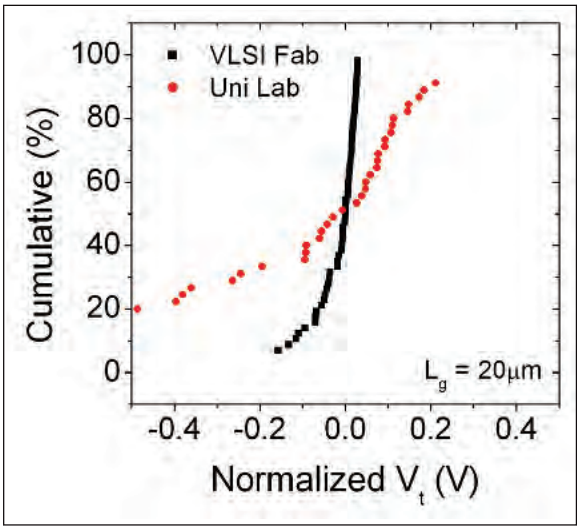


Figure 1. The spread of threshold voltage in the III-V transistors made by Sematech is comparable to that of a batch of silicon devices, and far tighter than that produced in University labs

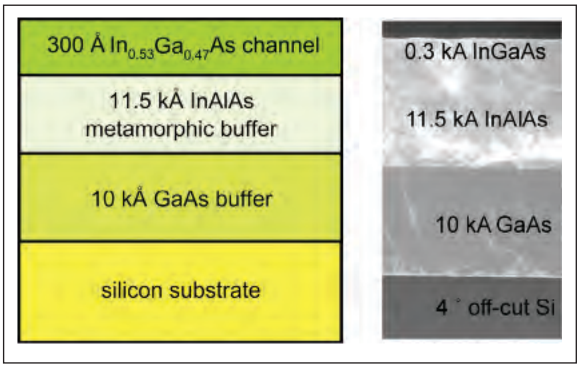


Figure 2. A metamorphic buffer is employed to bridge the gap in atomic lattice constant between silicon and indium-based III-Vs

Encouraging results

MOSFETs produced by Sematech's engineers have promising characteristics. The spread of the threshold voltage for these transistors is far tighter than it is for those produced using traditional III-V processing technologies, and similar to that of batches of silicon CMOS transistors (see Figure 1). The electron mobility in the III-V MOSFETs with a gate length of 20 μm peaks at 2000 cm^2/Vs, a value roughly four times higher than that realized in equivalent silicon transistors.

Winning approval to develop III-V MOSFETs using silicon foundry tools is not easy, because these materials could linger in equipment and contaminate silicon devices produced in subsequent processing runs. "III-V materials are shallow-level dopants in silicon, so they could introduce threshold voltage shifts and possible reliability problems," explains Hill.

He and his co-workers adjusted foundry processes to both reduce the risk that this would happen and address environmental and safety concerns associated with working with III-Vs. Once this was all in place, they tested the new approach, step by step, using techniques such as total reflection X-ray fluorescence to scrutinize the cleanliness of their tools. "It appears that you can introduce III-Vs, to be run in the same tool set as silicon," says Hill. However, he stresses that far more wafers must be put through the lines before he can be absolutely certain of this.

Although 200 mm silicon substrates are widely used in foundries, the newest fabs are working with 300 mm variants, and 450 mm material is on the horizon. However, Hill believes that it should be fairly straightforward to transfer Sematech's processes to larger sizes: "The toolset is actually quite similar between 200 mm and 300 mm wafers."

MBE growth

To make its III-V-on-silicon MOSFETs, Sematech's engineers begin by cleaning a 200 mm substrate with a wet-etch, loading it into an MBE chamber and subjecting it to an *in-situ* clean. The choice of MBE tools capable of handling such a large substrate is actually quite large, according to Hill, because a platen that accommodates a 200 mm substrate is no larger that that holding multiple 6-inch or smaller wafers.

The MBE tool is loaded with 4° off-cut (100) silicon, specifically selected to reduce the number of anti-phase domains that occur when a polar semiconductor is deposited on a non-polar one. A buffer comprising 1 μm-thick layer of GaAs, plus a 1.05 μm-thick graded layer on InAlAs is grown on the silicon surface (see figure 2).

"The buffer technology that we are demonstrating here is designed as a vehicle to allow us to do all the integration and infrastructure development," says Hill. He does not view this technology as the one that will by used for VLSI

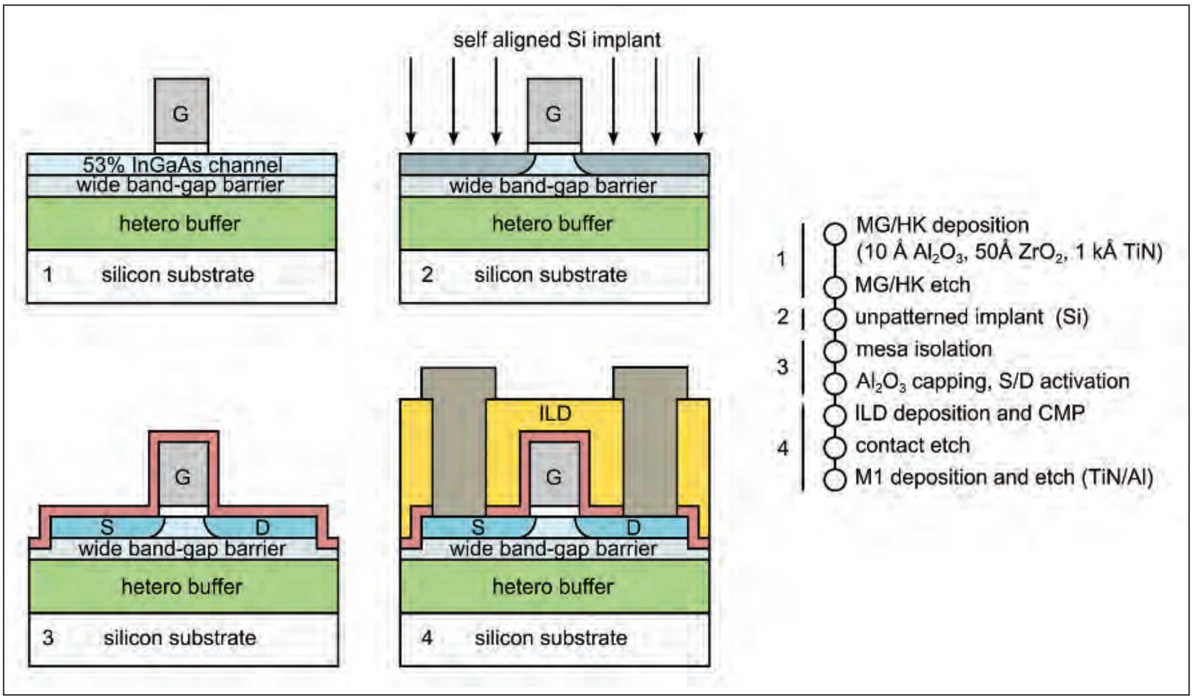


Figure 3 Sematech's three terminal MOSFET is made with a process flow that is very similar to that employed for the manufacture of silicon devices

CMOS integration, which will require a far thinner buffer. On top of the buffer sits a 16 nm-thick $In_{0.53}Ga_{0.47}As$ channel, a 4 nm-thick spacer and a 8 nm-thick barrier that are both made of $In_{0.53}Al_{0.47}As$, and an $In_{0.53}Ga_{0.47}As$ cap that is 3 nm thick. An Al_2O_3 and ZrO_2 gate is added, before silicon is implanted into the channel and source and drain contacts formed to yield a surface-channel MOSFET (see figure 3).

"It's a three terminal device, not a standard bulk MOSFET," says Hill, who compares it to a silicon-on-insulator MOSFET. One of the strengths of the Sematech device is that its InAlAs buffer has a wider bandgap than the InGaAs layer, which ensures decoupling of the channel from the underlying layers. This leads to immunity from short channel effects, which inhibit channel control by the gate and can include an increase in off-state leakage with increasing drain current and higher junction leakage. Short channel effects can prevent the transistor from being turned off as it is scaled to smaller and smaller dimensions.

The MOSFETs produced by Sematech have gate lengths varying from 20 μm to 0.5 μm. The shortest variants have a drive current of 471 μA/μm, a transconductance of 1005 μS/mm and an electron mobility of 1000 cm^2/Vs at a sheet doping of 1×10^{13} cm^{-2}. These devices do have one cause for concern, however – a leaky buffer. Measurements between isolated mesa structures indicate that buffer resistance is about 14 kΩ/☐, which is more than four orders of magnitude lower than that for typical metamorphic InAlAs buffers deposited on GaAs substrates. Transmission electron microscopy and atomic force microscopy measurements on the MOSFETs indicate that the buffer is riddled with defects. Their density in this layer is 10^9 cm^{-2}, a value high enough to account for the high leakage current in the buffer (see Figure 4).

"You can conclude the leakage is going through the buffer for two reasons," explains Hill. "The off-current does not scale with temperature, so it is not an interface state density problem; and the off-current does not really scale with gate length, so we know it is a very deep leakage."

Device on-performance is not hampered by the high defect density. According to Hill, that's because electron mobility is not governed by the mobility of the two-dimensional electron gas, which is limited by phonon scattering: "It's actually [determined] by the surface roughness and interface roughness scattering at the oxide-semiconductor interface."

The road ahead

Efforts at improving the buffer are on going. Very recently Semtech's engineers slashed the defect density in this layer, which should drive down the transistor's leakage current. One of the next goals is to thin the buffer to 0.5 μm or less, a step that must be taken to enable this layer to be used in a successor to silicon CMOS. To realize this, Sematech's engineers are looking at alternative material technologies, such as MOCVD

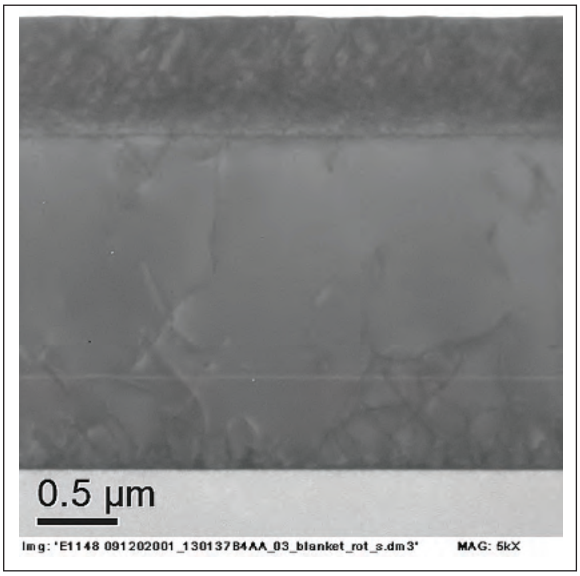


Figure 4 Transmission electron microscopy image of the cross-section of hetero-buffer. GaAs areal defect density was estimated to be ~1x10^9 cm^{-2}. The defectivity of the metamorphic buffer is significantly higher

growth, selective growth rather than blanket growth, and aspect ratio trapping. Investigating other types of transistor structures is also on the agenda. The type of MOSFET used by Sematech's engineers up until now was partly chosen because it can be fabricated using a process flow that is very similar to that used to produce silicon transistors. Now the team wants to look at processes for making various types of MOSHEMTs, including those with a recessed gate.

"There are many advantages and disadvantages of each technique, and it is not clear to us at this point which one is going to be the winner," says Hill. "One of our next steps is to build flows with all these different device types and compare them at gate lengths that are similar to where the silicon industry is right now."

In addition to scaling buffer thickness and gate length, Sematech's engineers will try to reduce contact resistance and junction resistance, and improve the gate stack. It is possible that they will complement this effort with this electron transport device with one based on hole transport, because both types of transistor are needed to build a silicon CMOS successor. "There has been some work published on antimonides with mobilities of about 1000 cm^2/Vs, and in some ways an all III-V solution may be advantageous from an integration strategy," muses Hill. "But germanium technology is more mature."

If all this effort is to lead to III-V MOSFET production in silicon foundries in four or so years time, solving of technical goals must go hand in hand with manufacturing technology developments. According to Hill, it will take a couple of years to order tools, install them and ramp up manufacturing. "That infrastructure development has to be started now to get on the correct time scales." Hopefully the toolmakers will hear this rallying call, act on it and help III-Vs to play a key role in extending Moore's Law.

What next for the Compound Semiconductor Industry?

CS Europe conference takes place on the 22nd March in the heart of Europe. Pioneering companies from around the globe will give their take on the best opportunities for compound semiconductors, and what has to be done to seize these opportunities. If you want to learn from the insight of these insiders, be sure to book your place at CS Europe. Your challenge is met by someone else's solution and CS Europe aims to provide the platform that allows the CS community to not just share ideas but develop solutions in manufacturing and furthering the reach of Compound Semiconductor devices.

Klaus H. Ploog

Pioneer of Molecular Beam Epitaxy (MBE) Keynote Speaker

Topic: **What next for the Compound Semiconductor Industry?**

Klaus H. Ploog is one of the pioneers of molecular beam epitaxy (MBE), a versatile tool to fabricate semiconductor and metal nanostructures. The MBE technique has been established in the early1970s, i.e. long before the hype on "Nano" started to dominate the word wide research funding policies in the late 1990s.

Using molecular beam epitaxy, he has designed and fabricated numerous new semiconductor and magnetic nanostructures that showed unique quantum size effects.

These man-made nanostructures have led to a number of novel device concepts, including high-electronmobility transistors (HEMTs), quantum well and quantum dot lasers, quantum cascade lasers, etc.

His research achievements have been published in more than 1500 papers in international refereed journals, and he has received several prestigious awards. His current interest for the subject of sustainable energy concepts has emerged from his research on Group-III Nitrides for solid-state lighting beginning in 1995, where he has paved the way for more efficient blue, green and violet GaN-based LEDs by using non-polar epitaxial layers and heterostructures.

Dr. Petteri Uusimaa

President, Modulight

Topic: **How to make a state-of-the-art visible red laser, what its specs are, and what new markets it can target**

Prior to joining Modulight Dr Petteri held numerous manager positions in international research projects in which he managed relations to international funding companies as well as was the principal scientist in the programs. Since 1997 Petteri has been managing semiconductor sales to multinational companies and acted as a President & CEO of Modulight since incorporating the company in 2000. Dr. Petteri Uusimaa has a PhD in semiconductor physics from Tampere University of Technology (TUT).

Jan-Gustav Werthen, Ph.D.

Senior Director, Photovoltaics
JDSU

Topic: **The urgency for the world to make power grids digital (smart grids) and photovoltaic developments for electricity production from solar.**

Jan-Gustav Werthen brings more than 26 years of technology experience to JDSU. As senior director of Photovoltaics, Jan drives overall business and product development that includes power-over-fiber products and solar CPV cells. Jan joined JDSU in 2005 as part of the acquisition of company that he founded called Photonic Power Systems, Inc. From 1992 – 2005, Jan was CEO of Photonic Power Systems, where he built a semiconductor device and subsystems organization from the ground up and grew sales over $1 million annually, addressing worldwide markets.

Prior to running his own company, Jan held management positions at companies such as VS Corporation, an early player in the fiber-to-the-home market, Varian Associates, and Xerox. Jan received his Ph.D. and M.S. in Materials Science and Engineering from Stanford University.

Jeff Shealy

Division Vice President
RFMD

Topic: Role of GaN RF Power Technology for Tomorrow's Commercial and Defense Wireless Applications

Jeff Shealy is vice president of the Infrastructure Product Line at RFMD, where he is responsible for strategic planning and execution of the corporate infrastructure strategy. Dr. Shealy was a principle founder of RF Nitro Communications, Inc., where he served as president and CEO until RFMD acquired the company in October 2001. Dr. Shealy is a Howard Hughes Doctoral Fellow and has held positions at Hughes Research Labs and Hughes Network Systems. He received his MBA from the Babcock School of Business at Wake Forest University and he holds a Ph.D. in electrical engineering from the University of California at Santa Barbara. Dr. Shealy is a member of the IEEE Electron Device Society.

Dr Otto Berger

Corporate Advanced Technology Director
TriQuint Semiconductor, Inc

Topic: 3G/4G requirements for wireless systems and the role GaAs and GaN devices will play in meeting these requirements

Dr. Otto Berger is TriQuint's Corporate Advanced Technology Director, overseeing the company's portfolio of acoustic technologies, 150mm GaAs process developments and advanced packaging techniques at TriQuint Munich, Germany. He leads innovation developments in these fields to evolve TriQuint technology for future product generations. Dr. Berger began his professional career at Siemens Semiconductor and moved to TriQuint in 2002 through the acquisition of Infineon's GaAs business. He has worked in various roles in process development, product engineering and fab management within the GaAs field for more than 20 years. Dr. Berger received his PhD degree in physics from the University of Muenster, Germany.

Marc Rocchi

CEO, OMMIC

Topic: What's needed from GaAs and GaN for tomorrow's wireless

Marc Rocchi received his degree in Electrical Engineering and Solid State Physics from the Ecole Supérieure d'Electricité de Paris in 1972 . In 1976 , he joined the Philips Research Lab in France to work on the design of high -speed digital GaAs circuits and in 1983 , he became head of the GaAs RFIC department. In 1988 , he moved to Philips semiconductors in Eindhoven to lead the CMOS process and characterization group as part of the 1Mbit SRAM project. Since 1990 he has successively been general manager of Philips Microwave Limeil and CEO of OMMIC . He is now Chairman of the board of directors of OMMIC

Alexander Bachmann

Marketing Engineer
OSRAM Opto Semiconductors GmbH

Topic: Recent Progress on Green InGaN Laser Diode Development at OSRAM Opto Semiconductors

After the studies in physics, Alexander Bachmann worked on the development of electrically pumped vertical-cavity surface-emitting laser diodes at the Walter Schottky Institut of the Technical University of Munich. Emitting in the near- to mid-infrared spectral region, these devices are perfect light sources for trace gas sensing applications. In 2010 he joined OSRAM Opto Semiconductors for the marketing of visible lasers for pico projectors. With first products already being available on the market, a huge market growth is expected for the next years, driving the development of blue and particularly green laser diodes.

Dr. Michael Fiebig

Director Marketing and Business Development Solid State Lighting
OSRAM Opto Semiconductors GmbH

Topic: What are the success factors for the deployment of Solid State Lighting?

Dr. Michael Fiebig gained his PhD in Physics at the University of Hanover in 1998. During his doctoral thesis he worked on Diode-pumped solid-state-lasers in the

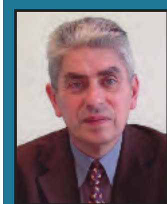
Klaus H. Ploog

Dr Petteri Uusimaa

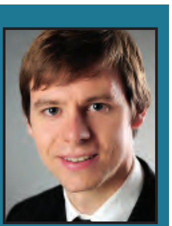
Jan-Gustav Werthen, Ph.D

Jeff Shealy

Dr Otto Berger



Marc Rocchi



Alexander Bachmann

Dr. Michael Fiebig

Dr Markus Behet

Dr. Ulf Meiners

Mark Murphy

Mats Reimark

spectral region at 2µm for medical applications. In 1998 he joined Lambda Physics as Product Manager for Excimer Lasers for display and industrial applications. From 2001 he joined OOSRAM Opto Semicondutors and was heading the Marketing segment for Consumer and Communication until 2008. Since 2008 he is leading the Marketing and Business Development in the business segment Solid State Lighting at OSRAM Opto Semiconductors.

Dr. Markus Behet

Europe Business Development Manager
Dow Corning Compound Semiconductor

Topic: SiC Advances for Power Electronic Applications

Dr. Markus Behet received his PhD in Electrical Engineering and Semiconductor Physics from the Technical University Aachen in 1995. From 1995 - 1998 he was R&D Manager for epitaxial growth and device processing of advanced III/V Semiconductors for High Frequency and Infrared Laser applications at IMEC in Leuven/Belgium. In 1999 – 2002 he joined Siemens Semiconductor and later Infineon Technologies where he was responsible for Business Development and Marketing of GaAs mmW products and foundry projects.

From 2002 - 2010 he held several Marketing and Sales positions for GaAs handset, foundry and mmW markets at TriQuint Semiconductor. In 2010 he joined Dow Corning as Development Manager for SiC based Compound Semiconductor Solutions.

Dr. Ulf Meiners

Chief Technical Officer, UMS

Mark Murphy

Director Marketing, RF Power & Base, NXP
Topic: High performance compound semiconductors for infrastructure, automotive and defense applications

Ulf Meiners received the Ph.D. in physics from the Technische Universität Munich, Germany and has been working in the compound semiconductor domain since more than 20 years. He is the Chief Technical Officer of the UMS group and the Technical Managing Director of UMS GmbH, Germany.

Mark Murphy received a BEng in Electrical and Information Eng from Queens University Belfast and has been working in the semiconductor industry for more than 20 years. First at Analog Devices, followed by Philips & is currently at NXP where he is the Marketing Director for the Product Line "RF Power & Base Stations".

Mats Reimark

CEO, TranSiC

Topic: How will SiC power devices help getting a greener planet

Mats Reimark has been a director in international organizations for more than 10 years. He is, since May 2009, CEO at TranSiC AB a company specializing in development and manufacturing of bipolar transistors in Silicon Carbide. Prior to joining TranSiC Mats has had a long career at GM with assignments such as Director Hybrid Powertrain Engineering Europe, Chief Engineer Technology at Fiat-GM Powertrain and Director Engine and Controls Engineering SAAB.

Dr. Philippe Roussel

Project manager Power Electronics and Compound Semiconductors
Yole Développement

Topic: GaN power electronics: Market forecasts and industry status

Yole Développement (www.yole.fr) is a market research and strategy consulting company based in Lyon, France.

Dr Philippe Roussel has headed the Compound Semiconductors division since 1998. Yole produces numerous market reports and is currently publishing their analysis of the SiC, GaN, AlN, Sapphire power and RF device as well as high-brightness LED markets
Dr. Philippe ROUSSEL is graduated from the University of LYON in Electronics and Microelectronics. He was granted a Ph-D in Integrated Electronics Systems from the Applied Sciences National Institute (INSA) in LYON.

He is working at YOLE DEVELOPPEMENT since 1998 and is leading the techno-economical market analysis in the fields of Compound Semiconductors and Power Electronics at materials, equipment and devices level.

Scott Parker

Executive Vice President Sales and Marcom
Oclaro, Inc

Topic: Future Proofing Networks with 100 Gigabit Optics

Mr. Parker was previously with Avanex Corporation, most recently serving as the Company's Senior Vice President of Sales. Prior to joining Avanex, Mr. Parker held senior management positions at two start-up companies funded by Sequoia Capital. Previously, Mr. Parker served as Senior Vice President of Sales and Marketing for JDS

Uniphase where he integrated the sales and customer service teams from numerous acquisitions. He also held sales and general manager positions at VLSI, National Semiconductor and Intel. Mr. Parker earned an M.B.A and bachelor's degree in marketing from the University of Utah.

Dr. Ertugrul Sönmez

Business Development
MicroGaN GmbH

Topic: **Efficient High-Voltage GaN Devices and ICs for Next Generation Power Management Solutions**

Ertugrul received his Diplom-Ingenieur degrees in electrical engineering from University of Ulm, in 1998. In 1998, he joined the department of Electron Devices and Circuits as a member of the scientific staff, earning the Doktor-Ingenieur degree in 2007. His main fields of research were compact silicon bipolar transistor modeling and analog RF MMIC design at 24GHz. He has authored and co-authored more than 40 publications and conference contributions.

In March 2005, he joint ATMEL Germany GmbH in Heilbronn as Marketing Manager, to be responsible for the world wide UWB RFID product line. In June 2005, he joined TES Electronic Solutions GmbH in Stuttgart, a service provider of ATMEL Germany GmbH. His main activities were to lead the ultra wide band MMIC design.

In December 2006, he has been called by MicroGaN GmbH as the strategic Business Developer to bring in his experience in semiconductors and markets.

Roy Blunt

SEMI International Compound Standards

Topic: **Standardisation in compound semiconductors - an essential step for furthering the efficiency & profitability of the industry.**

Roy Blunt graduated from Imperial College London in 1969 and joined Plessey Research Caswell Ltd., where he worked on a variety of R&D projects before becoming part of the GaAs IC pilot production team and developing a particular interest in compound semiconductor characterisation techniques (metrology).

In 1988 he left Plessey to become part of the founding team of Epitaxial Products International Ltd in Cardiff - now IQE (Europe) Ltd.

He has been involved in standards work since the early 1980s and was a co-founder and, for many years, co-chairman of the SEMI European Compound Semiconductor Technical Committee which has been very active in standards development both on its own and in co-ordination with the North American and Japanese SEMI Compound Semiconductor committees.

Dr Mike Cooke

Chief Technology Officer
Oxford Instruments Plasma Technology

Topic: **Batch and single wafer processing strategies for HBLEDs**

Dr Mike Cooke joined Oxford Instruments Plasma Technology in 1992. As Chief Technology Officer, he leads the team of expert development technologists responsible for developments such as PEALD and scaling plasma tools towards 450mm.

Dr. Thomas Uhrmann

Business Development Manager
EV Group (EVG)

Topic: **Engineered Substrates for future compound semiconductor devices**

Thomas Uhrmann is Business Development Manager for Compound Semiconductors and Si-based Power Devices at EV Group (EVG). In his current role, he is responsible to introduce and manage technological innovations for the fabrication of high-brightness light emitting diodes (HB-LEDs) at EVG.

Uhrmann holds an engineering degree in mechatronics from the University of Applied Sciences in Regensburg and a PhD in microelectronics from Vienna University of Technology. Uhrmann authored and co-authored several papers on semiconductor diode structures, micro or nanomagnetism and related areas.

Mike Czerniak

Product Marketing Manager, Exhaust Gas Management
Edwards

Topic: **GaN - meeting emissions regulations**

Mike Czerniak received his PhD at Manchester University, and started as a scientist at Philips' UK laboratories before moving to its fab in Nijmegen, working on compound semiconductor applications. He was in marketing at Cambridge Instruments and VG Semicon; he is now the product marketing manager of the Exhaust Gas Management Division of Edwards, Clevedon, North Somerset BS21 6TH, UK

Dr. Phillipe Roussel

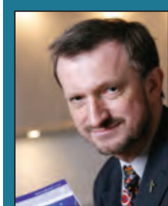
Scott Parker

Dr. Ertugrul Sönmez

Roy Blunt

Dr. Mike Cooke

Dr. Thomas Uhrmann



Mike Czerniak

GaN HEMTs: **faster, more capable and better understood**

Low-resistance channel contacts that speed transistors to record-breaking frequencies, localized boron-doping that boosts blocking voltages and studies of HEMT ageing mechanisms all featured at the latest International Electron Devices Meeting. **Richard Stevenson reports.**

Advances in silicon technology have dominated the agenda at the International Electronic Devices Meeting (IEDM) for more than fifty years. However, recently this meeting has also featured a handful of presentations on GaN HEMTs, showcasing the progress made with this device. According to papers at the most recent meeting, not only is this class of transistor operating at far faster speeds than ever before and blocking higher voltages – a more detailed understanding of why it fails is coming to light, and superior models are being developed to aid the building of circuits based on these HEMTs.

One of the highlights from the latest IEDM, which was held in San Francisco from 6-8 December 2010, was a paper from a team from HRL Laboratories claiming the record for the fastest GaN HEMTs. These transistors, which have gate lengths as short as 40 nm, produce a peak cut-off frequency of 220 GHz and a maximum oscillation frequency of 400 GHz. The record-breaking results are believed to stem from an impressive set of DC characteristics: on-resistance is just 0.81 Ω.mm; drain current hits 1.61 A/mm; off-state breakdown voltage is 42 V; and extrinsic transconductance peaks at 723 mS/mm, reducing the contribution from parasitic capacitances.

HRL's HEMTs employ a barrier made from AlN. This wide bandgap material has the benefit of producing strong polarization effects, but it also creates a high potential barrier for electrons, making it difficult to form a low-resistance ohmic contact to the channel. The issue is addressed by re-growth of heavily doped GaN contacts by MBE, according to West-coast team. They have fabricated double-heterostructure HEMT epistructures by MBE on 3-inch SiC. An $Al_{0.08}Ga_{0.92}N$ layer was deposited first, followed by a 20 nm-thick GaN channel and then a top barrier comprising 3.5 nm of AlN and 2.5 nm of GaN (see Figure 1). The thin top barrier cuts gate-to-channel-distance while maintaining a high two-dimensional electron gas density and a low gate-leakage current.

The HRL team produced transistors with gate lengths ranging from 40 nm to 200 nm. Chlorine-based reactive ion etching exposed part of the channel, before MBE added 50 nm-thick GaN layers with a silicon doping level of 7×10^{19} cm^{-3}. These formed the basis for source and drain electrodes that were created by adding titanium and platinum. A tri-layer electron-beam technique created T-shaped gates made from platinum and gold, before these devices were passivated with 50 nm of SiN.

Cutting gate length from 200 nm to 40 nm increased transconductance from 672 mS/mm to 723 mS/mm and reduced threshold voltage by 0.5 V, indicating that gate scaling was not impeded by short channel effects. Measurements of the cut-off frequency at a range of gate lengths confirmed this and indicated that miniaturization reduced parasitic delay. Modeling showed parasitic charging time accounted for one-tenth of the total delay time for 40 nm transistors with a source-drain voltage of 2 V. The gate transit time scales with gate length, which is another promising sign that further reductions in device size should increase the speed of these transistors.

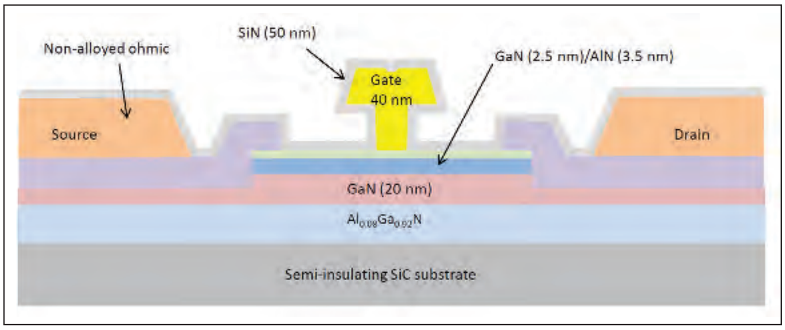


Figure 1. MBE re-growth of heavily n-doped GaN contacts has helped to speed HRL's HEMTs

Channel stoppers

Modifications to transistor architectures were also behind the hike in blocking voltages of HEMTs produced by Panasonic's Advanced Technology Research Laboratories. By introducing an array of 'channel stoppers' that terminate the leakage current at the interface with the silicon substrate, this team increased off-state breakdown voltage in HEMTs with GaN layers just 1.4 μm thick from 760 V to 1340 V. Turning to 1.9 μm-thick GaN bolstered the blocking voltage to 1900 V, and the team claims that additional thickening of GaN should increases this to 3 kV.

Simply increases the thickness of GaN layers in conventional devices – which could find application in power switching systems, such as inverters for industrial use and uninterruptible power supplies – has been widely touted as a route to increasing the HEMT's blocking voltage. But in practice such efforts, which have the downside of increasing chipmaking costs, fail to deliver on this front. The reason for this was unclear until the recent efforts by this Japanese team. According to them, conventional devices suffer from a significant leakage current that stems from sheet electrons forming an inversion layer at the substrate-epilayer interface. The Kyoto team has confirmed the presence of an inversion layer by fabricating metal-insulator-semiconductor diodes and measured their capacitance-voltage characteristics.

To stem the flow of leakage current, Panasonic's engineers insert channel stoppers. These stoppers, which are formed by selective boron ion implantation at the periphery of the chip, widen the depletion layer in silicon at high positive surface bias. This, in turn, increases the overall blocking voltage thanks to the addition of the breakdown voltage of the depletion layer.

Unreliable reliability tests

Meanwhile, researchers Jungwoo Joh and Jesús del Alamo from MIT have revealed that it can be inappropriate to determine a HEMT's RF reliability from DC tests. That's because the degradation mechanisms for DC and RF operation are significantly different.

"Obviously life tests under RF conditions close to field, but mildly accelerated, would best represent the reliability of these devices," said Joh to *Compound Semiconductor*. He and del Alamo found that RF stress degrades a device far more severely than DC stress at the same voltage, and this degradation gets more severe with increasing power compression. In addition, the pair of MIT researchers discovered that RF stress induces an increase in source resistance due to a new mechanism that is possibly related to hot carriers. The key message of their study is this: DC life tests underestimate RF reliability.

This important conclusion was drawn from a series of measurements on single-stage MMICs with 4 x 100 μm GaN HEMTs. Performance was evaluated at a current of 100 mA/mm, a source-drain voltage of 28 V, and a saturated power output (input power was 23 dB). The RF performance at this voltage is similar to that at 40 V, the designed operating condition for these MMICs.

The first experiment began by DC stressing the device for 5 hours, using a drain-source voltage of 40 V and a quiescent current of 100 mA/mm. This led to little change in device characteristics, aside from a small increase in current collapse. An RF stress test followed, involving increases in input power from 20 dB to 26 dB. This led to major changes in MMIC performance: significant increases in current collapse and sheet resistance; a permanent degradation in the maximum drain current; and a substantial cut in the output power.

Joh and del Alamo then looked in turn at three operating conditions that could potentially cause enhanced degradation at high compression: the "on" regime, the high-voltage "off" regime; or the "high-power" regime. They ruled out the first two, and although they couldn't directly test the third scenario – in this condition there is very high power dissipation, which leads to incredibly high channel temperatures that kill the device – pulsed conditions revealed a sharp increase in sheet resistance beyond 40 V, especially for a high stress current.

Fluorine: a fine dopant

Reliability assessment was also the central theme of a study led by Kevin Chen from Hong Kong University of Science and Technology. He and his colleagues studied the behavior of enhancement-mode AlGaN/GaN HEMTs fabricated by fluorine plasma ion implantation. This technique offers a low-cost approach to making this class of transistor and has the merit of self-alignment between implantation and gate metallization.

In GaN and related materials, fluorine ions exhibit a negative charge state. "When incorporated in the AlGaN barrier, these ions can deplete the two-dimensional electron gas channel, shifting the threshold voltage to positive values and converting the device from depletion-mode to enhancement-mode," explains Chen. The enhancement-mode form of the device, which is also referred to as 'normally off', is more desirable for power switching applications - it allows a simpler gate drive; and if it fails, the system is left in a safe state.

Fluorine plasma ion implantation technology has been previously used in other semiconductor materials, such as silicon and GaAs, where it has compromised reliability. The concern has been that this technology would also impair GaN transistor reliability, although preliminary results indicate that this does not impact the electrical and thermal reliability of device made from this wide bandgap semiconductor.

The team, led by Chen and including John Roberts from the US GaN-on-silicon HEMT trailblazer Nitronex, has recently focused their efforts on studying reliability under high gate bias and low drain bias, the standard condition for operating a power switch in its "on" state. In this state, especially when the gate is overdriven to either minimize the on-resistance or accommodate current surge, the Schottky gate tends to feature a non-negligible current – this also raises reliability concerns.

One of the goals of the team's recent work has been to investigate whether the fluorine ions, which are mostly located in the gate barrier layer, are stable under gate forward overdrive. If they are unstable and cause reliability issues, the team would aim to identify the critical gate bias and consequently the operating conditions to drive a device without degradation.

The team fabricated AlGaN/GaN HEMTs with a 1.5 μm gate length and gate-source spacing, and a gate-drain spacing of 2 μm. They found that the critical gate overdrive voltage was 3.6 V and 2.8 V at drain-source voltages of 2 V and 0.85 V, respectively. At higher voltages, the channel turn-on voltage experienced a small, persistent negative shift, and at lower voltages the transistor realized excellent stability.

The negative shift in channel turn-on voltage is an undesirable characteristic. "A large negative shift means that the E-mode device could eventually drift to a D-mode one," explains Chen. "In practice, we need to stabilize the on-voltage at the positive value."

Impact ionization of fluorine ions due to hot electron injection is viewed as the primary driver behind the shift in on-voltage with temperature. "Impact ionization is one of the few reliability-relevant physical processes that becomes weaker as temperature goes up, " says Chen. "In semiconductor devices, most degradation processes could be accelerated at higher temperature. With regard to the on-voltage shift, it becomes smaller and eventually disappears as the temperature is raised."

Modeling HEMTs

The various approaches to modeling the behavior of GaN HEMTs in RF power amplifiers was touched on in a paper by David John and co-workers at NXP Semiconductors, who have pioneered the development of a surface-potential based model. This joins a growing list of models for predicting HEMT behavior, which all have their weaknesses, according to John. Table-based models, which use an interpolating spline on measured data, can give erroneous values for bias outside the range. Threshold voltage based models can struggle at threshold values and empirical models fail to scale. We cannot predict how geometrical changes impact performance.

"From metal-oxide-semiconductor modeling, surface-potential-based models are known to be the preferred approach for scaling, extrapolation, distortion modeling, statistical modeling and so on," says John. " All Compact Model Council standardization efforts focus on the surface-potential-based models for this reason."

NXP's model resembles that for a conventional MOSFET. However, it reflects one fundamental difference between these two types of transistor: HEMTs are based on accumulation at the surface, while MOSFETs operates in inversion. To account for this, John and his co-workers derived the equations for currents and charges from scratch using nonlinear, binomial expansions of the electronic charge density. After the engineers had constructed this core model that provides fast simulation times, they compared its predictions to numerical simulations of a gated section of a full device.

"The numerical simulations checked that the approximations we have made in order to arrive at compact expressions are consistent with the idealized structure that we are using to describe the device," explains John. These efforts showed that the core model is good at describing current as a function of bias and catering for the bias dependence of the capacitance.

The researchers then built a macromodel that encompasses the core model. This is claimed to account for the regions under the gate foot and the drain-side gate edge with an approach that is based on physically justifiable differences in the underlying model parameters. Resistors, capacitors and inductors describe passive parasitic elements and the rise in device temperature resulting from power consumption is captured with a simple thermal network.

To test the model's validity, NXP researchers have compared its predictions to real data obtained from on-wafer measurements of multiple-finger, multiple-cell GaN HEMTs. This effort revealed that the model captures DC measurements at different temperatures, including a negative output conductance at high powers that stems from strong self-heating.

Simulations of RF behavior are also close to measured results, according to capacitance and transconductance comparisons at 2.6 GHz.

The model can also be used to simulate circuits after it has been calibrated to measurements, a necessary step for any compact model. "We are constantly working to improve our model, and to further validate and benchmark it," says John. "There is still work to do."

That view holds true for many other aspects related to the GaN HEMTs. The good news, however, is that progress is clearly being made on many of these fronts. It will be interesting to see what IEDM hold in store at the end of 2011.

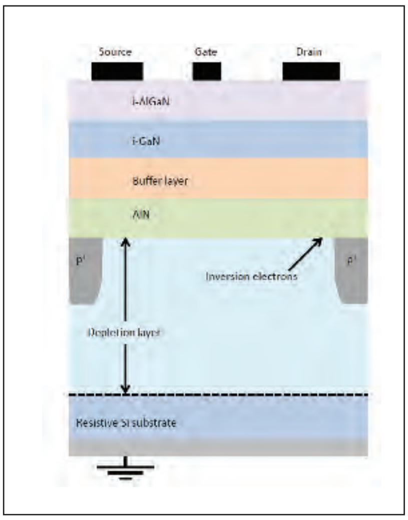


Figure 2. Introducing boron-doped channel stoppers delivers a hike in the HEMT blocking voltage

Shaping up LED Chips

Novel chip geometries, such as triangular and hexagonal devices, can deliver massive increases in light extraction by cutting optical confinement in both the vertical and horizontal directions, says **Hoi Wai Choi from the Semiconductor Lighting and Display Laboratory at The University of Hong Kong.**

LEDs have evolved from candela-class monochromatic point sources that are only good for indicator lights to 120 lm/W high-power, white-light lamps widely used as LCD backlighting. The tremendous progress can be attributed to great progress in material epitaxy skills, device design and processing techniques, together with advanced packaging strategies. With dozens of advanced features loaded into today's LED chip, isn't it strange that chip geometries have hardly changed over the last decade?

Rectangular and square geometries are probably the norm because it is easy to process chips in these shapes.

Figure 1. Laser-micro-machined LED chips

Since sawing involves only continuous linear cuts, rectangular chips seem the logical way to go. However, geometries with high degrees of symmetries generally do not favour light extraction.

Maximising light extraction is one of the keys to enabling the LED to reach is full potential. Inside this device, a significant proportion of the light can be trapped, because any light that impinges on the semiconductor-air interface beyond the critical angle will be completely reflected. The value of critical angle is governed by the difference in the refractive index of the two materials, which is quite large for the pairing of GaN and air. Today light extraction efficiencies rarely exceed 20 percent, but if this figure can double, LEDs will then be in a great position to dominate the general lighting market.

Excessive reflection of light at interfaces results in light confinement and subsequent re-absorption, resulting in heat generation. So improvements in light extraction have the added bonus of directly combating heat dissipation issues.

One of the most common approaches to minimise optical confinement in the vertical direction is surface texturing. This process may involve either random roughening, or the introduction of regular and periodic arrays of microstructures and nanostructures, which are also known as photonic crystals.

However, little attention has been paid to lateral optical confinement, which depends on the dimensions and geometry of the LED chip. In the highly symmetrical rectangular or square structure, a light ray that is reflected due to total internal reflection at one interface will most likely be reflected at subsequent interfaces. This can be understood from the fact that all interfaces, or facets, of

such chips are either parallel or orthogonal to each other; the incident angle of a light ray remains unchanged after successive reflections unless scattered, so that such confined photons are eventually reabsorbed.

However, it is possible to stop wasting photons in this way. What's needed is a switch to a chip geometry involving facets that are not parallel to each other, which is an approach that we have pioneered at the Semiconductor Light and Display Laboratory at The University of Hong Kong.

Any shape you want

The enabling technology for realising LEDs of unconventional geometries is laser micromachining. Although lasers have now been widely adopted for chip dicing, they have continued to be used for making linear cuts even though laser beams can easily be steered to carve virtually any shape. Our chip-shaping experiments are conducted with our custom designed and assembled optical setup. The workstation comprise of a third-harmonic ultraviolet, diode-pumped solid-state laser source that features a collimated beam that is focused into a tiny spot onto an x-y-θ motorised stage. By translation or rotation of the stages controlled by our in-house developed software, we can form chips of any arbitrary shapes. These are cut from LED dies fabricated on InGaN/GaN wafers grown on *c*-plane sapphire substrates.

Our belief in the inherent advantages of these novel chip geometries is supported by optical ray-trace simulations. By examining the proportion of light rays that can be extracted from LEDs of different geometries, their efficiencies can be predicted. The results of our set of simulations on LED chips of circular, triangular, squarish, pentagonal, hexagonal, heptagonal, octagonal and circular (the circle is in fact a polygon with an infinite number of sides) geometries are summarised in Table 1.

What stands out from the set of figures is the fact that square LEDs have distinctively lower extraction efficiencies than any other

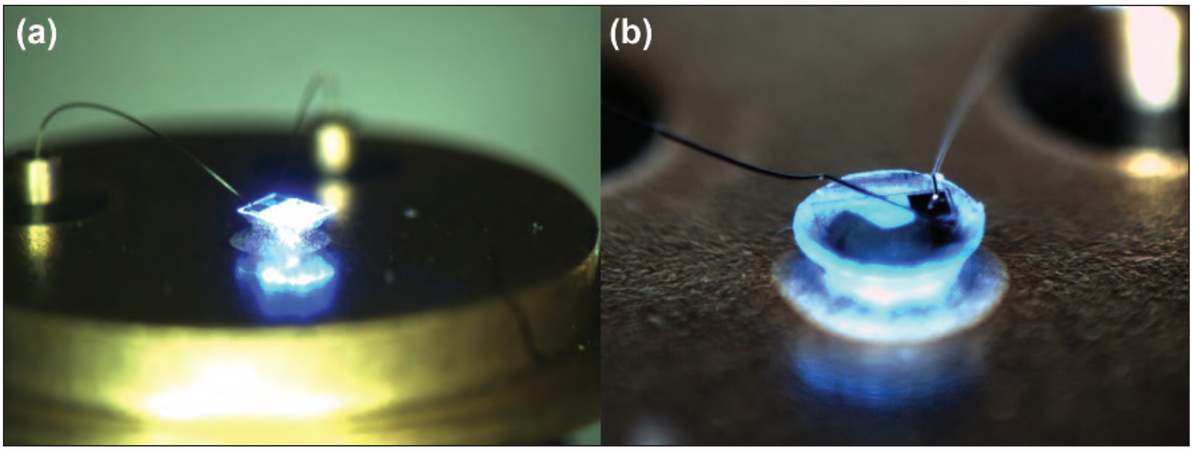


Figure 2. LEDs of (a) inverted pyramidal and (b) inverted conical geometries

shapes. Considering the fact that LED chips in the market are invariably diced into squares or rectangles, device designers should give serious thought to re-designing the chip.

Our findings from these simulations are backed up by measurements on packaged but un-encapsulated LED chips laser micro-machined into various shapes (see Figure 1). These results show that the square LED is on average 16 percent less efficient than other polygons. Of course, one could argue that the chip packing density, and thus chip count across a wafer, might be compromised. Therefore, we propose the use of triangles and hexagons; such shapes can be closed-packed into any array without sacrificing chip space and thus make economic sense.

An additional feature introduced into our optical setup enables machining of three-dimensional freeform structures. A mirror inserted into the optical path between the focusing optics and the machining plane allows the focused beam to strikes the wafer at an oblique angle. LEDs of truncated pyramidal (TP) structure, as depicted in Figure 2(a), are formed simply by applying four successive oblique cuts along the four edges of devices. On average light enhancement is increased by 89 percent over similar chips with vertical facets, consistent with our theoretical prediction of a 85 percent gain obtained by ray-tracing.

The inclined sidewalls serve as reflectors to redirect laterally-propagating photons into the escape cone. Devices of TP-geometry also emit with a wider divergence angle. Combining oblique angle machining and rotary machining, LEDs of truncated conical structures can also be formed (see Figure 2(b)). Subsequently, a reflective metallic layer is deposited onto the bottom and inclined sidewall surfaces of the chip to form an integrated reflector cup.

This structure is particularly beneficial for building white LEDs with homogeneous emission. In a typical white LED, an epoxy mixture containing phosphor particles is coated prior to encapsulation. The phosphor mixture is allowed to reflow in order to cover both the chip surface and sidewall facets, resulting in a dome-shape-like non-uniformity, the effects of which are particularly prominent at the edges. Such thickness non-uniformities give rise to non-homogeneity of colour emission at different viewing angles.

With the integrated reflector cup design, light emission via sidewalls is suppressed effectively. The majority of the light rays are emitted from the top planar surface, so that the divergence angle of the device can be reduced by 16°. Consequently, only the top planar surface needs to be phosphor coated; planar coating produces significantly improved uniformity that paves the way for superior colour homogeneity.

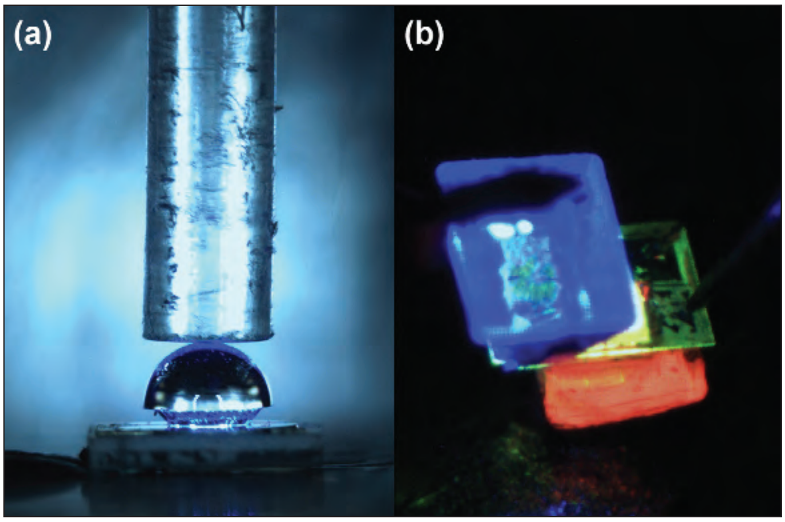


Figure 3. (a) A fibre coupled hemispherical LED assembly and (b) RGB LED stack

Coupling LED emission to fibres

It is possible to incorporate a hemispherical lens by inverting and flip-chip bonding the truncated conical chip to a package. The lens can be attached via liquid capillary bonding to produce a nanometre scale air-gap with exceptionally high transmission across the interface. At close proximity the lens is also able to capture most of the emitted light, focusing this to a tight spot with high power density. Such an assembly is ideal for optical coupling to a fibre (see Figure 3(a)).

To test its efficiency, the aperture of a 2mm-diameter plastic optical fibre was aligned to the focal spot of the LED assembly. Measurements determined a coupling efficiency of 53.8 percent, the highest value reported to the best of our knowledge. fibre-coupled LED sources find uses in a diverse range of applications from optical microscopy to short-range optical communications. Apart from the integration of optics, the monolithic integration of LED chips has also been demonstrated as a viable solution for building colour-tuneable LED assemblies.

Three LEDs chips of the primary colours, cut into truncated pyramidal geometries, were vertically stacked on top of each other in the order of decreasing wavelength from the bottom to the top, as illustrated in Figure 3(b). The inclined sidewalls are mirror-coated to suppress lateral leakage.

With this stacking arrangement, light emitted from chips at the bottom of the stack emits through the upper chips; the top blue LED chip serves as the output window. As the optical paths of the three chips overlap with each other, their colours are naturally mixed along the optical path without requiring additional optics. By individually controlling the intensities of the three colours via bias current, a wide range of colours can be produced with excellent homogeneity and performance (see Figure 4 for examples).

Such stacked devices are obviously useful for building high-resolution LED display panels. However, they are also excellent candidates as plain white light LEDs. Being free of phosphor, the stacked LEDs emit white light with high efficiency, excellent homogeneity, high colour-rendering index and long-term stability; all of this is achieved without colour-conversion losses.

So let's get moving and get in shape! With smart tweaks in design, extended functionalities and enhanced efficiencies can be achieved with amazing results, without the need for additional components.

With this stacking arrangement, light emitted from chips at the bottom of the stack emits through the upper chips; the top blue LED chip serves as the output window. As the optical paths of the three chips overlap with each other, their colors are naturally mixed along the optical path without requiring additional optics

Figure 4. Wide range of colors emitted by a stacked LED

Shape	Light extraction efficiency (%)
Triangle	15.07
Square	12.98
Pentagon	15.09
Hexagon	14.39
Heptagon	14.54
Octagon	14.43
Circle	13.98

Table 1. Light extraction efficiencies of LED chips with different geometries

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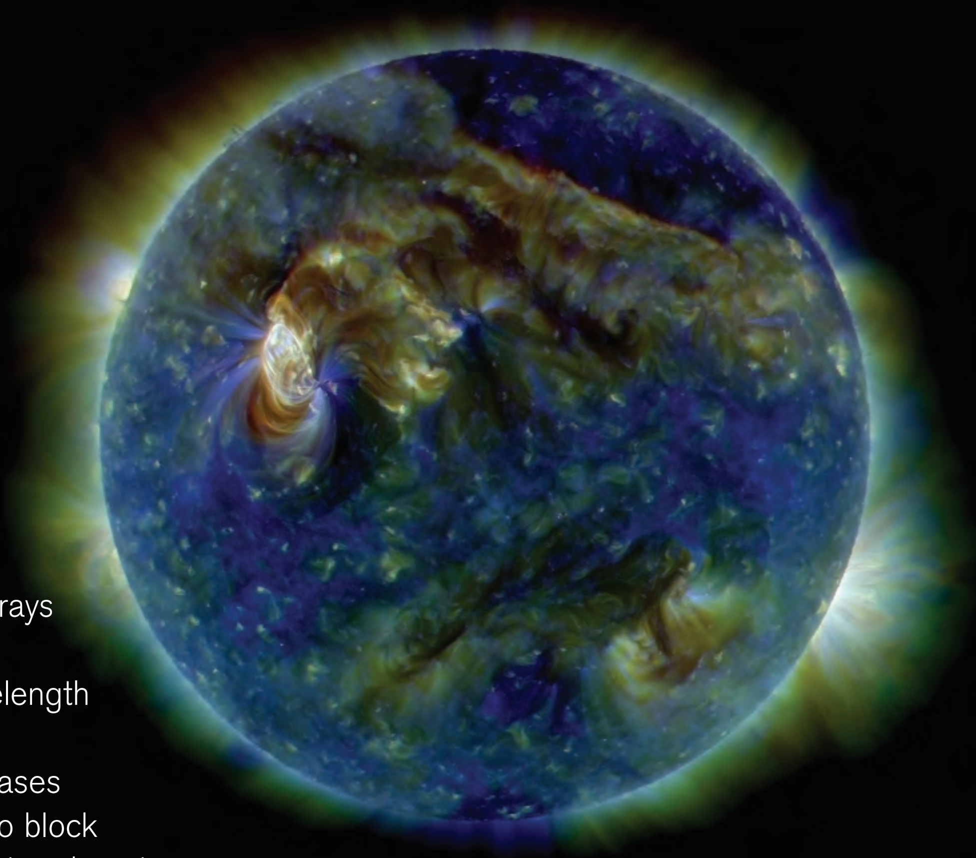
Extreme ultraviolet imaging with hybrid AlGaN arrays



Silicon extreme ultraviolet detector arrays require non-standard methods to be prevented from receiving longer wavelength radiation, e.g. by using multiple filters. Switching to AlGaN equivalents increases robustness and eliminates the need to block out visible and infrared light, which in turn boosts detector performance, say **IMEC's Pawel Malinowski, Kyriaki Minoglou and Piet De Moor.**

At first glance, the fields of solar astronomy and silicon chip manufacture are poles apart. But they do have one thing in common – the need for efficient and reliable imaging of extreme ultraviolet (EUV) radiation, which spans the range 10-120 nm.

In solar physics, there is tremendous interest in phenomena occurring on the Sun's surface (photosphere) and in its atmosphere (chromosphere and corona), such as coronal mass ejections and flares that cause staggering amounts of radiation to be emitted towards the Earth. Such processes occur at extremely high energies, so very short wavelength detectors are needed to observe what is taking place.

Meanwhile, the silicon industry is continuing its never-ending goal of shrinking transistor sizes by starting to develop lithographic processes involving EUV patterning. This requires detectors sensitive at these wavelengths, which can aid efforts to find and refine techniques for controlling the properties of the UV beam. Solar scientists and silicon engineers can use existing silicon devices for the EUV detection needs. But greater performance is possible by turning to detectors based on GaN, which have an inherently simpler system design and are more robust to UV radiation.

Silicon's weaknesses

One of the biggest advantages of using silicon to build any device is that this material and its related process technology are mature, and consequently well understood. However, its bandgap of 1.12 eV means that it absorbs not only ultraviolet radiation, but the entire visible spectrum too, plus infrared radiation up to around 1100nm (see Figure 1). This makes silicon the perfect material for the most common digital cameras and advanced imagers operating in the visible part of the spectrum. But if silicon is employed as the active material for detecting ultraviolet radiation, its sensitivity to the longer wavelengths must be taken into account.

In solar science this is important considering the fact that the solar spectrum is several orders of magnitude more intense in the EUV than in the visible range. In practice,

Image Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

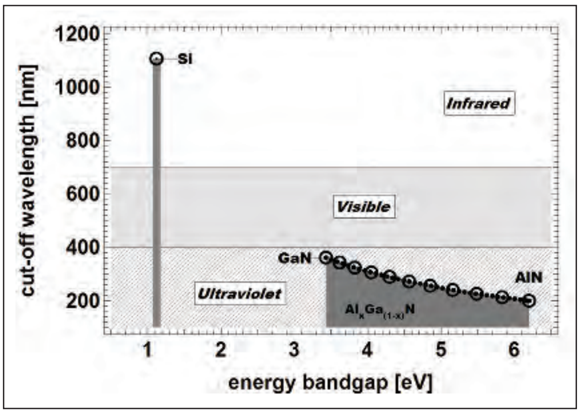


Fig. 1. Cut-off wavelength (maximum detectable wavelength) of a material vs. its energy bandgap. Gallium nitride (365 nm) is sensitive only in the ultraviolet range ("visible blind"). Increasing the aluminum concentration in the compound above 40 percent ($Al_{0.4}Ga_{0.6}N$) provides "solar blindness": cut-off below 280 nm, which is the lowest wavelength produced by the Sun to reach the surface of Earth (sea level) through the atmosphere

this means that additional filters are needed for removing unnecessary visible and infrared wavelengths. Adding filters brings major, unwanted consequences. In the EUV, all materials are highly absorbing, so any layer between the radiation source and the detector is highly undesirable because it considerably limits incoming flux. What's more, if these filters degrade – for example, contamination and/or pinhole formation – this can degrade instrument's performance. Rectifying this in a silicon foundry may not be a major issue, but it certainly is in a telescope operating in the EUV that is attached to a satellite or on-board a space station. Compounding all these issues, non-standard processing procedures are needed to make ultraviolet silicon-based imagers.

III-Ns strengths

Turning to a wide bandgap semiconductor based on nitride alloys promises to improve the design and performance of EUV detectors. The binary compound GaN has already been used to make flame detectors operating in furnaces that can detect signals in the presence of hot backgrounds with no saturation, contrary to devices based on other technologies. These detectors are commonly referred to as 'visible blind', and have a cut-off wavelength – the upper limit of absorption – of 365 nm.

Far shorter cut-off wavelengths are possible by increasing the aluminum content in AlGaN. Take this to the extreme, AlN, and the bandgap hits 6.2 eV, translating to the highest detectable wavelength of only 200 nm, which is in the vacuum ultraviolet range. If an aluminum composition of at least 40 percent is applied, it's possible to fabricate what is known as a 'solar blind' detector. This device is completely insensitive to solar radiation reaching the Earth's surface, because the ozone layer in our atmosphere absorbs all radiation below 280 nm, the cut-off wavelength for $Al_{0.4}Ga_{0.6}N$. Thanks to this complete absence of sensitivity above a certain UV wavelength, imagers and detectors can be built with far fewer filters that offer superior detectivity, due to a reduction in background signal.

Degradation under high doses of UV radiation is also diminished by switching from silicon to AlGaN. This equips the detecting systems with greater robustness and better long-term stability. Additionally, AlGaN-based imagers do not require cooling, facilitating the instrument design.

Efforts to develop GaN photodetectors for various applications have been going on for a couple of decades, with single-pixel photodetectors receiving the most attention. Some work has also been directed at the development of two-dimensional imagers, which are challenging to make, because the imager has to be integrated with the readout circuit. Uniting these two is not easy because the nitride active layers come with unwanted baggage – the substrate that provides a platform for their growth.

'Face-up' or 'face-down'?

One option for integrating nitride layers and the read-out circuit is a 'face-up' approach, which requires the fabrication of through-wafer-vias to contact the readout through the substrate. This is possible for relatively large pixel-to-pixel pitches and thin substrates, but at the cost of a decreasing fill-factor - a part of the active pixel has to be used for interconnection. Complicating matters, fabricating vias with a high aspect ratio is tough in silicon, and would be even more challenging with the sapphire and SiC substrates that are commonly used for AlGaN heteroepitaxy.

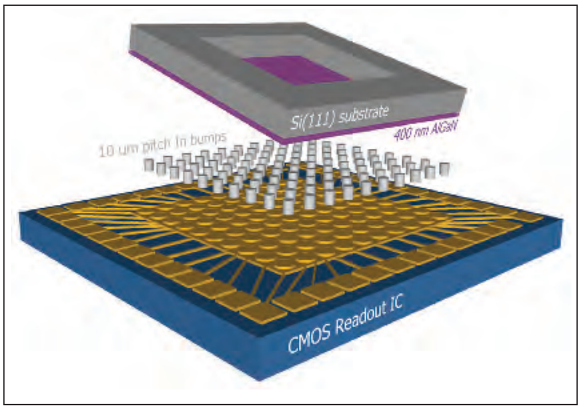


Fig. 2. Exploded schematic of the hybrid imager, with AlGaN-on-silicon detector chip (top) integrated by flip-chip bonding with the CMOS readout (bottom) using 10 μm pixel-to-pixel indium solder bumps. Image not to scale

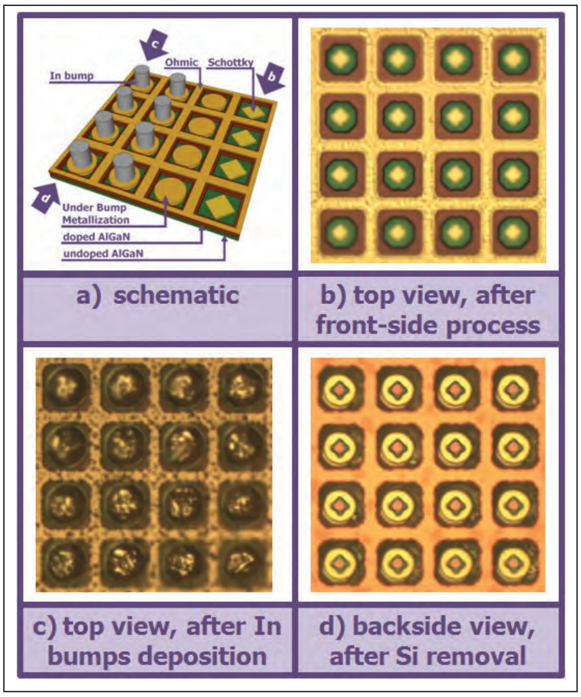


Fig. 3. AlGaN Focal Plane Array with 10 μm pitch: a) schematic showing consequent processing steps together; b) array fragment after MESA etching and deposition of the ohmic and Schottky contacts; c) array after indium bumps deposition, with one bump per one Schottky diode pixel; and d) the same array seen from the backside after silicon substrate removal (through the optically transparent AlGaN layer), showing all levels from a) from the other side of the wafer

A 'face-down' approach also has its downsides. First and foremost, you have to work in the backside illumination configuration.

Several groups, who all have faced challenges associated with substrate absorption, have used this geometry. Building a detector of low-energy ultraviolet radiation is relatively easy, because sapphire is transparent in this spectral range. But this material is opaque in the EUV regime.

If silicon is used for AlGaN epitaxy, backside illumination is impossible, so the substrate has to be completely removed. Do this, and you are left holding an epitaxial stack that is less than a micron thick. Handling this without damaging it is tricky, but even so, this is still the most promising way to make AlGaN detectors.

At Imec, which is based in Leuven, Belgium, we have adopted this approach for an EUV imager that has been developed in the framework of the Blind to Optical Light Detectors (BOLD) project from the European Space Agency (ESA). The concept was established together with CRHEA-CNRS, based in Valbonne, France, responsible for the AlGaN epitaxy. Another partner in the project was Royal Observatory of Belgium, based in Brussels, working on system specifications. The project's primary goal is fabrication of a EUV imaging instrument that can be placed onboard the Solar Orbiter spacecraft and used to study the Sun's atmosphere. Technical specifications for the imager are very challenging: It should provide EUV images not only with a 10 μm pixel-to-pixel pitch, but also with a rejection ratio of visible radiation of several orders of magnitude. To meet these goals, we and our project partners have agreed on a design that involves an AlGaN-on-silicon active layer on which the 256x256 pixel focal plane array (FPA) is fabricated (see Figures 2 and 3). A flip-chip bonding technique integrates the AlGaN 2D pixel array with the custom-design readout, manufactured in a commercial CMOS technology.

Indium bumps are used as high-density interconnects. These must have good uniformity to ensure reliable connection. Meeting these criteria is tough, because the distance between two adjacent bumps must be less than half-pitch, which equates to 5 μm, and that the height of the bump must be at least 3 μm.

Another challenge is removing the silicon substrate. This is done using an SF_6-based, inductively coupled plasma reactive-ion etching, which is highly selective to the AlN at the interface of the epitaxial layer and the substrate. A submicron membrane of the active material that is supported by an array of indium bumps is left after this

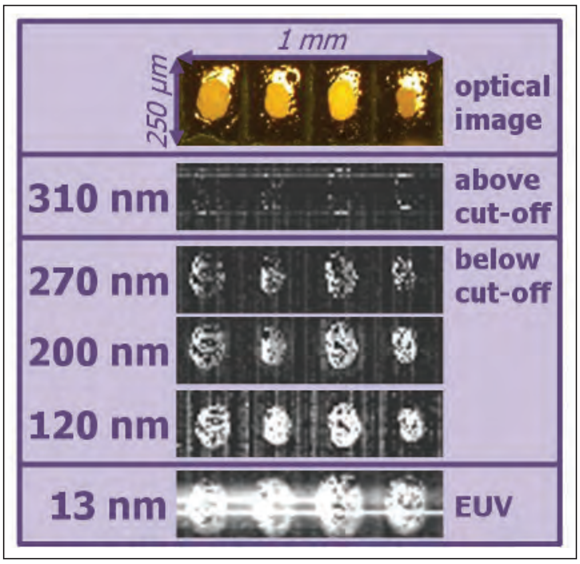


Fig. 4. A 100x25 pixel fragment of the array after integration and substrate removal, showing the AlGaN layer (yellow) exposed to radiation with the silicon substrate frame around (brown). The response pattern under illumination with wavelengths below the cut-off wavelength (280 nm) corresponds to the shape of the substrate opening. Sensitivity down to the wavelength of 13 nm is demonstrated with the synchrotron radiation

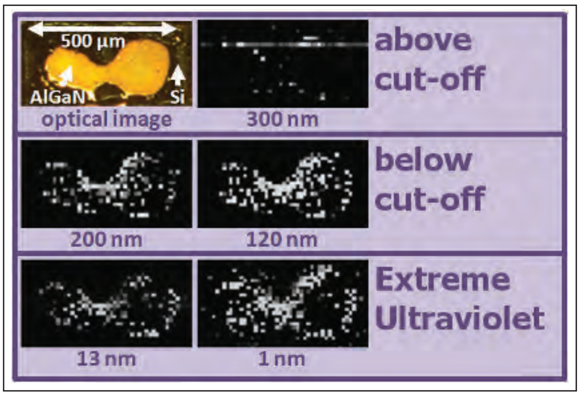


Fig. 5 A 50x25 pixel fragment of the array after integration and substrate removal, showing the AlGaN layer (yellow) exposed to radiation with the silicon substrate frame around (brown). The response pattern under illumination with wavelengths below the cut-off wavelength (280 nm) corresponds to the shape of the substrate opening. Sensitivity down to the wavelength of 1 nm is demonstrated with the synchrotron radiation. At such a low wavelength silicon becomes transparent, which is visible as more pixels are activated at the edges of the opening, where the Si substrate is thinner

step has been completed. There are several critical requirements for this AlGaN layer: It must be thin enough for optimum performance in the EUV range, where the penetration depth is very small; it must be completely free from cracks; and it must contain as few defects as possible, to minimize the recombination losses after carrier generation. To avoid curling of the AlGaN layer due to relaxation and the resulting debonding of the detector chip, a 1-mm-wide frame of silicon is left around the active area, which is supported by an array of dummy interconnects (see the shape of the silicon substrate in Fig. 2). Integrated chips are then encapsulated in a package, wire-bonded and characterized in any facility equipped with the EUV radiation source.

Spanning the UV

Relatively simple systems can be used to perform measurements under ultraviolet illumination – commercially available lamps in combination with filter wheels or with a monochromator serve the purpose perfectly. However, characterization below 200 nm requires a much more complicated, vacuum configuration, because high-energy radiation is strongly absorbed in air.

Our imagers were characterized with the radiation from a synchrotron located at PTB/BESSY II in Berlin, Germany. Using a dedicated readout system with vacuum feedthroughs, the imagers were placed in the beamline and measured after aligning the beam to the active area of the detector chip. Images from a 100x25 pixels region were analyzed as a representative part of the 256x256 array (see figures 4 and 5). Both these samples had a silicon substrate grid patterned on top of the entire AlGaN active layer, apart from the 1-mm-wide frame around it. Thanks to this approach, it is possible to have a fixed pattern in the image and to explore different post-processing schemes.

Samples had a cut-off wavelength of 280 nm, due to the deployment of an $Al_{0.4}Ga_{0.6}N$ active layer. At longer wavelengths no response was registered, and at lower wavelengths the pixels produced a response corresponding to the area in the substrate opening. Since the substrate is not transparent, it acts as a shadow mask, allowing better distinction of the photogenerated signal. Reducing the wavelength even further, it's possible to obtain images at the Lyman-α line (121.6 nm) and in the EUV range – the target spectral span for our device.

Excitation of our devices with radiation as short as 13 nm produces a response, which is very promising for applications in the EUV lithography. It is worth noting that at this excitation wavelength more pixels at the edge of the opening show response. This is because at the edge the silicon substrate is thin enough to allow penetration of the high-energy photons. Even though not all the pixels in these examples are operational, this experimental data provides a proof-of-concept for this imager: It is possible to demonstrate a solar-blind response in a two-dimensional array with 10 μm pixel-to-pixel pitch.

Process investigation and optimization is ongoing, and the next goals are to obtain a uniform response and good fabrication repeatability. The results from the first batches of demonstrators reveal many possible improvements. Concerning applications, these AlGaN imagers promise to serve many areas outside the original EUV solar observation. Not only could they have an impact in EUV lithography; they may also serve other scientific applications requiring long-term stability and intrinsic blindness to visible and infrared light.

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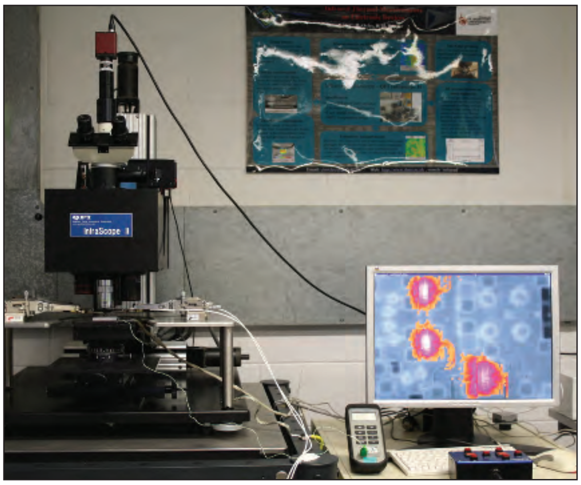
Probe propels IR thermal microscopy to a new level

Adding a tiny probe to an IR microscope improves its temperature measurement capability, in turn giving new insights into the local heating profile of HEMTs and LEDs, according to a UK team comprising **Chris Oxley, Richard Hopper, Dominic Prime, Mark Leaper and Gwynne Evans from De Montfort University and Andrew Levick from the National Physical Laboratory.**

Devices are being driven at higher and higher power densities. Cranking up the current in LEDs increases their brightness, making them suitable for deployment in car headlights, projectors and general illumination. Meanwhile, the emergence of RF transistors made from GaN rather than GaAs has increased the W/mm^2 figure by an order of magnitude.

Creating these new chips - which can extract far more performance from the same-sized footprint - is helping to drive the compound semiconductor industry forward. Customers incorporating these chips into their products are able to buy fewer of them, making whatever they build not only cheaper to produce, but also simpler, smaller, lighter and potentially more reliable.

It is very rare to enjoy gains without paying a penalty somewhere, and in this case it is the issues relating to a hotter device. Temperatures tend to vary across the chip, creating localised hot spots that are seen as a common cause of device failure. Exposing their location and recording the local temperature offers an important first step on the road to improving the thermal management of the chip and ultimately increasing its reliability. Raman thermography offers one well-developed approach to uncovering local temperatures on a chip. This technique



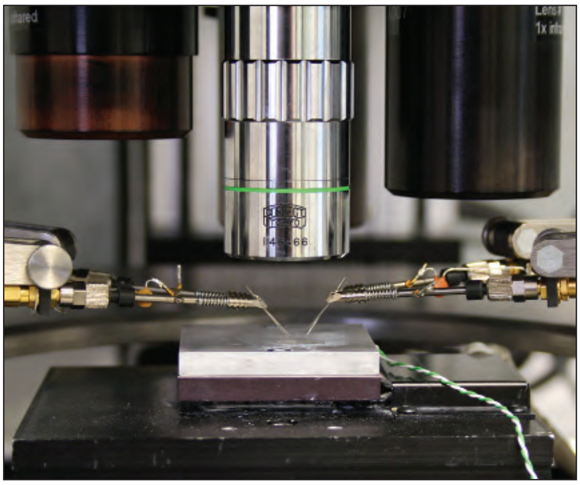


Figure 1: The Quantum Focus IR microscope has a 256 x 256 pixel InSb detector array cooled to 77 K to detect radiation in the 2-5 μm wavelength band. Using a 25x objective the spatial resolution is around 3 μm over a field of view 230 μm x 230 μm. The temperature sensitivity is 0.1 °C and it has a temperature range of 300 °C. The instrument has been provided with the capability of DC and RF probing, enabling electrical bias and electrical measurements to be made during thermal characterisation of the device

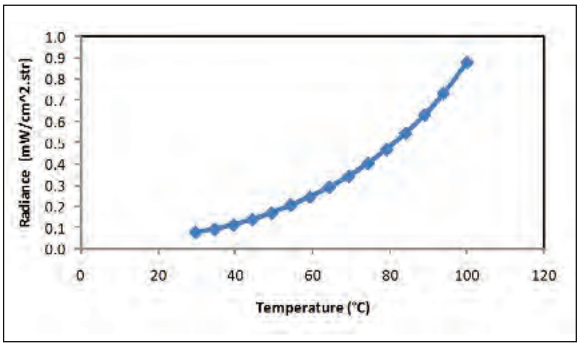


Figure 2: Radiance vs. temperature calibration curve (10 µm diameter micro-particle)

can extract material temperature from the shifts in the wavelength of monochromatic light interacting with crystal vibrations. The great strength of this technique is its high spatial resolution – sub-micron (~500 nm) measurements are possible. However, building-up a temperature profile of the device demands raster scanning of the monochromatic source, a laser spot, across the chip's semiconductor surface.

Obtaining a good temperature map takes a long time, because Raman signals are notoriously weak. Individual measurements require several seconds or more, and mapping out the temperature of an entire device can be impractical. Further, if temperature profiles are required across gold contact and semiconductor areas, then measurements have to be made from the back surface of the device.

While faster measurements are possible by turning to infrared (IR) microscopy, the technique has two major drawbacks: inferior spatial resolution and greater uncertainty in the local temperature. Like Raman thermography, diffraction defines the fundamental limit of the spatial resolution. However, while Raman thermography often uses excitation from a 532 nm argon ion laser or 632 nm HeNe laser, IR emissions are passive and the microscope collects radiation typically spanning the 2-5 µm range.

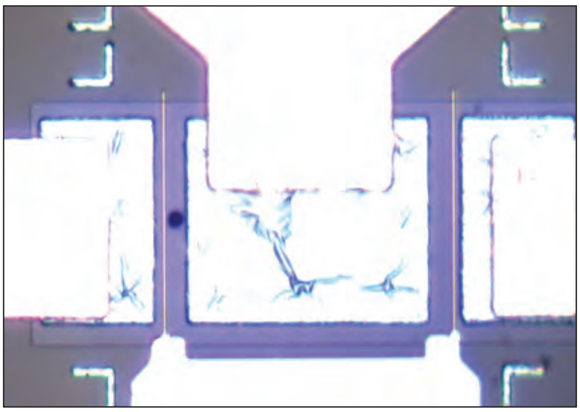


Figure 3: Imaging showing the position of the micro-particle sensor on the HEMT

Emissivity issues

This inherent weakness, a diffraction-limited spatial resolution, is impossible to address. However, there are steps that can be taken to tackle the other drawback of IR microscopy - poor accuracy of temperature measurements. This problem stems from uncertainties associated with the emissivity of the local surface (emissivity is a measure of how efficient the surface is at emitting radiation, and is highest for a perfect blackbody).

The conventional approach for catering for variations in emissivity begins by placing the device on a heated stage under the IR microscope objective and bringing it up it to a known temperature, which is measured by a calibrated thermocouple.

An IR microscope collects radiation from different parts of the heated electronic device. By knowing the radiation emitted from a blackbody at the same temperature and over an identical range of wavelengths, it is possible to compute the surface emissivity across the device.

The next step is to power up the device, measure the radiation it emits, and then calculate its temperature profile using known emissivity values. With this approach, hot surface areas can be identified very quickly.

However, the accuracy of these temperature measurements relies on accurately knowing surface emissivity, which can be a challenge. Materials employed in many III-Vs, including nitride devices, have low emissivity, high reflectance and/or high transparency to infrared radiation.

For example, gold, which in many instances is used for contacts and interconnections, has an incredibly low emissivity (it is about 2 percent of that of a blackbody) and strongly reflects background radiation, which interferes with the surface emissivity measurement. The upshot is an 'apparent' higher measured surface emissivity.

Another issue is that semiconductor materials have different degrees of transparency to IR radiation. This means that radiation is not just collected from the front surface – it can also come from material interfaces and the back surface. The type of bond (eutectic, epoxy etc) to the package tends to govern the intensity of radiation stemming from the back surface.

The interfering IR radiation from these sub-layers also gives rise to an apparently higher surface emissivity, leading to subsequent temperature calculations that are lower than the actual temperature.

Traditionally, this problem is addressed by coating the device with a high emissivity coating, but this can visually obscure the device and cause heat spreading. In addition, spatial temperature resolution suffers, and there is also a greater likelihood of device damage.

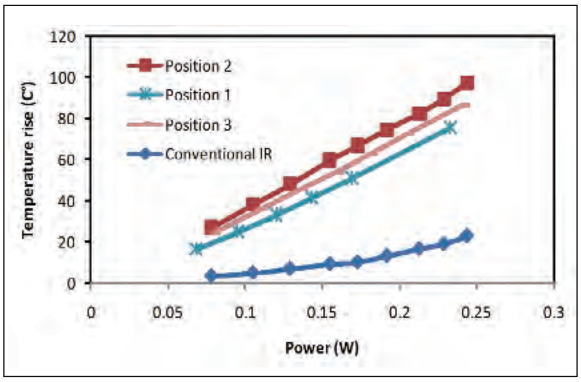


Figure 4: Peak temperature rise in the channel region of an AlGaN/GaN HEMT measured using micro-particle and conventional IR techniques. Conventional IR results were measured at Position 2

A tiny probe

At De Montfort University, which is based in Leicester, UK, we have developed a novel IR micro-particle sensor technology that overcomes the problems of performing IR temperature measurements on low emissivity and highly transparent materials. The IR micro-particle carbon-based sensor, which has a high and known emissivity, is placed in isothermal contact with the surface of the device. The IR radiation emitted by the micro-particle sensor is collected by the microscope (Figure 1) and used to obtain a more accurate indication of the surface temperature, which is now independent of the material properties of the device under test.

The micro-particle sensor heats up very rapidly, enabling temperature measurements to be made without resorting to lengthy acquisition times. Three-dimensional thermal calculations indicate that the thermal time constant for a 3 µm-diameter micro-particle sensor is in the microsecond region, which is three orders of magnitude less than the millisecond sampling rate of the IR microscope. The size of the micro-particle has very little impact on the level of emitted radiation density, so long as its diameter exceeds approximately 8 µm. If the particle is smaller, the radiation level is lower – it is 25 percent less when the particle's diameter is 3 µm. This fall in intensity probably stems from the combination of the onset of the diffraction limit of the microscope and quantum-like effects within the micro-particle.

We have directly calibrated our micro-particle sensor by measuring its emission over a range of temperatures (Figure 2 shows a typical calibration curve for a 10 µm diameter IR micro-particle sensor). The micro-particle sensor can be viewed as a "pseudo contact-less thermal probe" that can be moved in essence by controlled steps across the front-face of a device (metal and semiconductor areas) to build up its surface temperature profile. The device being measured remains in a circuit/package configuration required for the application.

The method is complementary to Raman thermography, as temperature measurements can be extended across metal regions. We have found that the peak surface temperature measurements on a TLM AlGaN/GaN heterostructure agreed well with Raman measurements made on the same device under similar conditions.

Our IR microscope with a micro-particle probe has mapped the temperature profile of various devices. This includes the channel region of an AlGaN/GaN HEMT (see Figure 3), which was biased with a drain-source voltage of 10 V and a gate-source voltage ranging from 0 to –5 V. The results obtained by this method have been compared with those produced by conventional IR temperature measurements (see Figure 4).

The technique shows the potential of being able to map the surface temperature inside the 5 µm channel region without having to coat the device with a high emissivity coating. The problems in uniformly coating such a small channel will be huge, with non-uniformity giving rise to anomalous temperature measurements. To make matters worse, the coating may substantially change performance of the transistor. Further, the micro-sensor can be removed whereas the coating cannot.

Another class of device we have studied is a white-emitting, AlGaN phosphor LED. This device produces strong optical emission in the 0.4 - 0.8 µm spectral range, and a very weak output in the 2 - 5 µm IR waveband. Conventional IR is unsuited to this type of measurement, because the phosphor material is semi-transparent to IR radiation. Turning to our 'micro-particle' sensor approach (see Figure 5) sidesteps this issue, providing a direct measurement of the LED's surface temperature (see Figure 6).

Our approach measurement offers the feasibility of thermal mapping the front-face of the LED, as the measured emission in the 2 to 5 µm waveband will be maximised by the high emissivity 'micro-particle' sensor. Also, we believe this radiation will be focused by our

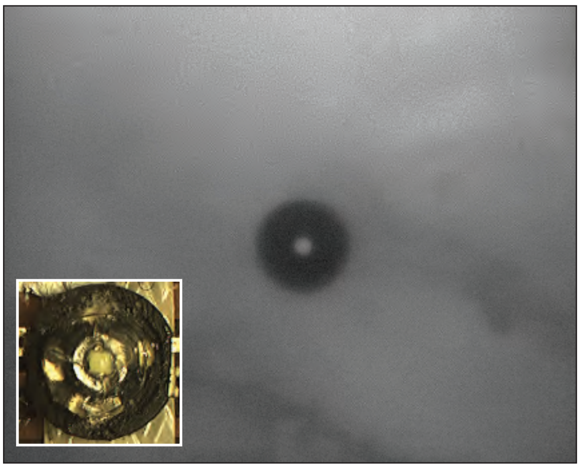


Figure 5: Micro-particle placed on the junction area of the diode(Inset) Optical image of the diode, the lens has been removed for access to the diode.

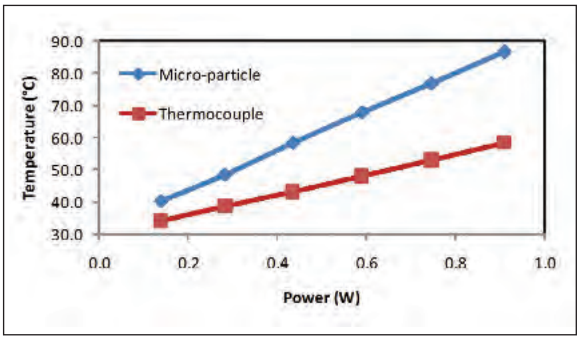


Figure 6 The temperature of the junction was monitored with increasing DC power to the diode and compared with a reading from miniature (50 µm diameter) thermocouple bonded onto the package next to the diode

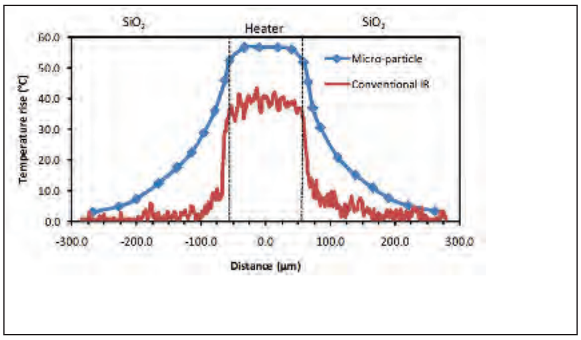


Figure 7: Comparison between micro-particle and conventional IR measurement on a MEMS device

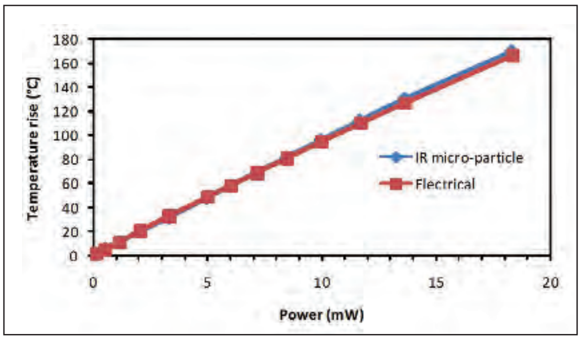


Figure 8: Comparison between micro-particle at a single point and electrical measurement on a MEMS device

microscope and any radiation in the 2 to 5 µm band emitted by the LED will be seen as weak, out-of-focus background radiation. Thermal mapping of the front-face of the LED will provide an improved measurement of the maximum junction temperature and will assist in identifying hotspots and therefore potential failure points.

Our tool also outperforms the conventional IR microscope in delivering a more accurate temperature profile of a MEMS micro-heater. While conventional IR measurements mistakenly record lower temperatures on both the gold metal heater and the optically transparent silicon dioxide layer, our technique offers a more realistic thermal profile, with an exponential fall-off in temperature recorded from the heater element to the cooler region of the device.

Validation of the measurement (Figure 7) was carried out by knowing the thermal coefficient of the resistor heater. This enabled plotting the average temperature of the heater and comparing this with the micro-particle sensor measurement (Figure 8) at a single point on the heater and over a range of DC input powers. These measurements have enabled us to make more accurate thermal maps of the sensor region of MEMS devices used as high performance gas sensors.

The metal surface and delicate nature of the heated membrane precludes Raman thermography and thermal probing using a miniature thermocouple. We have made similar measurements to assist in the optimisation of thermal heaters used in electron microscopy.
We believe this work will pioneer the way forward in the development of pseudo-contactless micro-sensors which can be positioned and used to scan across the surface of a structure to enable 2D temperature mapping. The sensors described are already much smaller than miniature thermocouples, which inherit the thermal mass of external connections to measurement equipment and the problems of attachment to the device. The essence of the technique may enable the development of moveable nano-scale thermal sensors to temperature probe the coming generations of nano-scale devices.

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Further reading

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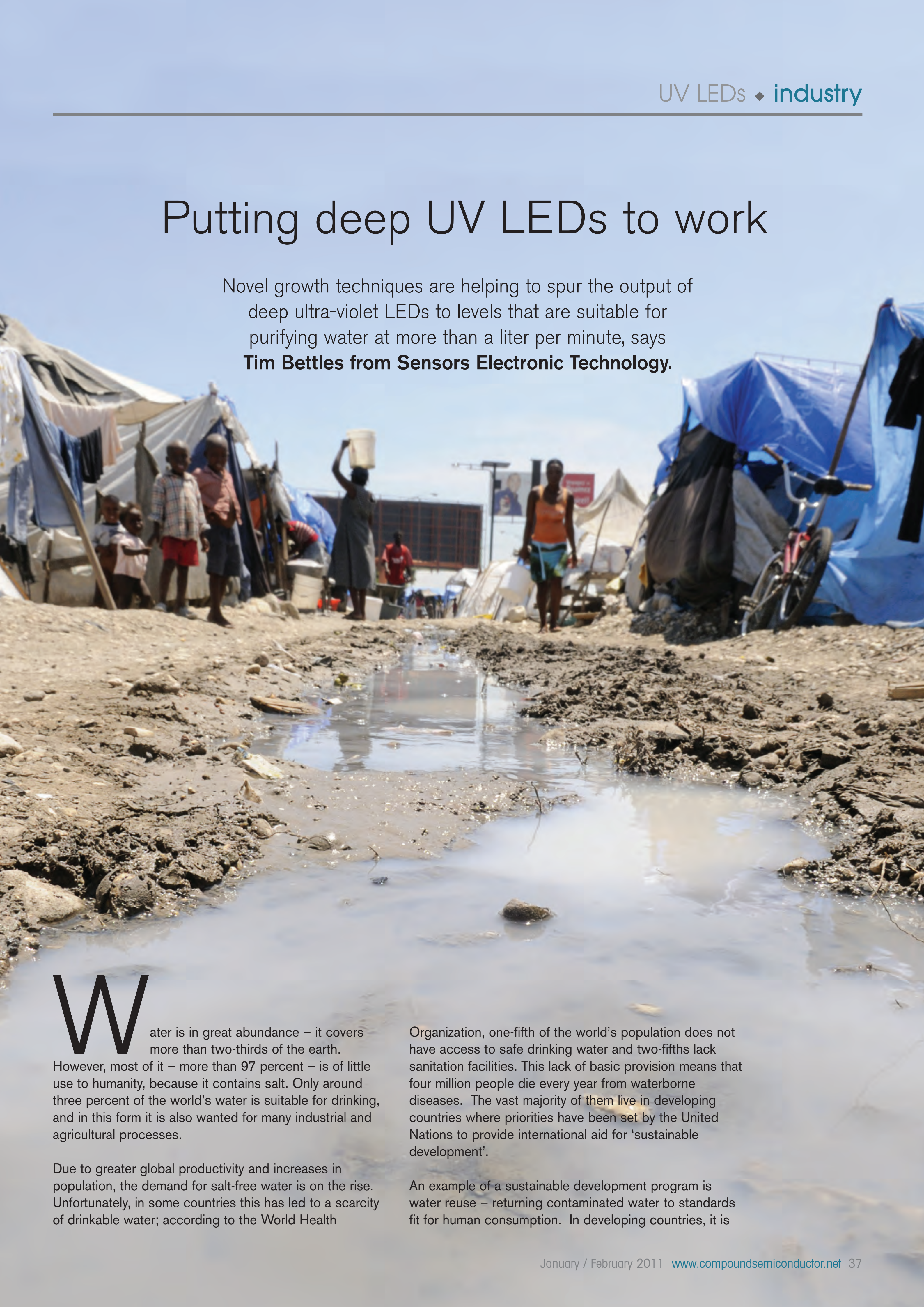
Putting deep UV LEDs to work

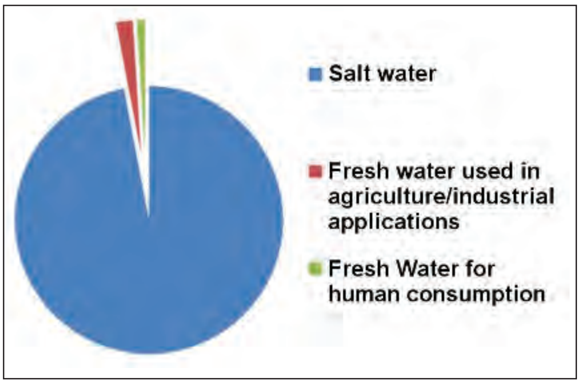
Novel growth techniques are helping to spur the output of deep ultra-violet LEDs to levels that are suitable for purifying water at more than a liter per minute, says **Tim Bettles from Sensors Electronic Technology.**



Water is in great abundance – it covers more than two-thirds of the earth. However, most of it – more than 97 percent – is of little use to humanity, because it contains salt. Only around three percent of the world's water is suitable for drinking, and in this form it is also wanted for many industrial and agricultural processes.

Due to greater global productivity and increases in population, the demand for salt-free water is on the rise. Unfortunately, in some countries this has led to a scarcity of drinkable water; according to the World Health Organization, one-fifth of the world's population does not have access to safe drinking water and two-fifths lack sanitation facilities. This lack of basic provision means that four million people die every year from waterborne diseases. The vast majority of them live in developing countries where priorities have been set by the United Nations to provide international aid for 'sustainable development'.

An example of a sustainable development program is water reuse – returning contaminated water to standards fit for human consumption. In developing countries, it is



A very small proportion of the world's water is suitable for drinking

estimated the two out of every three people do not have access to toilets or latrines and over 90 percent of wastewater is discharged back into the water system without any treatment. This practice spreads fatal, water-related diseases such as cholera, hepatitis, dengue fever and other parasitic diseases that can be attributed to many of the four million deaths and many more disabilities. Reducing these deaths by producing potable water from contaminated water is not cheap: Today a typical small community treatment system costs upwards of $5 million. So a dire need exists for a low cost-of-operation, easy-to-use, sustainable water-cleaning system.

One of the most effective methods for treating unsafe water is UV disinfection. As a physical, chemical-free disinfection process, it has much to recommend it: It is easy to use, with no danger of over dosing; unlike chemical disinfection, it requires very little contact time; it does not require storage of hazardous materials; there are no toxic by-products; and the process itself has little or no environmental impact (although the mercury based UV lamps do need to be disposed of frequently).

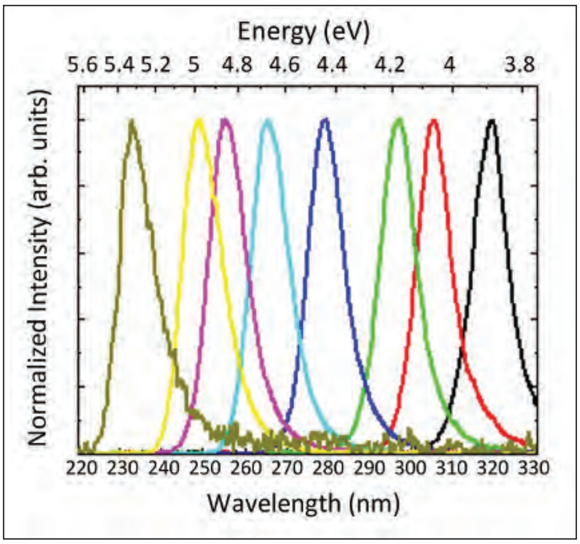


Figure 1. Normalized room-temperature electro-luminescence (EL) spectra of DUV LEDs with peak emissions at 235 nm, 250 nm, 255 nm, 265 nm, 280 nm, 295 nm, 305 nm and 320 nm

Using UV light to disinfect drinking water is well established. It's an approach that has been used for nearly one hundred years, and is recognized by many organizations around the world including the US Environmental Protection Agency (EPA). Wavelengthsranging from 240 nm to 280 nm can attack the DNA of micro-organisms, destroying their genetic information and preventing their reproductive capability. Without the ability to reproduce, these micro-organisms are rendered harmless when consumed by humans.

The major drawback of current UV systems is associated with their mercury lamps. These are bulky, fragile, require regular maintenance, have limited lifetime and present a disposal issue.

Recent developments in III-Nitride wide bandgap semiconductor technology demonstrate promising results to overcome these shortages of conventional UV light sources. A very attractive alternative is the AlGaN-based LED, which has peak emission wavelength shorter than 365 nm. These deep UV LEDs, or DUV LEDs, promise to enable the production of UV disinfection systems that will equip families and individuals with water purification systems that can provide a sustainable source of safe drinking water.

The UV spectrum can be sub-divided into four ranges: UV-A (320 nm – 400 nm); UV-B (290 nm – 320 nm); UV-C (200 nm – 290 nm); and vacuum UV (40 nm – 200 nm). The very longest of these wavelengths can be reached with active regions that pair GaN with InGaN, but for wavelengths of 365 nm or below, a combination of AlGaN and GaN must be employed.

At Sensor Electronic Technology, Inc. (SET), a company based in Columbia, SC, we have been pioneering the development of these UV sources. Thanks to these efforts, we were the first company to the market with a product line spanning the spectral range 240 - 355 nm (see Figure 1).

DUV LEDs are far more difficult to make than their blue and white cousins, due to issues related to strain, doping, efficiency and polarization (see "Six barriers to making UV LEDs", p.40). To overcome these challenges, we have developed two new epitaxial growth techniques: migration enhanced (ME) MOCVD and migration enhanced lateral epitaxial overgrowth (MELEO). These deposition technologies can decrease dislocation densities by orders of magnitude, which in turn enables the growth of thick, high-quality AlGaN, AlInGaN, AlInN and AlN epitaxial layers (see Figure 2). Better quality materials also offer additional benefits: a longer carrier non-radiative recombination lifetime, (see Figure2 (a)), higher efficiency and better device reliability. And further improvements in device performance are possible by employing superlattice buffers to reduce strain (see Figure 2(b)), alongside phonon band engineering approaches to negate the negative effects of the polarization fields and realize very high internal quantum efficiency.

Capturing electrons

We have also developed new quantum well configurations for deep UV LEDs that incorporate very narrow quantum wells within an wider 'energy tub'. In the example shown in figure 2(d), the bandstructure is engineered so that the difference in the energy of an electron when it enters the energy tub and when it is at the top of the quantum wells is equal to or greater than the energy of a polar optical phonon in the device material. Electrons emitting this form of phonon cool down much faster on entering the energy tub, and the chances of the carriers remaining there are high, due to the difference in composition on the p-type side of the LED. Now localized in the well, the electrons are more likely to recombine with holes to emit light.

Our efforts at refining band structure, growth methodologies and device processes have culminated in the fabrication of DUV LEDs with CW output powers in the milliwatts range and pulsed powers over 100 mW (see Figure 3). Lifetimes now exceed 5,000 hours for many DUV LED wavelengths for devices run continuously at 20 mA at room temperature without any heat sinking.

Recently, DUV LEDs have also passed space qualification – so far they have demonstrated over 26,000 hours of pulsed operation with no significant power drop or spectral shift. The qualification process was performed at Stanford University and National Security Technologies (NSTec) on our 255 nm UVTOP LEDs, with tests involving extreme radiation hardness, temperature cycling and 14g rms random mechanical vibrations.

For water disinfection applications, CW powers of tens of milliwatts or more are required. To meet this demand, we have developed and launched multi-chip LED lamps and products with powers over 100 mW at 275 nm; each

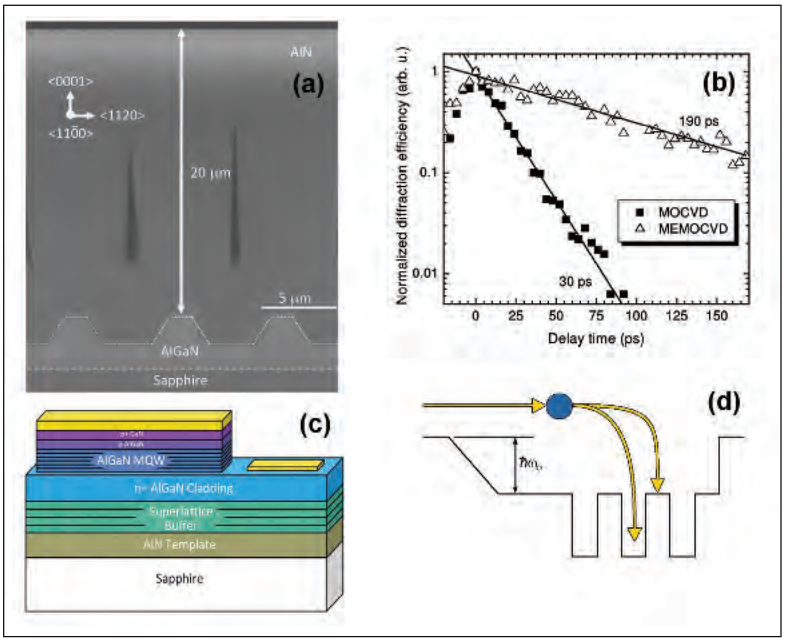


Figure 2 (a) SEM micrographs of a fully coalesced 20 μm thick AlN sample grown by MELEO (b) Light-induced transient grating (LITG) decay in MOCVD and MEMOCVD-grown AlGaN epilayers for the grating period of 7.7 μm. Carrier lifetimes were estimated by fitting the decay transients with single exponents (lines) (c) Typical deep UV LED design (d) Schematic band diagram of DUV LED for capturing electrons in the light emitting region

lamp containing as many as 100 single chips. In the same manner, DUV LEDs having different emission wavelengths are often combined together in one package to create broadband UV LEDs and multi-wavelength LEDs. Multi-wavelength DUV LEDs have up to 26 individually addressable wavelengths and can be directly coupled to an optical fiber, enabling spectroscopic and fluorometer applications.

Efforts at producing high-power single-chip LEDs are underway. Powers of 100 mW at an emission wavelength of 275 nm have been demonstrated on a 1.5 mm x 1.5 mm chip with an active area of 1 mm^2 packaged in a TO-3 metal can.

Our efforts at refining band structure, growth methodologies and device processes have culminated in the fabrication of DUV LEDs with CW output powers in the milliwatts range and pulsed powers hitting 100 mW

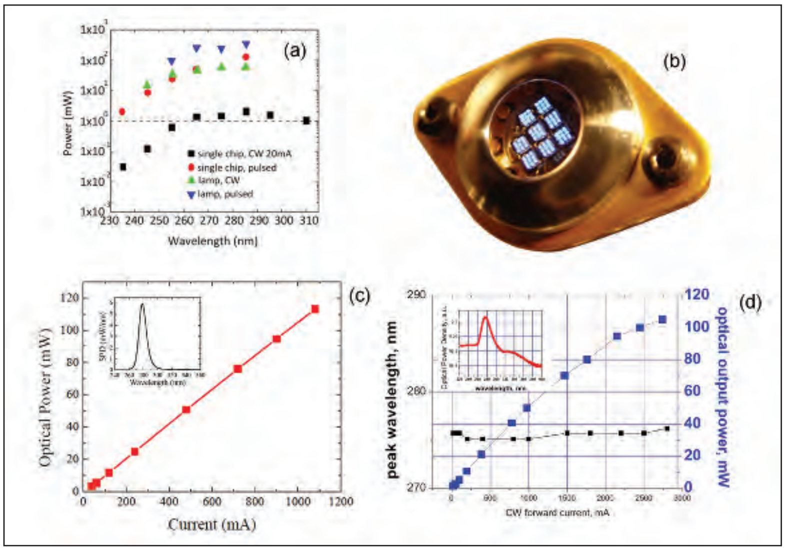


Figure 3 (a) optical power of single-chip DUV LEDs and DUV LED lamps for CW and pulsed modes (b) UVClean high power LED lamp from SET (c) SET's UVClean multi-chip lamp with over 100 mW of CW optical power at 275 nm at room temperature (d) SET's large-area single-chip LED with over 100 mW CW optical output power at 275 nm

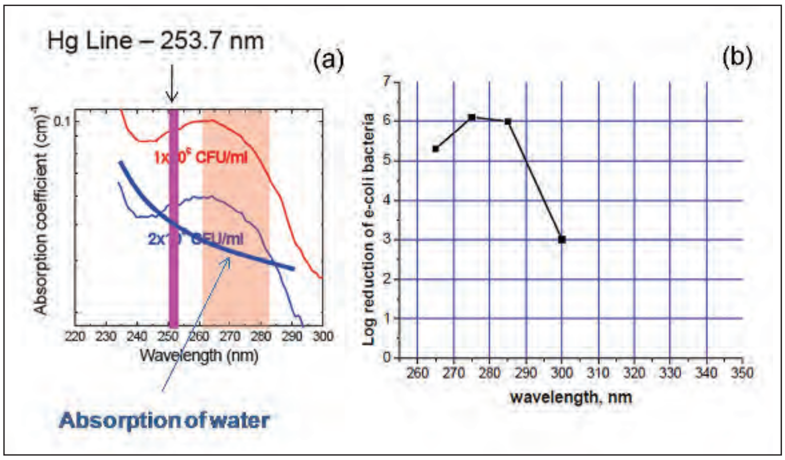


Figure 4 (a) Water shifts the most effective wavelength for water treatement (b) Optimim wavelength for disinfection of potable water has been demonstrated to be 275 nm

Six challenges to making UV LEDs

There are many challenges to overcome when fabricating UV LEDs. Six of the key ones are:

- Managing the strain to enable growth of crack-free, thick, doped AlGaN epitaxial layers. Strain is much higher in DUV LEDs than in their visible counterparts due to larger lattice mismatch between AlN/AlGaN and sapphire.
- Realizing n-type doping in AlGaN with high aluminum composition. AlGaN with more than 50 percent aluminum is required for fabrication of sub-300 nm DUV LEDs. Due to a larger donor activation energy in higher aluminum-content AlGaN, room-temperature electron concentration decreases and sheet resistance increases, leading to severe current crowding effects in the devices.
- Reducing concentration of non-radiative recombination centers in AlGaN that are responsible for low internal quantum efficiency.
- Catering for the strong polarization effects in the AlGaN-based quantum well active region of DUV LEDs. Fields resulting from polarization can pull apart injected electrons and holes, ultimately reducing the radiative recombination rate.
- Realizing a sufficiently high p-type doping of the AlGaN electron blocking or cladding layers, which is much more difficult than it is in p-GaN. Low p-doping efficiency of AlGaN is the main reason for high forward voltages and poor p-contact. Switching to lower aluminum content p-AlGaN or even a p-GaN contact layer is not necessarily beneficial, because it reduces light extraction due to strong UV light absorption in the p-contact layer.
- Obtaining reasonable light extraction efficiencies. In DUV LEDs, extraction efficiencies tend to be lower than those in InGaN-based devices, due in the main to a combination of strong absorption in p-contact layers and larger internal reflection at the AlN/sapphire interface.

The Department of Defense has a significant interest in DUV LEDs to detect and identify biological and chemical agents that may be in use by enemy forces. Current detect methods require large, heavy equipment and a great deal of power. To address these deficiencies, DARPA's (Defense Advanced Research Projects Agency) CMUVT program is targeting high performance UV semiconductor devices; 100mW LEDs operating at 250 – 275 nm with 20 percent wall-plug efficiency and 10 mW, 220 – 250 nm laser diodes. Today DUV LEDs address markets such as life sciences and scientific analysis where they are ideally suited for fluorescence and fluorescence lifetime measurements. The characteristics of DUV LEDs, including wavelength selection between 240 nm and 355 nm, switching speeds in the range of a few nanoseconds, small physical size with high power density and simplified optics and electronics present very large benefits over traditional UV light sources in the same wavelength range. This set of desirable characteristics has driven adoption of LEDs in systems for medical analysis, gas detection and monitoring and medical disinfection. However, with recent advancements in high-power LED lamp technology and the development of high-power, single-chip LEDs, development activity in many household applications has significantly increased. The resulting UV components from the DARPA CMUVT program will not only significantly improve size, weight, power and capability of chemical/biological-agent detectors, but will also allow the current development of consumer type systems to be realized in high volume markets.

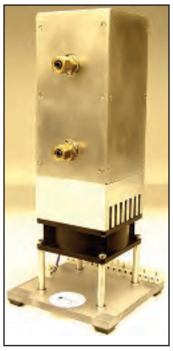
Believed to be the largest market opportunity for UV LEDs, development has begun on LED-based point-of-use (POU) in-line water systems under NSF SBIR support. POU systems are designed to clean water on-demand in a small scale where it is to be (kitchen faucet, refrigerator dispenser, etc) rather than in a large centralized location. With fast turn on/off speeds, small footprint, low voltage operation and the ability to operate in cold environments, LEDs offer many advantages in this application space over traditional mercury lamps. However, mercury vapor fluorescent lamp technology is well established and for markets where size, turn on/off speeds and power requirements are not issues, it is unlikely that LEDs will replace this technology until later in their product life cycle. Instead, DUV LEDs will open new market opportunities that cannot be addressed with mercury lamps.

Previously HydroPhoton demonstrated UV LEDs in a portable on-demand water purifier which reduced the level of E-coli. by 99.99 percent in water flowing at a rate of 150 ml per minute. ("Brighter LEDs improve water purification rates", *Compound Semiconductor*, Nov 14, 2005)Thanks to the support of the National Science Foundation (NSF), this work has been continued recently with high power DUV LEDs used to disinfect higher water flows. Traditional UV disinfection systems use far shorter 253.7 nm light, as this is the wavelength attainable using mercury lamps. However, it is widely known in the field that 265 nm is the peak wavelength of absorption of DNA, and practical analysis has shown that 275 nm is the most effective wavelength for eradicating pathogens such as E-coli. in water (see Figure 4). This wavelength shift is due to the absorption of water, which increases as the wavelength becomes shorter.

DUV LED water disinfection systems employing 275 nm sources have been produced. The systems, which feature our 275 nm DUV LED lamps, have been tested for E-coli. and MS2 disinfection at flow rates of 0.5 to 2 liters per minute. The water purification chamber, 3-inches in diameter and 6-inches long, was tested with 34 mW of DUV LED optical power (<4.5 W of electrical power). E-coli. was now reduced by 99.99 percent in water flowing at a rate of more than 1 liter per minute. These results are encouraging, and further gains in this direction in DUV LED performance and water disinfection chamber designs will soon open up new market opportunities in point of use applications that can benefit from LED advantages.

Applications for Deep UV LEDs

- Protein Analysis
- Medical Diagnostics
- Drug Discovery
- End Point Detection
- Blood Gas Analysis
- Petro-Chemical Analysis
- Gas Detection
- Bio-Threat Detection
- Phototherapy
- UV Curing
- Water Disinfection
- Air Disinfection
- Surface Disinfection



SET's UVClean LED-based water purification chamber

Internal gratings create powerful, spectrally pure lasers with high efficiencies

The combination of reliable output powers of 7W, peak power conversion efficiencies in excess of 60 percent and spectral widths below 1nm can be realized by incorporating integrating distributed feedback gratings into broad-area lasers, says **Paul Crump from the Ferdinand Braun Institut, Germany.**

High-power diode lasers are increasingly important sources for direct use in many industrial applications, such as cutting and welding. In direct application systems, the output from many diode lasers is optically combined into a single high brightness source, typically coupled into an optical fibre and directly delivered to the work surface – as illustrated in figure 1.

Today direct diode technology is a promising alternative to solid-state and fibre-laser systems for many industrial applications. Its performance is limited predominantly by the semiconductor lasers themselves, which operate with over 60 percent power conversion efficiency.

Further order-of-magnitude class improvements in the fibre-coupled power-density are possible via spectral multiplexing – a technique that combines multiple diode laser modules using spectrally selective optics. However, the practical maximum number of useable, combinable wavelengths is limited by the performance of the diode lasers. These typically have 95 percent of the power content ($\Delta\lambda$(95%)) spread over a spectral width of 5 nm, and exhibit a wavelength shift with temperature of 0.4 nm/K in 960-980 nm range. However, if smaller values for $\Delta\lambda$(95%) and better temperature stability could be realised, this would pave the way to introducing more wavelengths into direct diode systems, thereby increasing their brightness. Diode lasers are also important commercially as pump sources for solid state and fibre lasers. These systems will also benefit from a smaller value of $\Delta\lambda$(95%) and a reduced wavelength shift with temperature: specific absorption lines could be targeted for higher performance (97x-nm in Yb:YAG for high absorption, or 88x-nm in Nd:YAG for higher efficiency). Additionally, efficient high-power pump lasers with narrow stable line widths could also meet the needs of new technologies, such as diode-pumped alkali vapour lasers.

There are many techniques that can be used to narrow and stabilise the emission spectrum of high power diode lasers. Adding external optical elements is one option, and it is also possible to introduce internal gratings within the

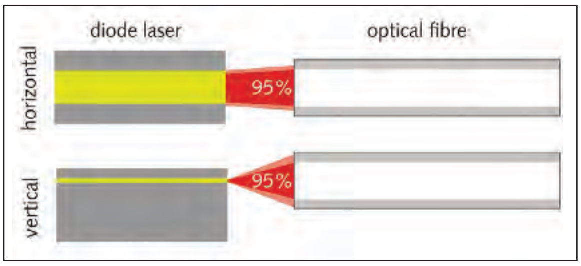


Fig 1: Fiber coupled diode lasers (left) are the enabling technology for many of today's state of the art, high-efficiency industrial laser systems (right). High-efficiency diode lasers with narrow, stable spectral lines are needed for further improvements in the brightness of such systems. Credit: FBH/Immerz, TRUMPF

semiconductor diode laser. Whichever route is chosen will only lead to commercial success if it does not compromise power, power conversion efficiency and lifetime. Any changes must also maintain a sufficiently small far field emission angle: This is essential for realising low-cost, high-yield fibre coupling. Specifically, what is needed is a divergence angle of less than 50° for 95 percent of the power content of the laser.

Maintaining device efficiency while decreasing spectral width is not easy. State-of-the-art high-power, broad-area diode lasers emitting in the 900-1000 nm range can deliver CW output powers of 10 W at conversion efficiencies of over 65 percent, but fall to efficiencies of around 50 percent when internal gratings are added.

Our team at the Ferdinand Braun Institut (FBH), which is located in Berlin, Germany, has overcome this loss in performance with the addition of a grating that enables the fabrication of high-power lasers with 60 power conversion efficiency. Several technologies can be used to make high-power, broad-area diode lasers with internal gratings, and we adopt a two-stage epitaxy approach with the growth process halted part way through so that a grating can be patterned uniformly over the wafer using holographic techniques to deliver distributed feedback (DFB). The remaining portion of the vertical structure is then grown over the patterned surface.

realising this high-performance from our DFB broad-area lasers is the result of extensive development. Efforts have focused on edge-emitting single-emitter diode lasers with a 90 µm stripe width operating at 970 nm, grown using MOCVD on GaAs substrates (see Figure 2).

Accommodating aluminum

High efficiencies are only possible with high-performance laser architectures that accommodate a grating layer while complying with the constraints associated with making and designing this class of device. AlGaAs layers are often used in part of the vertical structure of high-performance lasers. However, integrated overgrown gratings must be patterned outside of the growth reactor, leading to oxidation of the aluminum, which generates defects.

We overcame this problem by turning to aluminum-free grating regions. These structured layers must be overgrown, which leads to further defect generation, partly because aluminum concentration varies in the layers grown over a patterned surface. Reducing the aluminum concentration helps, and we have found that $Al_{0.15}Ga_{0.85}As$ layers can minimise the defect density and still prevent carriers leaking from the active region.

Grating-based lasers that are suitable for fibre coupling must also have a small vertical far-field angle. This is realised by employing a relatively thick waveguide that helps to direct 95 percent of the light into a vertical angle below 45°. This 2.1 µm-thick waveguide also provides

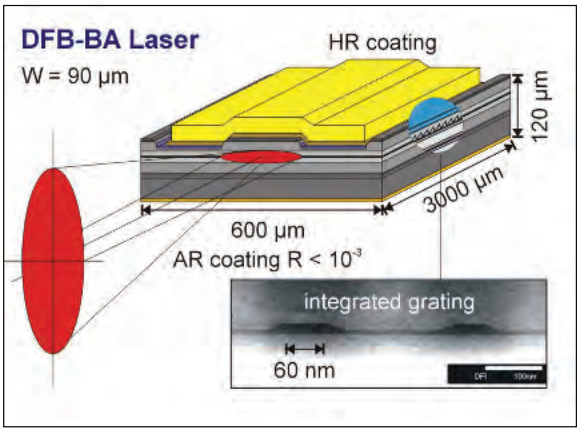


Fig 2: (top) Schematic representation of a DFB, broad-area diode laser produced at the FBH. The inset shows an example TEM cross-section of the grating region. (Above) All devices are mounted junction-down on copper-tungsten submounts for assessment and use in external optical systems. The tips of a pair of tweezers are shown as a size reference.
Credit: FBH, FBH/schurian.com

design flexibility in the later placement of the grating layer, so that the grating strength can be varied as needed. With this approach we have fabricated reference 90 µm stripe single lasers without a grating emitting at 975 nm that deliver a peak power conversion of 65 percent at 10 W output power. This performance, which is suitable for grating integration, was realised despite design limitations and reported at Photonics West 2010.

Overgrown grating layers must combine low loss with high material quality. This was not the case for the earliest AlGaAs-based overgrown gratings in GaAs diode lasers produced in the early 1990s, which introduced optical losses of over $20 cm^{-1}$. The aluminum-free overgrown grating regions in long-term use at the FBH typically have losses of $1 cm^{-1}$, and we have made further improvements in their performance to yield lasers with high-power conversion efficiencies. Gratings can compromise laser performance by increasing operating voltages by 0.2V or more, which impedes realising really high efficiencies. These issues were addressed by minimising the material

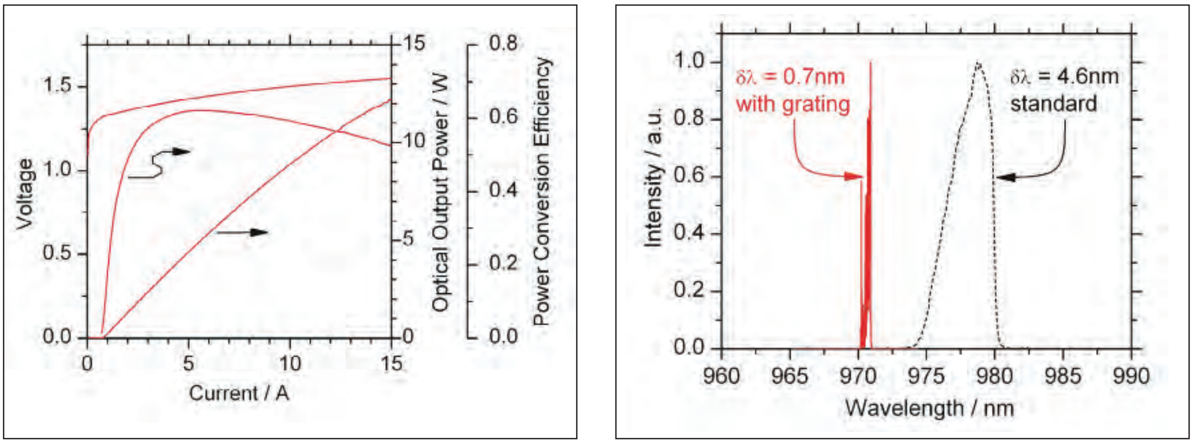


Fig 3: High-power diode lasers with integrated overgrown gratings reach high powers with a peak power efficiency of over 60 percent (left). The spectral width, δλ, at 10 W continuous output power is substantially reduced in comparison to a reference device without internal grating (right). Credit: FBH

perturbation due to the grating, in order to cut defect generation. A very thin aluminum-free grating layer of 10 nm-thick InGaP was used in the new design, located a long distance (0.77 μm) from the active region of the device to ensure a low grating coupling strength (κ ~ 0.5 cm^{1}). Introducing this layer and fine-tuning etch and overgrowth conditions eliminated both excess optical loss and operating voltage – current can now flow without restriction through the p-side grating layer. The deployment of a low strength grating has an additional benefit: Increased slope efficiency. That's because lower-strength gratings provide less feedback, increasing the proportion of light leaving the laser. These factors combine to enable the fabrication of more powerful lasers.

Matching gains and gratings

To optimise laser efficiency, it is also essential to select the best relative location of the material gain and the grating wavelength. The active region generates optical gain, and the grating provides reflection – together they combine to produce lasing. However, the grating wavelength and the lasing wavelength vary very differently with temperature. For every °C change, the grating shifts by 0.08 nm and the gain moves by five times as much.

These differences hamper laser performance. In 7-10 W lasers driven in continuous-wave operation internal current heating raises device temperature by 30°C, preventing gain and grating wavelengths from being in sync over the whole operating range. When the gain is offset from the grating wavelength, light is less strongly amplified, causing the device to operate less efficiently.

In our design, gain and wavelength are selected so that they meet at the operating point of 7W. The downside of this approach is that the laser has a large threshold current, reducing overall power conversion. But if we had designed our device so that the gain and grating matched at the threshold current and the peak efficiency of the device was higher, this would compromise the output power – gain would drop so much at high currents that the device would over-heat. Thanks to all this detailed development work, we have produced diode lasers with an integrated overgrown grating that deliver a peak power conversion efficiency of 62 percent, as reported at Photonics West 2011. This falls by just 4 percent at the operating power of 10W. Spectral width with 95 percent power content at 10 W is 0.7 nm. These efficiencies are slightly lower than those of the grating-free reference device. The overriding reason for this slight reduction in performance is the offset between the grating and the gain wavelength. Reliability tests reveal that these lasers operate failure-free for over 4000 hours (to date) at an output power of 7W at 25°C (see Figure 3).

Although these newly developed, grating-stabilised devices have substantially increased laser efficiency, further gains are necessary. Specifically, the efficiency should be maintained at more than 60 percent at higher output powers. There are two possible pathways to success: improving the performance of the baseline design; or reducing the influence of detuning, for example through improved heatsinking. On top of this, the process must be scaled for high volume manufacture - for larger volumes, 4-inch production will be necessary. However, the breakthrough efficiency achieved in these grating-stabilised, high-power lasers will enable a wide range of new and improved industrial laser systems.

This work was funded within the German Federal Ministry of Education and Research (BMBF) development program, INLAS. For more details see: "Reliable operation of 976 nm high power DFB broad area lasers with over 60 percent power conversion efficiency" Paul Crump *et al.* Paper 7953-50, Photonics West 2011

Novel nitride lasers take the upper hand

KEY PERFORMANCE characteristics of non-polar and semi-polar lasers are now eclipsing those of their conventional cousins.

University of California, Santa Barbara spin-off Soraa is claiming output power and efficiency records for it blue, continuous wave single-mode lasers. What's more, Japanese material specialist Sumitomo has pushed nitride lasers further into the green with a semi-polar laser emitting at 534 nm, and it has also revealed that the threshold current of this type of device is two to three times lower than that of an equivalent one built on the *c*-plane.

James Raring, Soraa's VP of laser engineering, says that the advantages of turning to semi-polar and non-polar planes include a higher gain and a lower effective mass for the holes, attributes that increase design flexibility.

"We believe that this is enabling us to get low threshold currents and high slope efficiencies without catastrophic facet damage," says Raring.

This west coast start-up, which is based in Goleta, California, has produced a 447 nm edge-emitting laser with a 900 µm cavity that delivers an output of more than 800 mW, and a shorter version with a 600 µm cavity that has a peak wall plug efficiency (WPE) of 23.2 percent. In addition, the company has made a 521 nm laser that delivers more than 60 mW and produces a WPE in excess of 1.9 percent.

All the green and blue lasers have been built on undisclosed, non *c*-plane orientations of GaN using conventional semiconductor processing technology for this wide bandgap material. The devices were 1.5-2.5 µm wide and featured a surface ridge laser architecture designed for single lateral mode operation.

Soraa's most powerful blue laser had a threshold current and voltage of 45 mA and 3.8 V. Slope efficiency was 1.55 W/A at a case temperature of 20 °C. The shorter variant had a threshold current and voltage of 30 mA and 3.8 V, a slope efficiency of 1.68 W/A, and a WPE of 23.2 percent at a laser output of 180 mW.

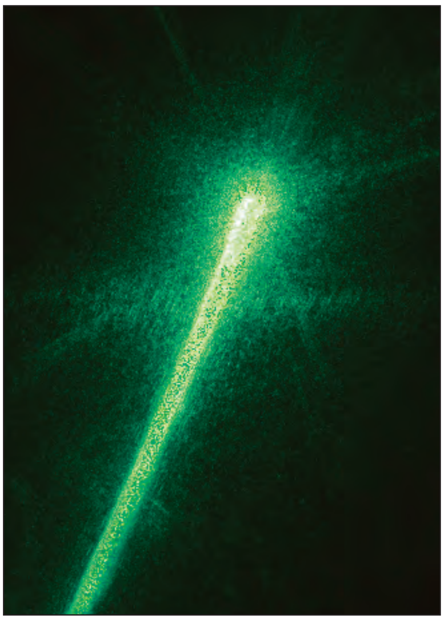
At an output of 100 mW, the efficiency of these laser chips is about 40 percent higher than those reported by Osram Opto Semiconductors at last year's Photonics West meeting. Soraa says that this highlights the attractiveness of non *c*-plane lasers for applications requiring high efficiency, such as next generation displays.

Soraa's latest family of non c-plane lasers include a 521 nm device delivering a 60 mW continuous output

Reliability testing of five blue lasers revealed a mean lifetime of 10,000 hours. These tests involved initially driving lasers at 60 mW and recording the time it took for the output power to fall by 20 percent.

According to Paul Rudy, general manager of Soraa's laser division, the approach that they adopt to evaluate device lifetime is widely used in the high-power laser diode industry that serves biomedical and industrial applications.

"In the display community lots of folks use 30 percent and some folks use 50 percent," says Rudy. "But for the purposes of the paper we thought we'd be conservative."



Green lasers with a 600 µm cavity that are fabricated by the start-up had a threshold voltage and current of 7.3 V and 130 mA, and a slope efficiency of 0.3 W/A.

The 60 mW, CW output of this device compares favorably with the 50 mW output of Osram's 524 nm laser, which the German outfit reported in summer 2010.

Meanwhile, researchers at Sumitomo have been comparing the threshold current of green lasers built on the c-plane and the $(20\bar{2}1)$ plane.

The Japanese outfit produced a series of semi-polar, 600 µm cavity lasers with dielectric coatings on the facets that realized threshold current densities of just 5.4 kA/cm^2, 5.2 kA/cm^2 and 4.3 kA/cm^2 at emission wavelengths of 533.6 nm, 527.2 nm and 525.6 nm, respectively. In comparison, the threshold currents of *c*-plane green nitride lasers recently reported by Nichia and Osram are far higher: 18 kA/cm^2, 9 kA/cm^2 and 3.8 kA/cm^2 at 531.7 nm, 524 nm and 518 nm, respectively. A high threshold current is a major impediment to the production of powerful diode lasers. The standard route to cranking up laser power is to reduce reflectance at the facets, a step that increases threshold current and junction temperature. If the temperature gets too high, it hampers performance and cuts laser lifetime.

Sumitomo's 525.5 nm laser has a threshold voltage of 6.38 V, a slope efficiency of 0.15 W/A and a maximum continuous-wave output of 36.4 mW. The team believes that a higher output is possible through refinements in the growth and fabrication processes used to make the laser, and optimization of its architecture.

Soraa also expects to take the power of its lasers to a new level and improve their efficiency. "This small group is working hard on blue and green," says Rudy. "We still don't think that we've turned all the knobs and optimized everything."

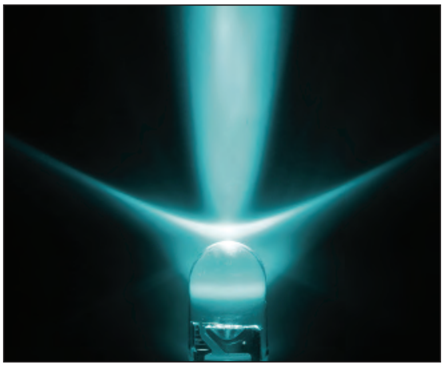
J. Raring *et al*. Appl. Phys. Express **3** 112101 (2010)
M. Adachi *et al*. Appl. Phys. Express **3** 121001 (2010)

Theorists question Auger as the primary cause of LED droop

BAND–TO-BAND Auger recombination does not account for droop, the decline in nitride LED efficiency at increasing drive currents. That's the claim of a team of theorists based in the US and Italy, which is at odds with previous calculations of Chris Van de Walle's group at the University of California, Santa Barbara. Last year these West-coast academics performed first-principles, density-functional electronic structure simulations on GaN and InN, and used these results to determine that Auger recombination was a likely cause of LED droop.

These calculations, like those of the US-Italian team, considered the Auger coefficient for non-radiative processes involving two electrons and one hole at a range of bandgaps.

Van De Walle's team found that the strongest Auger process revolves around resonant electron scattering from the lowest to the second lowest conduction band. This Auger coefficient peaks at 2 x 10^{-30} cm^6 s^{-1} for InGaN with a bandgap of 2.5 eV.
In contrast, perturbation theory calculations by the three-man team from Boston University and the Politecnico di Torino, Italy, indicate that the Auger coefficient for the resonant interband coefficient is far, far lower – less than 10^{-32} cm^6 s^{-1}. And it occurs at a higher energy, 2.8 eV.



In addition, this triumvirate of Francesco Bertazzi, Michele Goano and Enrico Bellotti has calculated the Auger coefficient for processes involving two holes and one electron. This process has no resonance peak, steadily decreases as the bandgap increases, and is less than 10^{-32} cm^6 s^{-1} for an InGaN bandgap greater than 2 eV.
The US-Italian team has tried to fathom why its value for the Auger resonance peak is 0.3 eV higher than that provided by UCSB .

They believe that this discrepancy stems from employing different values for the energies of the lowest and second lowest conduction bands in InGaN. They began by adopting a 'nonlocal empirical pseudopotential method' to calculate the band structure for InN and GaN, an approach that allows parameters to be tweaked so that the electronic structure can replicate the main features obtained by either experiment or first principles calculations. Application of what is described as a modified virtual crystal approximation yielded the electronic structure for the conduction and valence bands in InGaN.

In comparison, the UCSB team first determined the energy difference between the lowest and second lowest conduction bands in InN and GaN, before linearly extrapolating values for InGaN.

The US-Italian team says that the difference between the value of the energy of the resonance peak calculated by them and the UCSB team impacts the calculation of the Auger coefficient. However, its impact is not large enough to account for the three orders of magnitude difference between the two calculations.

According to them, this massive difference could stem from the West coast team's failure to fully account for the symmetry of the electronic states that are involved in the calculation of the Auger recombination strength in InGaN alloys.

F. Bertazzi et al. (2010) Appl. Phys. Lett. **97** 231118

III-V MOSFETs scale successfully

Engineers from The University of Texas at Austin claim to have produced the first $In_{0.7}Ga_{0.3}As$ channel MOSFET with a sub-50 nm gate. Realizing a device on this length scale is a key step towards the development of III-V transistors that are credible alternatives to those produced with state-of-the-art silicon CMOS processes.

The 40 nm gate-length device made by the US team has an impressive set of attributes: a current drive of 507 mA/mm at a gate voltage of 1 V, an intrinsic transconductance of 1475 mS/mm, an on-off ratio of 1 x 10^5, and a sub-threshold swing 132 mV/dec at a source-drain voltage of 50 mV.

The engineers have focused their efforts on a buried channel device. This is claimed to be better at maintaining high mobility than surface channel equivalents, thanks to the separation of the channel from the oxide/III-V interface. According to the team, this class of device is also able to realize a far lower gate leakage current than HEMTs if a high-κ gate dielectric is employed.

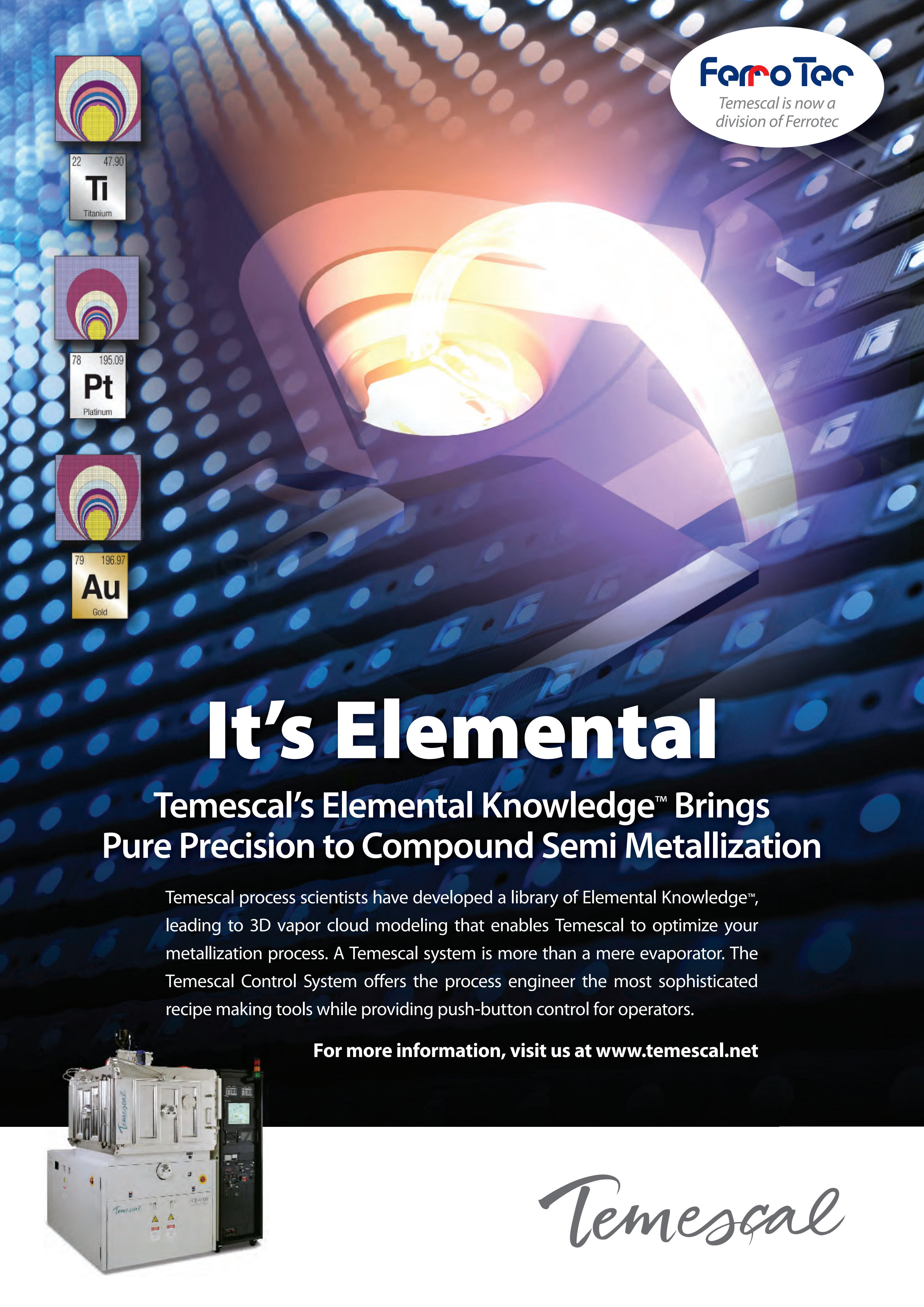
MBE was used to produce MOSFET epistructures on 3-inch semi-insulating InP. They comprised a 300 nm-thick $In_{0.52}Al_{0.48}As$ buffer; a 10 nm quantum well $In_{0.7}Ga_{0.3}As$ channel; a double barrier with a 1.5 nm-thick layer of $In_{0.52}Al_{0.48}As$ and a 2 nm-thick layer of InP; and a 20 nm thick, heavily doped InGaAs cap.

Buried channel MOSFETs were made by isolating mesas and removing the cap in the gate region by wet etching with citric acid. Atomic layer deposition added a 5 nm-thick layer of Al_2O_3 onto the III-V surface, and TaN was added to form the gate electrode. E-beam lithography and reactive ion etching defined the shape of this gate, before e-beam evaporation of palladium and germanium created source and drain ohmic contacts.

One of the weaknesses of the MOSFET is its low extrinsic conductance of 570 mS/mm, which stems from a relatively high external resistance. This is a result of the large source-to-drain separation – it is about 3 μm – which can be reduced by employing a self-aligned process, a step that is necessary for future CMOS applications.

The team believes that it should also be possible to realize better gate control by either shrinking the oxide thickness or turning to a dielectric with a higher κ value, a step that will also compensate for short channel effects.

F. Xue et al. (2010) Electron. Lett. **46** 1694


FerroTec
Temescal is now a division of Ferrotec
22 47.90 Ti Titanium
78 195.09 Pt Platinum
79 196.97 Au Gold
It's Elemental
Temescal's Elemental Knowledge™ Brings Pure Precision to Compound Semi Metallization
Temescal process scientists have developed a library of Elemental Knowledge™, leading to 3D vapor cloud modeling that enables Temescal to optimize your metallization process. A Temescal system is more than a mere evaporator. The Temescal Control System offers the process engineer the most sophisticated recipe making tools while providing push-button control for operators.
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