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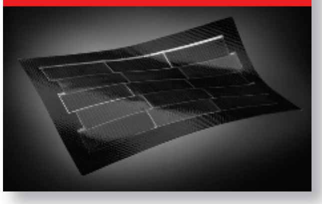
Opportunities for III-V cells on earth



Bringing CPV to the rooftops

Europium gets GaN into the red

Saving the grid with SiC-on-silicon

Streamlining for LED bulb success

Headlights

Lighting with lasers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editorialview

by Dr Richard Stevenson, Editor

A sensible split

SOMETIMES SPLITTING UP makes sense. Two entities can grow far enough apart that they cease to be a complimentary bedfellows – and they are more likely to prosper when standing independently.

Cree has found itself at this crossroads, and recently made the decision to split, allowing management to focus on LEDs and lighting while carving off the power and RF business.

Rewind the clock a few years, and there was a time it made perfect sense for Cree to be a single entity. Back then this North Carolina outfit could be viewed as a vertically integrated chipmaker, producing devices on its homegrown substrates. But this arrangement doesn't work nearly as well today, because Cree is inevitably struggling to simultaneously serve engineers wanting to download the specs of RF and power devices, and Joe Public, who wants to know just how good the Cree bulbs is.

Cree is focusing on the latter, trying to woo consumers by building up its reputation as a maker of high-quality LED bulbs. Publicity is coming from lighting up the Superbowl, and teaming up with football player Abby Wambach, highest all-time international goal scorer, to promote its bulbs.

However, while it would be easy to focus on why this break up is good for the lighting business, let's not forget RF and power: It may only account for 6 percent of the company's $1.65 billion annual turnover, but it is the more profitable sector.

Cree is saying very little about the impact of the split, so to offer some insight into it, we have spoken to Lux Research analyst, Pallavi Madakasira (you can hear her views on p18).

Madakasira is upbeat about the Cree RF and power business, arguing that it is held in high regard. However, she believes that if it is to be highly successful, it must develop power modules that can compete with the likes of ABB, Infineon and STMicroelectronics.

It will be interesting to see if it can execute on this front, and whether Cree's LED and lighting sector can grow a business that sells more bulbs, while making a tidy profit.

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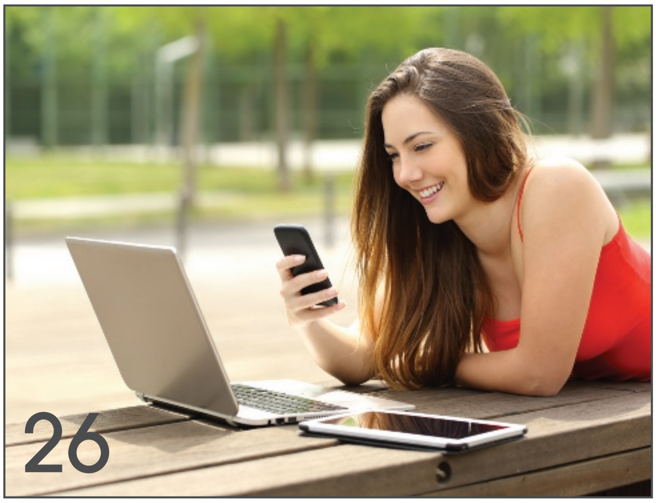

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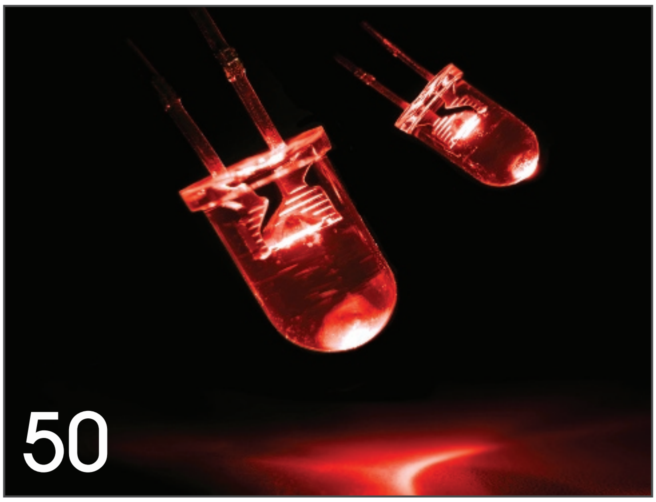


Soitec sets new record for CPV module

SOITEC has announced a new step in its SmartCell project, to develop a four-junction solar cell. After setting an efficiency world record in December 2014, the four-junction SmartCell has now been successfully integrated in a concentrated photovoltaic (CPV) module, enabling a conversion of 38.9 percent of the solar energy into electrical power.

This represents a significant increase compared to the existing world record for CPV modules according to the company. Paul Boudre, CEO of Soitec, explained, "While we announced earlier this year Soitec's refocus on its core semiconductor materials business, we also decided to keep all assets related to our SmartCell project in the company's new strategic scope. Indeed, it opens many business opportunities in different kinds of industries for Soitec. In the present case, the SmartCell paves the way for further cost reductions in solar energy, as it can be integrated in a record-efficiency CPV module suitable for mass production. This project demonstrates Soitec's leadership in the field of innovative semiconductor materials and technologies dedicated to high-performance applications as well as our ability to achieve major breakthroughs. I am very proud of the tremendous results achieved by our team."

CPV modules use Fresnel lenses to concentrate sunlight onto small, multi-junction solar cells. For the new world record in module efficiency, SmartCells were integrated in a CPV module employing the same platform as existing CPV modules using traditional three-junction cells. The SmartCells proved to have a superior conversion yield due to their four junctions. The record module efficiency has been measured indoors and outdoors. More than 10,000 outdoor data sets have been recorded. Fraunhofer ISE performed a detailed analysis and revealed a module efficiency of 38.9 percent ±0.9 percent for a 1,000 W/m^2 direct normal irradiation and a 25°C cell temperature. The record module has an aperture area of 812 cm^2 and uses 36 lenses, secondary optical elements and SmartCells.

As a stand-alone cell prior to being assembled in a CPV module, the SmartCell previously set a world record efficiency of 46.0 percent, as published on December 1, 2014. It was developed by Soitec in cooperation with Fraunhofer ISE and CEA-Leti.

SmartCell's development has been supported by the German Federal Ministry for Economic Affairs and Energy and the Federal Ministry for Environment (through the Magnus project) and by the Investissements d'Avenir (Invest for the Future" French government's investment program (through the Guepard project managed by the French environment and energy management agency - ADEME).

Cree to restructure LED business

US LED firm Cree has announced a restructuring of its LED business due to recent market trends that have resulted in higher LED average selling price erosion than previously forecast and the continued under-utilisation of Cree's LED factory.

The company plans to reduce excess capacity and overhead to improve the cost structure moving forward. Additionally, it is increasing LED reserves to reflect the more aggressive pricing environment experienced in the current quarter, and to factor in a more conservative pricing outlook for fiscal year 2016.

The restructuring charges are targeted to be approximately $85 million and the anticipated amounts by category are as follows, including what will be included in GAAP and Non-GAAP results: The company anticipates that the majority of the capacity and overhead related charges will be reflected in operating expenses for the fourth quarter of fiscal year 2015 ending on June 28, 2015, with the balance in the first half of fiscal year 2016. The company anticipates that the channel revenue reserves will be reflected as a reduction of revenue in fiscal Q4, and the inventory reserves will be reflected as an increase in cost of revenue in fiscal Q4.

For fiscal Q4, the company now targets revenue to be approximately $375 million, which includes the $27 million revenue reserve discussed above.

- Lighting products revenue is targeted to increase slightly sequentially, as strong growth in commercial lighting is expected to more than offset a greater-than-targeted seasonal slowdown in consumer bulb sales.

- Power & RF products revenue is tracking in-line with the company's targets for fiscal Q4.
- LED products customer unit demand is generally in-line with our targets for the quarter; however, the combination of the revenue reserves and lower pricing in the quarter is forecast to reduce fiscal Q4 revenue by approximately $35 million.
- Overall gross margin and operating margin are now forecast to be lower than previously targeted due to the restructuring costs, the more aggressive LED pricing environment, and the larger than targeted seasonal slowdown in consumer lighting.
- During fiscal Q4, the company completed the previously announced $550 million share buyback program by repurchasing 4.8 million shares of its common stock at an average price of $33.37 per share, with an aggregate value of $160 million. For fiscal year 2015, the company repurchased 16.0 million shares of its common stock at an average price of $34.33.

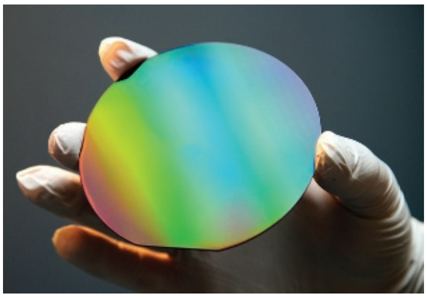
Exagan Raises €5.7 million to make GaN power devices on 200 mm wafers

EXAGAN, a start-up innovator of GaN semiconductor technology that enables smaller and more efficient electrical converters, has announced it has raised €5.7 million in first-round financing that will be used to produce high-speed power switching devices on 200mm wafers.

The investors include French venture funds with a record of identifying and fostering promising, fast-growth, early-stage technology companies: Technocom2, managed by Innovacom, a pioneering French venture capital firm; CM-CIC Innovation, the investment arm of the European bank group, Crédit Mutuel-CIC Group; IRDInov, a regional seed investor in emerging, fast-growth companies; CEA investissement, a manager of funds invested in technology companies, and which invested via the CEA strategic fund; and Soitec a company providing leading edge semiconductor materials.

Following Exagan's recent announcement of an agreement with X-FAB to produce devices on 200mm wafers, the financing will help support its mission of becoming Europe's primary supplier of GaN-based power switches for the solar, automotive, IT electronics and other markets. That mission includes its strategic partnership with CEA-Leti, which is developing applications with some of its industrial partners based on Exagan's G-FET 650 V platform and its unprecedented power-switching performance with extremely low conduction losses.

Exagan, based in Grenoble with a branch office in Toulouse, was spun off by Leti and Soitec in 2014 and licenses materials and technology from both organisations. "This significant first round of financing validates our efforts over the past five years with Leti and Soitec to commercialize GaN-on-silicon technology and supports our commitment to provide customers with qualified GaN devices in large volumes," said Frédéric Dupont, Exagan CEO and co-founder. "We are focused on offering our customers reliable, high-performance devices that are developed with industrial partners already sourcing technologies



or products for the targeted markets." Vincent Deltrieu, a partner at Innovacom, said: "Exagan has developed a G-FETTM product platform that offers major competitive advantages for electrical-converter makers serving the power-electronics industry. By leveraging the platform's efficiency and power-saving features, Exagan is well positioned to establish itself as a key technology provider in this high-growth market that has the potential to exceed 1 billion euros in the coming years."

Stéphane Simoncini, investment director at CM-CIC Innovation, said: "Frédéric and Exagan COO and co-founder Fabrice Letertre are the ideal team to accomplish Exagan's business and technology goals. With their technical and business vision, they are opening a huge market segment in power electronics, between silicon and SiC."

Jean-Michel Petit, managing director of IRDInov, said: "Based on our experience with the automotive and aerospace industries, we are convinced of the potential markets for GaN power electronic devices. This is all the more reason to further develop its presence in Toulouse, which has a concentration of competencies in power-electronics applications and many potential future clients."

Soitec CEO Paul Boudre said: "Soitec is obviously excited about this successful round of financing for Exagan. Their GAN-on-silicon technology, which leverages our own materials expertise, opens very interesting opportunities in promising markets such as electronics, automotive and energy.

Exagan is well positioned to drive innovation in power switching technology, due to its location in Grenoble among the strong mix of innovative companies and technology-integration clusters."

Soitec and CEA Investissement also provided financial support to Exagan prior to the first round of venture-fund backing. Leti CEO Marie Semeria said the company has invested many years in developing GaN technologies because it believes they will drive innovation in the power-electronics industry and accelerate development of sustainable-energy technologies.

"We are very excited about the prospects for Exagan, a European source of new GaN power switches for our key industrial partners in the fields of transportation and energy, as well as broader markets," she said. "Through our partnership with Exagan, Leti will accelerate its investment in this area to further develop our leading expertise in GaN technology and related systems and applications."

As one of three advanced-research institutes within the CEA Technological Research Division, CEA Tech-Leti serves as a bridge between basic research and production of micro- and nanotechnologies that improve the lives of people around the world. It is committed to creating innovation and transferring it to industry.

Backed by its portfolio of 2,800 patents, Leti partners with large industrials, SMEs and startups to tailor advanced solutions that strengthen their competitive positions.

It has launched 54 startups. Its 8,500m^2 of new-generation cleanroom space feature 200mm and 300mm wafer processing of micro and nano solutions for applications ranging from space to smart devices. With a staff of more than 1,800, Leti is based in Grenoble, France.

Exagan was created in 2014 with support from CEA-Leti and Soitec to accelerate the power-electronics industry's transition from silicon-based technology to smaller and more efficient electrical converters based on GaN-on-silicon technology.

Raytheon completes GaN milestones for Patriot radar

RAYTHEON has recently completed a series of milestones, bringing the Patriot Air and Missile Defence System with 360-degrees of coverage one step closer to production readiness.

The milestones involve upgrading the Patriot' radar main array with GaN based Active Electronically Scanned Array (AESA) technology. According to the company it means that their engineers, who are currently building a GaN-based AESA full size main panel radar array, are on track to having the system up and running in early 2016.

"A GaN-based AESA radar benefits netted sensors, and gives Patriot greater capability and reliability while significantly reducing operations and sustainment cost," said Ralph Acaba, vice president of Integrated Air and Missile Defense at Raytheon's Integrated Defense Systems business. "Raytheon recognizes how important this capability is for the warfighter and is investing its own resources to bring Patriot's GaN-based AESA radar to the point where it can enter engineering and manufacturing development with low risk."

The main AESA array is a bolt-on replacement antenna that measures roughly 2.7 m wide x 3.9 m tall, which is oriented toward the primary threat. Patriot's new rear panel arrays, which are a quarter the size of the main array, let the system look behind and to the sides

of the main array, enabling Patriot to engage threats in all directions.

Earlier this year, Raytheon built a GaN-based AESA Patriot rear-panel array, integrated it with the current Patriot radar using the existing, recently modernised, backend processing hardware and software, and tracked targets of opportunity to seamlessly create a 360° view.

The milestones accomplished to date include fabricating the main radar array's superstructure, and completing development work on the power and cooling sub-systems. In the months ahead, additional upgrades will focus on integrating the sub-systems and populating the array superstructure with GaN-based transmit-receive units (TRLRU).

SiC power modules save 40 percent power

MITSUBISHI ELECTRIC has announced that an all-SiC traction inverter installed in a 1000 series urban train operated by Odakyu Electric Railway in Japan, has been verified to achieve an approximate 40-percent savings in power consumption compared to a train using conventional circuitry.

The traction inverter, which is rated for 1,500V DC catenaries, was tested over a four-month period. The verification compared a car retrofitted with an all-SiC traction inverter and another car fitted with a conventional gate turn-off thyristor traction inverter, both of which were put into actual commercial service. The test measured power consumption and electric power regeneration ratio of the two cars' main circuits, which comprise traction inverters, high-efficiency main motors and filter reactors. The following results are average values measured between January 17 and May 8, 2015: 17 percent power savings during powered operation; an increase from 34.1 percent to 52.1 percent in power regeneration ratio, calculated as power from regenerative brakes to catenaries divided by total electric power to drive the rail car; and 40 percent power savings overall.

Solar Junction moves further into space

SOLAR JUNCTION, a provider of multi-junction solar cells for terrestrial concentrated photovoltaic (CPV) applications, has announced a plan to become the world's leading provider of solar cells for space power applications.

At the 2015 Space Power Workshop in Manhattan Beach, California in May, the company presented on its next-generation space solar cells, in particular a fully lattice-matched, four-junction (4J) space cell product.

Enabled by its proprietary dilute nitride technology platform, the 4J cell has predicted air mass zero (AM0) efficiencies exceeding 33 percent by 2016.

Solar Junction is currently producing a high efficiency three-junction (3J) space cell using its dilute nitride material as the bottom active junction on a GaAs substrate. 2014 saw the first commercial shipment of Solar Junction's 3J space cell, with AM0 efficiencies exceeding 31 percent, and the 3J product is undergoing qualification.

During the 2015 Space Power Workshop, The Aerospace Corporation presented radiation degradation results from two Aerospace AeroCube picosats currently on-orbit (since June 2014) carrying Solar Junction 3J space cells. The results demonstrate that dilute nitride materials have radiation hardness comparable to conventional cells and show great promise for Solar Junction's next-gen space products.

Early prototypes of Solar Junction's next-gen 4J space cell with an industry-standard Germanium bottom junction have reached AM0 efficiencies of 31 percent. By late 2016, Solar Junction plans bring to market its 4J, lattice-matched, dilute nitride, Germanium bottom junction space cell with a minimum average efficiency of 33 percent.

Transphorm announces new $70 million investment

TRANSPHORM, an early stage Californian semiconductor company focused on GaN-based power conversion chips, has announced a $70 million investment round led by investment firm KKR.

KKR's investment follows initial rounds of funding led by funds affiliated with Kleiner Perkins Caufield and Byers, Foundation Capital, Google Ventures, Soros Quantum Strategic Partners, INCJ, Fujitsu, Transphorm will use this funding to support its growth, product innovation and expansion.

Umesh Mishra, chairman of Transphorm Inc, stated: "Transphorm was launched to address the urgent and important problem of losses in power conversion, a process that converts electricity from the form it is delivered to the form that is ultimately used. We are delighted KKR has chosen to invest in Transphorm. By merging the technological leadership of Transphorm with the semiconductor business expertise of KKR, we are taking a major step forward in solving the global problem of energy wasted in power conversion."

Transphorm believes that there is a very large market for its products as its ultra-efficient power devices and modules can eliminate more than 40 percent of all electric conversion losses by using GaN. Transphorm has established strategic partnerships with a number of companies.

Yaskawa Electric Corporation, a motion control, robotics and systems engineering firm, launched the first GaN-based commercially produced solar photovoltaic (PV) inverter, powered by Transphorm GaN, in the Japan market earlier this year.

Transphorm's products enable approximately 50 percent smaller PV inverters in residential and small commercial installations up to 5kW, resulting in lower system, installation, and service costs while at the same time delivering more energy per solar panel to the grid.

Tata Power Solar, India's leading power conversion player, has also teamed with Transphorm to develop PV inverters. In order to provide customers with high quality volume production, Transphorm partnered with Fujitsu Semiconductor, to produce its products in Fujitsu's automotive-class wafer fabrication facility in Aizu-Wakamatsu, Japan.

"Transphorm's technology is paving the way for a revolutionary change in energy efficiency. Right now, Transphorm is the only place where customers can acquire reliable, production volume GaN products that meet or exceed required performance specs for commercial products.

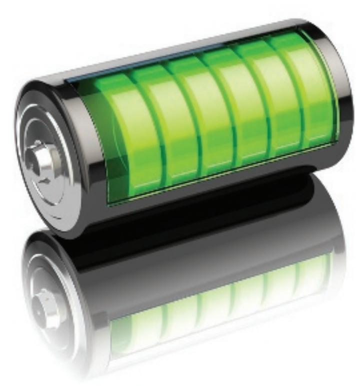
Long term, we believe this has the potential to replace all of the existing silicon-based technology used in high voltage products, and wide adoption of this technology will dramatically reduce the amount of energy that is wasted by electric devices," David Kerko, senior advisor of KKR, said.

Luftstrom project to make battery charging more efficient

TWELVE PARTNERS in the German automotive sector, its supply industry and the sciences are collaborating on a three year research project to investigate how batteries in electric vehicles can be charged more efficiently. Luftstrom (English: Airstream), as the project is called, will help accelerate the conversion to climate-friendly mobility.

The use of new GaN or SiC power semiconductors is expected to reduce losses during charging and, ultimately, make charging almost noiseless. Electric vehicles are mainly charged overnight.

However, charging in the charging device and voltage regulators creates heat that fans of water-cooled aggregates have to dissipate, for example. This can be quite noisy. As a result of the Luftstrom research, the electronic power components will lower the losses during charging by 30 percent. This means lower waste heat - and with less cooling



effort the cooling units become more compact and operate more quietly. Components that already cause very few losses, such as auxiliary power supplies, might even be able to do without the previously required water cooling - which means that the loud fans would be eliminated.

The key to low-loss power electronics lies in state-of-the-art power semiconductors based on GaN or SiC. The Luftstrom project will therefore also determine how such power semiconductors can be used reliably in charging devices, voltage regulators and inverters for auxiliary power units. Its research results will accelerate the transition to air-cooled and fan-less systems for future generations of electric vehicles.

The German Federal Ministry of Education and Research (BMBF) is contributing funding in the amount of about Euro 3.9 million to the Luftstrom research. Infineon Technologies has the project lead.

The twelve project partners include AVL Software and Functions GmbH, BMW AG, Daimler AG, Fraunhofer Institute for Integrated Systems and Component Technology IISB, the University of Applied Sciences Ostwestfalen-Lippe, Infineon Technologies AG, Lenze Drives GmbH, Robert Bosch GmbH, RWTH Aachen University, Siemens AG, Leibniz University Hannover, and Volkswagen AG.

3D LED firm Aledia complete $31 million funding

ALEDIA, a Grenoble-based developer and manufacturer of 3D LEDs based on its GaN-on-silicon platform, has closed its Series B financing round and the execution of development and supply contracts with major LED buyers. The round, totalling up to €28.4 million, includes new investments from Valeo, one of the world's largest automobile-equipment manufacturers and the world's second-largest supplier of car lighting systems; Ikea GreenTech AB, the venture capital arm of Ikea; and the Ecotechnologies fund of Bpifrance, the French national industrial bank. Aledia's existing international investors – Sofinnova Partners, Braemar Energy Ventures, Demeter Partners and CEAi/ATi – also participated in the round.

Originally developed by CEA-Leti, the company's 3D microwire LED technology is manufactured on large-diameter silicon wafers (200mm or 8-inch) in existing CMOS foundries. Not only do these 3D LEDs hold the potential to be much less expensive than traditional 2D LEDs, according to Aledia, but they allow for integration of electronics into the LED. The company is also working on next-generation displays.

"This financing round, abundantly oversubscribed, and particularly the presence of two very large potential corporate customers, testifies to the interest that our cost-disruptive nanowire LED technology is generating in the customer base, as well as in the financial community," said Giorgio Anania, CEO, chairman and co-founder of Aledia. Anania said: "We are progressing with the development of the technology and this financing round will allow us to accelerate significantly the speed of development and the customer traction.

In Valeo we have a major potential customer in the automotive LED market, generally viewed as the most profitable market segment. Simultaneously with the investment, we have signed a supply agreement with Valeo."

Maurizio Martinelli, Valeo Visibility Business Group president, said: "We are convinced that Aledia's 3D LED technology, together with Valeo's expertise in automobile lighting systems, has the potential to put on the market a technological breakthrough in innovative lighting systems, perfectly in line with Valeo Lighting System's mission to provide performance and style, and contribute to the safety of road users."

Christian Ehrenborg, MD of Ikea GreenTech AB, said: "This technology will be one important part in the Ikea Group strategy to supply high-quality, energy-saving lighting products to consumers worldwide. The low-price opportunity for residential use has the potential of faster implementation of the LED technology, leading to savings for customers. The connectivity functions of Aledia's technology also open up new interesting possibilities to make life at home more convenient and smarter."

Rohm and Fraunhofer demo SiC MOSFETs in a UPS

ROHM has collaborated with Fraunhofer Institute for Solar Energy Systems (ISE) in Freiburg to build a 10kW three phase UPS inverter using Rohm SiC MOSFETand Gate driver devices. The aim is demonstrate the performance of SiC devices at the application level.

SiC components offer great potential for reducing power converter system costs and decreasing the size of the heat-sink and inductive components by increasing efficiency and operating frequency. Because of smaller switching energies of the SiC transistors, the switching frequency can be raised by three to nine times compared to conventional inverters, which reduces the size of the passive components by almost the same factor.

Nevertheless the hardware designer is confronted with some challenges when designing such systems, says Rohm. The high di/dt and du/dt ratio during switching requires careful design of all switching loops and nodes. Every additional parasitic inductance in the design leads to voltage/current spikes that can, in a worst case scenario, lead to EMC problems. Small and carefully designed switching paths are a premise for a good SiC layout and are much more required for SiC- than for Si-systems. A UPS was chosen as the application as it is a growing market and also future UPS market will demand size and weight reduction. The results can also be easily adapted to drive inverters.

For this project the input voltage range is 700 V to 1000 V. The AC output grid voltage is 400V with a RMS current of ~15Arms. To have a good comparison 10kW is a suitable output power since the system will be three phase, easy to handle and is well suited to the power rating of available SiC devices.

Also a breakdown voltage of 1200V is usually needed. A 3-level MNPC (Mixed Neutral Point Clamped) topology was chosen. Other names for this topology are Neutral Point Piloted (NPP) and T-type topology. For a 400V grid, the blocking requirements of the four transistors lead to the applications of two 650V devices (S2206, 120mΩ, second generation SiC MOSFET and S6206, 12A, second generation SBD) and two 1200V devices (S2301, 80mΩ, second generation SiC MOSFET and S6301, 5A SBD). Simulations have shown that despite the high switching frequency of 100 kHz, low losses can be achieved in the semiconductor.

The switching frequency of 100kHz leads to small passive filter components at the output and small input capacitors which – apart from smaller size and weight – also mean lower system costs.

Low losses in the semiconductors enable the integration of one small active heatsink cooling all three phases. An external SBD has been chosen to optimise efficiency and thermal heat management.

Infrared LEDs: invisible driver of optoelectronics market

OVER THE PAST TEN YEARS, visible LEDs have been adopted widely in many different applications, as prices have fallen and new technologies have been developed to make full use of them.

The Infrared LED market is now also experiencing a similar increase, according to a research note from IHS.

The market for infrared ambient light and proximity sensors was expected to continue growing very quickly in the near future; however, it is now expected to slow down significantly, as the market for sensors in tablets and smartphones begins to saturate. But the market for infrared components is still expected to grow from $1.3 billion in 2014 to $1.5 billion in 2020.

So where is this growth coming from? The answer lies in the market for infrared LEDs, photodiodes, and phototransistors, says IHS.

Infrared LEDs have in the past been used in a variety of applications, mostly in remote controls for consumer goods. But over the past few years, there has been a huge increase in the popularity of consumer do-it-yourself (DIY) security cameras. Each of these cameras has a number of rings of infrared (IR) LEDs, to provide night vision capabilities, meaning that in each camera sold, there could be anywhere from 10 to 50 IR LEDs. The gain in popularity has had a major impact on the market in China where the majority of these cameras are manufactured.

Despite gains in security cameras, the real growth potential lies in the automotive market. Over the past 10 years, many leading automotive manufacturers have increased the number of sensors and 'smart' capabilities into their vehicles.

Many newer technologies - such as rain, light and tunnel sensors - now come standard on many vehicles.

Other applications of IR devices in cars include proximity, parking, lane detection and driver drowsiness sensors, and as such the IR LED market is growing strongly in the automotive market, with an 11 percent compound annual growth rate (CAGR) forecast from 2014 to 2020.

In automotive applications, each IR LED might be paired with a number of photodiodes or phototransistors to act as sensors. The success of the IR LED market is inherently linked to the success of the photodiodes and phototransistor market.

Advantech releases second generation GaN maritime up-converter

ADVANTECH WIRELESS, the Canadian developer of satellite broadband communications solutions, has released a 300W C-Band BUC (block up-converter) based on its Second Generation Super Compact TT Series GaN Technology.

The second generation 300W C-band GaN SSPA/SSPB (solid state power amplifier/ solid state power block) offers 60 percent RF linear power increase, while reducing the energy consumption by 30 percent, according to Advantech. It also reduces the weight and overall size by 45 percent. In terms of linear power, the 300W unit is the equivalent of a previous 500W SSPA, and of a 750W travelling wave tube (TWT). These units are specifically designed for maritime application, where bandwidth demand has increased exponentially, and where the high temperature in the Radome is always a challenge.

"The improved GaN reliability and low size allow perfect integration into the ship stabilised antennas, where size is extremely important for perfect balancing, and where heat generation has to be reduced to the minimum," stated Cristi Damian, VP business development at Advantech Wireless.

The Second Generation of 300W C-band GaN based systems, continues the tradition of the previous 200W C-band GaN based SSPAs from Advantech Wireless, already deployed and installed on thousands of ships in the sea, with outstanding performance."

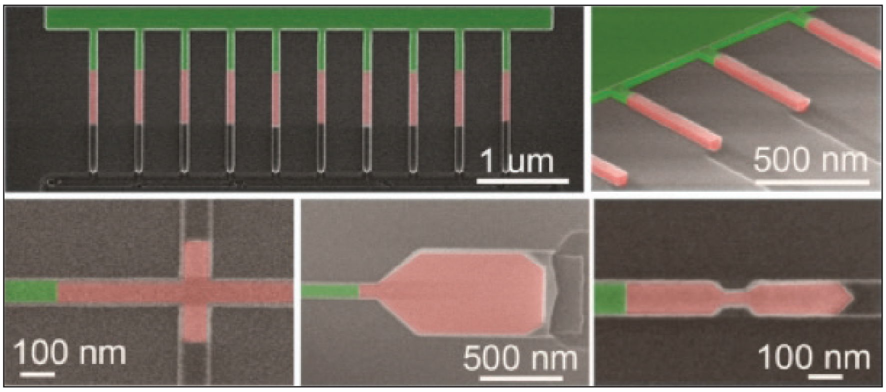
IBM develop a way to integrate III-V materials on silicon

A TEAM of IBM researchers in Zurich, Switzerland with support from colleagues in Yorktown Heights, New York has developed a process for growing compound semiconductor crystals that will allow them be integrated onto silicon wafers.

Appearing in the journal Applied Physics Letters, from AIP Publishing, the work may allow an extension to Moore's Law, according to the researchers. "The whole semiconductor industry wants to keep Moore's Law going. We need better performing transistors as we continue down-scaling, and transistors based on silicon won't give us improvements anymore," said Heinz Schmid, a researcher with IBM Research Zurich and the lead author on the paper.

The IBM team fabricated single crystal nanostructures, such as nanowires, nanostructures containing constrictions, and cross junctions, as well as 3D stacked nanowires, made with III–V semiconductors (InAs, InGaAs, GaAs). The new crystals were grown using an approach called template-assisted selective epitaxy (TASE) using MOCVD.

This approach allowed them to lithographically define oxide templates and fill them via epitaxy, in the end making nanowires, cross junctions, nanostructures containing constrictions and 3D stacked nanowires using the already established scaled processes of silicon technology.



SCANNING electron microscope images of single crystal structures made using template-assisted selective epitaxy (silicon is in green, and the compound semiconductor in red).

According to the researchers, the benefit of TASE is exemplified by the straightforward fabrication of nanoscale Hall structures as well as multiple gate field effect transistors (MuG-FETs) grown co-planar to the SOI layer. Hall measurements on InAs nanowire cross junctions revealed an electron mobility of 5400 cm^2/V s, while the alongside fabricated InAs MuG-FETs with ten 55 nm wide, 23 nm thick, and 390 nm long channels exhibit an on current of 660 μA/μm and a peak transconductance of 1.0 mS/μm at VDS = 0.5 V. "What sets this work apart from other methods is that the compound semiconductor does not contain detrimental defects, and that the process is fully compatible with current chip fabrication technology," said Schmid. "Importantly the method is also economically viable."

He added that more development will be required to achieve the same control over performance in III-V devices as currently exists for silicon. But the new method is the key to actually integrating the stacked materials on the silicon platform, Schmid said.

'Template-assisted selective epitaxy of III-V nanoscale devices for co-planar heterogeneous integration with Si' by H. Schmid et al, Appl. Phys. Lett. **106** 233101

Princeton Power unveils 30kW SiC-based converter

PRINCETON POWER SYSTEMS has demonstrated for the first time a grid-tied bi-directional power converter intended for commercial use based on a SiC switching technology platform.

The converter operates at 30kW power throughput and 480 V ac, using junction field effect transistor (JFET) devices provided by United Silicon Carbide (USCi) and Princeton Power Systems trigger cards integrated in a unique architecture. The converter demonstrated peak efficiency greater than 99 percent and sustained 100 percent power overloads. "Technology innovation in power conversion has been at the core of our mission since day one," said Ken McCauley, president and CEO of Princeton Power Systems. "This product demonstration shows that SiC technology can play a role in highly-efficient and cost-effective commercial products in the very near future, and we intend to expand its use to higher power levels and ultimately across our product line."

The power stage at the heart of the converter was jointly developed by USCi and Princeton Power, using JFET devices from USCi and triggers and controls developed by Princeton Power Systems. The integrated product was designed and tested at Princeton Power's Nationally Recognised Test Lab in Lawrenceville. "USCi is at the forefront of designing and delivering active switches based on silicon-carbide.

Our JFET and Cascode technology deliver the only standard gate drive SiC switch solution, while having the lowest specific on resistance in the industry. These advantages enable the most cost effective SiC solution in the world," said Chris Dries, president and CEO of USCi. "The demonstration at Princeton Power represents a breakthrough in operating an integrated power block using commercially-available SiC devices."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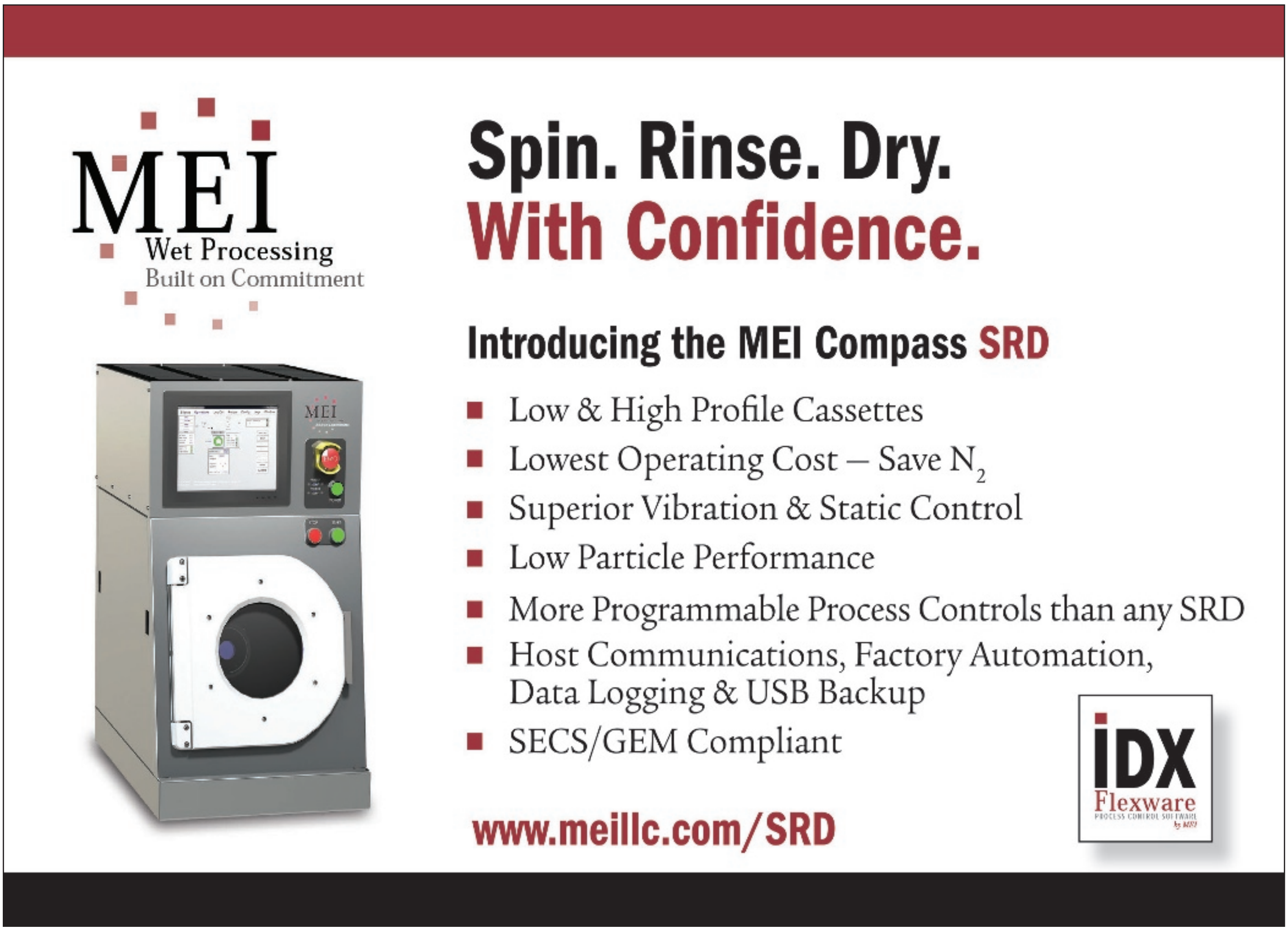
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THE PROBLEM WITH POWER

As power demands surge, electricity networks are under strain. Can SiC power electronics save the grid, asks Rebecca Pool

Left: Solar panels, a proliferation of electric vehicles and more are stretching today's electricity networks to the limit; silicon carbide-on-silicon devices can help.

AS OPERATORS of residential electricity networks across Europe strive to meet escalating demands for power, SiC-on-silicon power devices from Anvil Semiconductors are set to make a real difference.

The UK-based SiC device developer is taking part in a £500,000 UK government-funded initiative to develop cutting-edge technology to boost the efficiency of power distribution across UK networks.

Working alongside a host of key power players – Schneider Electric, Western Power Distribution, Turbo Power Systems, Exception EMS and Aston University, UK – Anvil will develop SiC-on-silicon Schottky diodes and MOSFETs for power electronic converters.

As Jill Shaw, chief executive of Anvil highlights: "We will be supplying our devices to our partners, but these will be new, so we are well and truly involved with working to get the best out of these devices."

New power, old infrastructure

The project follows a government-funded feasibility study to find a cost-effective way to integrate the rising levels of distributed power generation and storage to existing electricity infrastructure.

Recent figures from Imperial College London, UK, estimate that come 2020, a hefty 10 million homes in the UK could have solar panels, up from around half a million today. Meanwhile, Navigant Research predicts sales of light-duty electric vehicles will more than double from today's 2.7 million to 6.4 million by 2023.

However, integrating such distributed power generation and storage to today's electricity networks brings myriad issues. An influx of photovoltaics, for example, can lead to unacceptable local voltage rises on the network while more electric vehicles means more demand for power. Factor in the uncertainties of predicting the loads and demands in a future two-way power, and clearly it's time for the network to adapt.

However, the feasibility study brings hope. Research indicates that increasing the local network phase voltage on existing electricity infrastructure to 400 V would be a cost-effective way to handle the rising power demands and local voltages. And this is where Anvil's SiC-on-silicon devices are set to play a key role.

To step down the network voltage at each house to 230V, low-cost power electronics converters (PECs) will need to be installed in a meter box outside each home. So with this in mind, project partners are now developing a prototype that Western Power Distribution will deploy in a small-scale demonstration network of around 100 homes. And of course, developing new, low-cost 3C SiC devices for the PEC is a must.

> The project follows a government-funded feasibility study to find a cost-effective way to integrate the rising levels of distributed power generation and storage to existing electricity infrastructure

"The converter needs to be small and 99 percent efficient due to [space and] heat restraints within the meter box," highlights Shaw. "This drives the need for silicon carbide, but conventional devices just can't do this cheaply."

"Only by using our devices can you make this solution cost competitive, or cheaper than digging up electricity cables and replacing them," she adds.

Making MOSFETs

But a lot of work must take place first. As Shaw says: "We've developed the Schottky diodes but haven't yet got the MOSFETs so our partners [Turbo Power and Schneider] are developing prototype PECs around more expensive bulk SiC devices."

Right now Anvil is working with The Tyndall Institute, Ireland, on 'its first stage' MOSFETs. According to Shaw, device production started a few months ago, following process development to convince her and colleagues that they could get the performance they wanted out of their MOSFETs. And a finished device is expected in around six months.

"In about a year's time we will provide our MOSFETs," adds Shaw. "These will replace the [bulk SiC devices], and a converter will then be produced for the trial networks," she adds.

At this point, Western Power Distribution will test the converter on its trial site, and if successful, will be a long-term customer for the project partners. But this is just the beginning. After the three-year project, Shaw expects a period of further development for commercialisation. The potential market is huge, and the impact on Anvil could be profound.

"Assuming we meet Western Power's requirements, the operator will then start integrating the converter [at peoples' home] across its distributed network," she says. "But clearly Schneider has recognised that there is a lot more of a market than Western Power."

"So if successful, Schneider will commercialise the converter and [it could reach] all the distributed network operators in the UK and the rest of Europe," she adds. "This is a worldwide issue that's got to be coped with. And this is a relatively cheap and easy way of doing it."

CREE
POWER PLANS

Cree has released a statement of intent to spin out its Power and RF business, but little else. Rebecca Pool talks to Lux Research analyst, Pallavi Madakasira, to find out more.

LAST MONTH, Cree unveiled plans to spin out its Power and RF business, filing the paperwork to initiate a public offering process for the new company, with the US Securities and Exchange Commission.

At the time, details were scant. Cree intended to remain the majority stockholder of a future company, board member and telecoms industry veteran, Frank Plastina, would take the lead and the subsidiary was to raise cash to invest in the business to support future growth.

In a company release Cree simply stated: "The offering will enable management to focus on Cree's LED and Lighting businesses, while also creating a dedicated focus on the Power and RF business."

Despite requests from *Compound Semiconductor* for further comment, the only response from a company spokesperson, Cameron Reed, is: "This decision demonstrates the success and market opportunity, positioning both the LED/Lighting business and the Power and RF business with increased focus to better take advantage of the opportunity to accelerate growth."

"We do not have additional details available to share at this time, but will keep you appraised of updates as we have them," he continues.

Still, amid the silence, investors applauded the move with Cree shares jumping shortly after the announcement, and industry consensus, to date, supports the decision.

As Lux Research analyst, Pallavi Madakasira, highlights: "Cree's RF and Power business unit has been overshadowed drastically by its LED business. For the fiscal year ending in June, it's the most profitable line for Cree, but still only accounted for 6 percent of Cree's overall $1.65 billion revenue."

Clearly, a firmer focus on each business segment will benefit both. In recent months, Cree has been making more of its power module line, with Madakasira highlighting how the company has been busy pushing its business model downstream. "The company now wants to offer power modules as well as just discrete devices and is really trying to compete with the likes of Infineon and ST, to get into that module game," she says.

And, as always, making a success out of LEDs isn't easy. The consumer LED market is super price-sensitive while margins are, as Madakasira puts it, 'razor thin'.

Just as Cree released its $10 LED light bulb, vice president of corporate marketing, Mike Watson, told *Compound Semiconductor*: "We didn't think this segment was moving fast enough so we're giving consumers a reason to switch to LED lighting."

"They love the shape and the light that comes out of an incandescent," he said. "So we've given them a bulb that they are used to at a price point they will try."

Cree, recently released a bulb priced at less than $10, but as Madakasira points out: "From what we know of Cree's first [$10] LED bulb, the company was essentially wrapping cash around the bulb, and receiving very little return for every bulb sold."

"Cree has spent a tonne of money on just marketing its LED business as ultimately nobody had associated a LED bulb with the Cree brand," she asserts. "For them to have driven this traction into a consumer market, they've spent a lot of money."

Factor in industry developments, such as Dutch electronics giant, Philips, spinning off LED production and automotive lights operation – Lumileds – from its lightings systems business, so each could better grow, and a similar move from Cree was inevitable.

"Anyone in the LED business cannot considerably think about trying to combine LEDs with another business," says Madakasira. "Making money in LEDs today is so challenging, I think this is the smartest thing for Cree [to do]."

High regard

Of course, the RF and power industry is a different beast. Sales are not made on the back of a brand, but rather on reliability and performance, as devices can be easily sampled and tested by customers.

And despite its former LED and lighting leaning, this spells good news for Cree. "Cree's SiC technology is widely acknowledged to have some of the best properties and quality overall," says

Madakasira. "And let's not forget that the company is one of a handful of global suppliers of SiC substrates today, so it can really wield its wand and work out how to control the market."

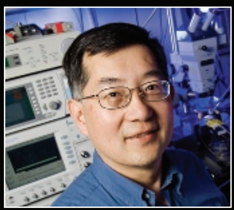
So the future looks bright for a more tightly focused RF and Power business company from Cree. According to Madakasira, conversations with end-customers across Asia, Europe and the US confirm that the company's RF GaN and SiC power products are held in wide regard.

Still, the analyst also highlights concerns over Cree's recent move towards power modules. "Cree needs to sharpen its focus on who it wants to bring on board as an inverter player," she says.

The analyst asserts the company has recently worked with 'no-name' companies that are keen to enter the inverter space, and is essentially teaching these new players the business.

But as she adds: "Considering Cree will be going head-to-head with the likes of ABB as well as Infineon and STMicroelectronics, which know exactly how to work the module business, I just wonder if this strategy is going to pay off."

A different light



Is the transistor laser ready to deliver the blindingly fast broadband speeds industry craves, asks Rebecca Pool

THIS SPRING, Milton Feng from the University of Illinois at Urbana-Champaign, US, won a hefty $657,000 from the Air Force Office of Scientific Research to raise the modulation speed and performance of his revolutionary transistor laser.

Working with long-standing industrial partner, Keysight Technologies, Feng and colleagues will spend the next three years pushing the modulation speed of the device up from gigahertz towards terahertz frequencies. And if successful, the high bandwidth laser will open the door to a new generation of high performance photonic ICs with blisteringly fast data transmission speeds.

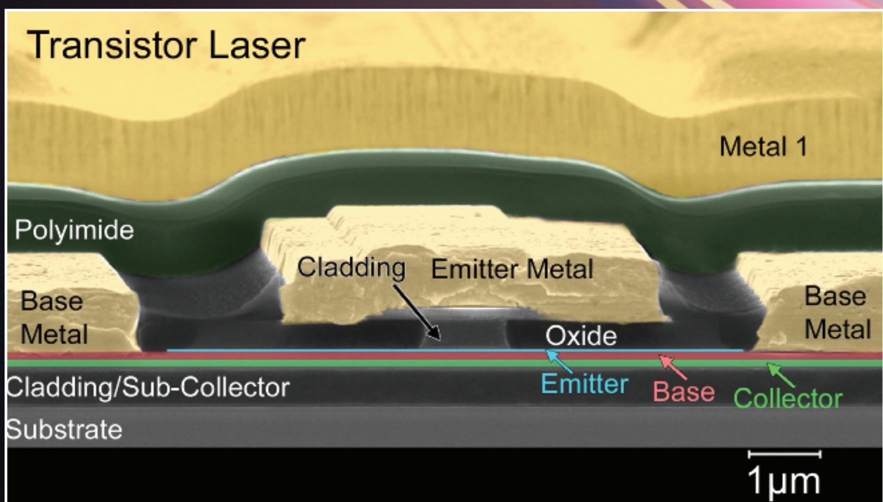
"Your typical semiconductor laser [diode] is based on a *p-n* junction diode and can probably only modulate up to 30 GHz as this is limited by the recombination of the diode," points out Feng. "So we decided to look at a bipolar junction transistor, and discovered that the recombination of this was much faster than the laser diode."

"We've since been collaborating with Keysight to make a terahertz transistor for their instrumentation work, and now we understand how that works, we figure we can use these ideas and apply them to a laser," says Feng.

Feng claims the world record for the fastest HBT, at 800 GHz, and using this experience will first establish a theoretical framework for pushing the modulation speed of his transistor laser into the terahertz and beyond.

The researchers have already demonstrated a transistor laser with a fast recombination lifetime – 30 ps – and modulated optical output with a 22 Gbps error-free transmission.

By taking this theoretical framework and studying the transistor laser epitaxial design, they will optimise the number



By incorporating multiple quantum wells and reflectors, Milton Feng hopes to reduce recombination lifetime to 5ps.

of quantum wells and incorporate reflectors to reduce recombination lifetime to below 5 ps, paving the way to terahertz modulation frequencies.

"Our work will look at the design of quantum wells into the base of the transistor to give us the trade-off between photon lifetime and recombination lifetime," he adds. "In our final year we'll demonstrate a transistor laser made of quantum dots and quantum wells with a lifetime below 5 ps and a modulation of 0.3 THz."

Extreme transistors

Working with Nick Holonyak, also at the University of Illinois, Feng created the first light-emitting transistor in 2004, and soon honed the device to emit light as a laser beam. This transistor laser functions as a transistor but with an electrical output and optical output rather than the usual two electrical outputs.

All transistors emit a small number of photons, but Feng's modified InGaAs-GaAs HBT has a layer of InGaAs inserted into its base structure to form a quantum well, and includes a reflective cavity to focus emitted light into infrared laser light.

Indeed, past tests reveal the quantum well boosts signal intensity by some 40 times, and Feng and colleagues have fabricated devices to emit light at 980 nm, 1550 nm and in the visible range. And while their original light-emitting devices operated at around -73°C, by improving MOCVD growth and quantum well design, the researchers now have devices operating a room temperature.

Reaching market

Following his light-emitting transistor success in the lab, Feng set up Quantum Electro Opto Systems (QEOS) in 2008, with University of Illinois Urbana-Champaign colleagues, Nick Holonyak and Gabriel Walter, to commercialise his first light-emitting transmitters for fibre-optics communications.

As Feng highlights, the QEOS light-emitting transistor eliminates the need for external driver and control circuitries, delivering a small form factor transmitter that consumes less than 1 mW/Gbps. "And it is about seven times faster than a laser diode," he adds.

The company unveiled its first devices in 2013 with target applications including active optical cables for connecting computing equipment with video monitoring equipment. "These are being incorporated into security communication cameras as you need high speed at low power," says Feng.

But what about the laser transistor? As well as boosting modulation frequencies, Feng is also looking to reduce the size of the transistor laser, and reduce its parasitic losses.

As he says: "We've proven this is possible, but haven't done this at room temperature yet – [but] it shouldn't be a problem."

He also believes manufacturing at larger scales will be straighforward; as he says: "The device is based on a commercial HBT which can be grown by anybody... companies like IQE and EpiWorks will be able to grow material for us."

The researcher also highlights how the device can function as a high speed nonlinear switch and signal mixer, commenting: "I believe the first useful applications will be as a laser mixer."

And crucially, the transistor laser has three ports – the emitter, base and collector – offering a greater system design freedom compared to the standard transistor and two-port diodes. "This three-terminal laser... opens up new possibilities for integration to photonic integrated circuits, although this is beyond our latest AirForce contract," he adds.

Innovation
keeps silicon on top

Lux Research forecasts novel circuit design, and more, will sustain silicon's mammoth market share and stunt compound semiconductor growth. Rebecca Pool reports.

AS WIDE BANDGAP materials, including SiC and GaN, make inroads to power electronics applications, silicon will hold on to its lion-share of the market, at least for the next decade, report US-based Lux Research analysts.

Thanks to innovations in circuit design, control, as well as module packaging, silicon-based power electronics will sustain a mighty 87 percent market share – worth some $20 billion – of the power electronics market in 2024.

"In reality silicon is reaching its theoretical limits of performance but through innovations, companies can eke out efficiency improvements, making [silicon-based power electronics] good enough for now," highlights Lux Research analyst, Pallavi Madakasira.

"What this really means is that for most applications, if not all, we are going to see delayed adoption of GaN and SiC in contrast to what [compound semiconductor] players would have hoped for," she adds.

Stretching silicon

Research from Madakasira and colleague, Tiffany Huang, reveals that innovations in circuit design will have, by far, the biggest impact on the efficiency of silicon-based devices.

According to Huang, many start ups, including Ambiq Micro, US, and India-based Ineda, have pioneered integrated circuits that dramatically reduce power consumption in today's silicon chips, in some cases, by almost a factor of ten.

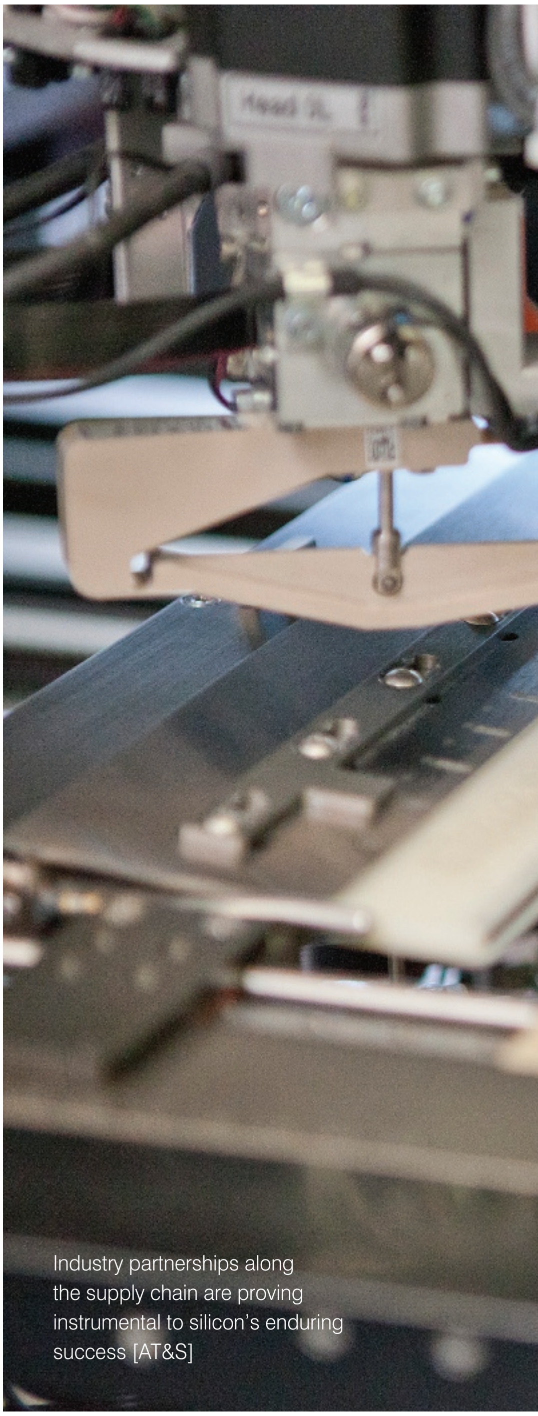
At the same time, established players, such as Texas Instruments, Qualcomm and Maxim Integrated, are working on ultra-low-power circuit design. And as Huang adds: "All these circuits also promise a small form factor which is good news for Internet of Things applications, as well as mobile devices."

Innovations in control methods are also set to keep silicon semiconductors alive for longer, by boosting chip efficiencies and reducing the footprint of chips in power modules.

Huang highlights how myriad US-based industry newcomers, including Cirasys, GridCo and FINsix as well as the likes of ABB, Dialog and Omron, are developing a vast array of advanced control methods for power conversion applications.

For example, University of Texas at Dallas spin-out, Cirasys, uses envelope tracking to optimise power supply voltages and boost silicon chip efficiencies. Meanwhile MIT graduate-founded FinSIX is pioneering power converters that switch at extremely high frequencies to reduce chip footprint and slash switch-mode power supply sizes.

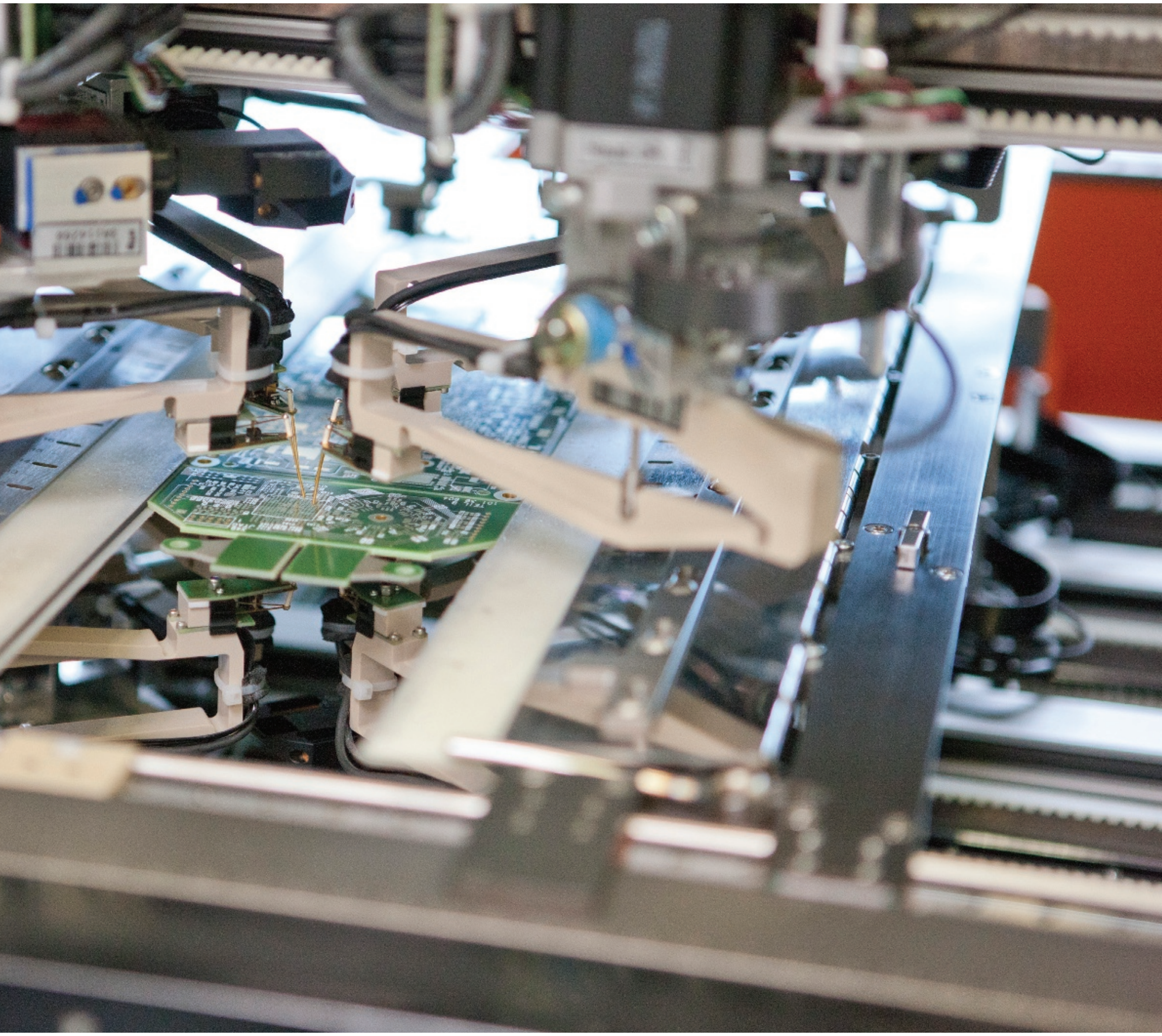
And lastly, electronics manufacturing heavyweights, such as Bosch, Schneider Electric and AT&S are also busy splashing cash and forging partnerships to drive module packaging forward.



Industry partnerships along the supply chain are proving instrumental to silicon's enduring success [AT&S]

As Huang points out, Bosch, for example, has shaved off the size of its IGBTs to maximise air flow and improve thermal management in modules while AT&S is stacking chips and developing 3D PCBs for a smaller, more energy-efficient package. "The large incumbents here have the cash on hand to develop technical products," she says.

And crucially, partnerships are proving as important as ever. "You tend to find that different players along the supply chain, from discrete companies to the OEMs, [are working together]," says Huang.



"For example, AT&S have partnered with Continental Automotive, which manufactures novel module packaging."

Indeed, the meeting of minds up and down silicon's established supply chain is proving to be a formidable driving force for silicon success across each innovation sector, be it circuit design, control, or module packaging. In each case, start-ups see success but incumbents dominate.

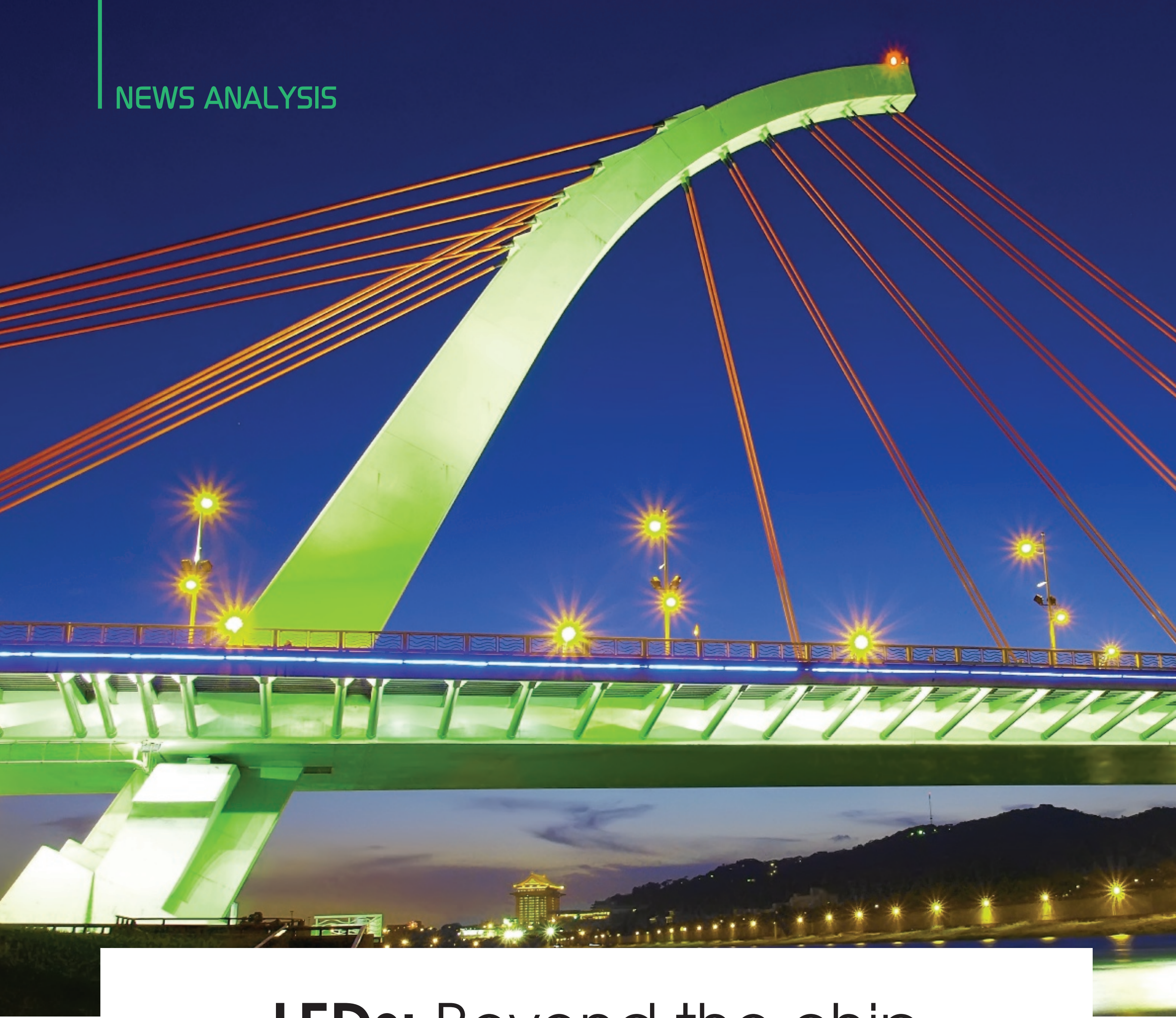
"Silicon is so well known and there are so many companies in the supply chain," says Huang. "From foundries to packaging companies, these players can really help OEMs drive innovation and push the limits of silicon devices."

"Silicon costs are also so much cheaper than using wide bandgap materials so we see these large incumbents sticking to what they know while developing wide bandgap devices on the side," she adds.

So where does silicon incumbent weight leave the likes of MACOM, EPC, GaN Systems and more? At least for now, waiting for power-hungrier applications to truly take-off.

"The bigger [silicon] companies will keep doing as much as possible to push the adoption of GaN and SiC out into the future," asserts Madakasira.

But, as she adds: "Emerging applications, such as driverless cars and the Internet of Things, will demand even more power efficiency and this will drive the impetus to switch to the more expensive, but more efficient, compound semiconductor materials."



LEDs: Beyond the chip

Why is SemiLEDs increasing its portfolio, by adding flip-chip designs to its family of LEDS that sport a vertical architecture? Rebecca Pool investigates.

PERHAPS BEST KNOWN for its highly successful, vertical architecture, high power LEDs, SemiLEDs of Taiwan recently joined the growing pack of LED manufacturers to offer flip-chip devices.

The company's recent line of white LEDs in enhanced flip-chip, chip-scale packages are based on a horizontal chip structure, and have been developed to capture a greater portion of the ever-growing lighting market.

As part of the flip-chip construction, the chip's electrical contacts are moved to the bottom of the chip, eliminating the need to run failure-prone bonding wires from the top of the chip to the package.

As a result, the chip is more robust, fully compatible with surface-mount processes and can be very closely mounted to other chips, opening the door to densely packed LED arrays for higher Lumen density applications.

"We've spent a lot of time developing our chip-scale packaging," highlights SemiLEDs' executive vice president of operations, Mark Tuttle. "Our flip chip was originally developed as a standalone version, but has been predominantly used in a chip-scale packaging formula and in terms of chip-scale packaging, we have a very small package."

While common surface mount device (SMD) LEDs come in at 3.5 mm by 3.5 mm, the chip-scale package dimensions are only 1.4 mm by 1.4 mm. And as Tuttle is keen to highlight, the emitters in its package have already been phosphor-coated, using its 'Ready White' proprietary coating process.

Crucially, for the lighting manufacturer, this step removes the need to apply phosphor at the package-level, a complex and time-consuming process.

"There's a lot of technology in phosphor and companies just don't want to invest and maintain this if they don't have to, so this shortens design time and time-to-market [for these manufacturers]," he says.

"So, with the chip-scale package and phosphor intact, they are already buying the correlated colour temperature and colour index that they need for a given application," he adds.

So with potential space savings and cost savings, SemiLEDs chip-scale packaged LEDs clearly offer new options to time-constrained lighting designers after more for their money, be it more Lumens per dollar, or even more Lumens per unit area.

As Tuttle's colleague and sales manager at SemiLEDs, Frank Wu, points out: "Right now, many in the industry are working at a systems level, so when you can pack LEDs closer together, you reduce the amount of material you need at the fixture or module level, reducing total cost of ownership here."

"We've seen key players in the market talk about Lumen per Watt, then Lumen per dollar and now we're seeing Lumen per unit area," he adds. "This is something we're very much working towards increasing."

Vertical designs

But what of SemiLEDs well-established vertical LEDs? In Tuttle's words, while the flip chip LEDs have, 'been a very different project', its focus is also firmly on a growing fleet of vertical LEDs.

Earlier this year, the company introduced its phosphor-converted LED chip series, a range of LED chips coated with the 'ReadyWhite' phosphor to emit red, green and amber light.

The LEDs join a family of white phosphor-coated LEDs, and in each, the vertical structure consists of a GaN layer coated with a mirror and then copper alloy, which acts as an anode, reflector and thermal conductor.

Crucially, ditching the typical sapphire substrate for a copper alloy base boosts heat dissipation through the chip and out of the heat sink while the vertical architecture enables a vertical current path to prevent current crowding. The end result is a high power LED with high efficacy and long lifetime.

"If you want the highest power output and to deliver the highest current in, and also get rid of the heat, then the vertical structure is still the best," highlights Tuttle. "Even though we now offer chip-scale packaging, the power is higher in the vertical architecture, it really is king of the hill."

But while SemiLEDs set out to develop its high-power LEDs for general lighting markets, its choice of applications has changed. "We've been producing high-power LEDs from the beginning but the general lighting has gone in a different direction, demanding lower power, and at most, medium-power LEDs," says Tuttle. "So when the general lighting market moved away from high power, then of course it moved away from us as well. We've been focusing on other markets for many years now."

One up and coming application is high-bay illumination – be it in a warehouse or stadium – where high-power lighting with a focus is key. Agricultural settings, from dairy barns to storage facilities, are also beginning to demand LED high-bay lighting systems.

But without a doubt UV LED applications are very critical to SemiLEDs right now. The company has already delivered LEDs for the industrial curing of adhesives and coatings, and is developing shorter-wavelength LEDs for purification applications.

A key aspect of the relatively low adoption of UV LEDs in industrial settings has been attributed to system integration issues, but SemiLEDs is hoping to change this. In recent years the company has moved from simply being a chip developer to manufacturing modules, and is now looking to provide ODM/OEM sevices to produce entire systems.

As Wu highlights: "When we started out with just chips, we had a lot of customers asking for an optimised package, so along the way we acquired companies to do packaging for us. Now we have people asking us to build an entire lamp."

Indeed, as Tuttle emphases, simply being a chip developer isn't a strategy for success any more. "The margins are just too small with chips, even custom chips," he says.

So what is? "We started with the LED and built on that," says Tuttle. "Our vertical structure had proven itself all the way through and is still the architecture of choice for high power."

"But in recent years, we have been looking more into modules as well as systems integration, so we're not just reliant on the fundamental core of the LED," he adds. "Like many other companies, we have known that you need to get away from the chip on its own and be involved with the whole integrated system."

Alta Devices thin film solar allows batteries to last longer outdoors and indoors

Uncovering new opportunities for III-V cells

Terrestrial opportunities for III-V cells are not limited to concentrating photovoltaics: These devices can also form flexible, efficient power sources for unmanned aircraft, smartphones, tablets and automobiles.

BY ROBERT PARENTI FROM ALTA DEVICES

WHEN NEIL ARMSTRONG took his first steps on the moon on July 20, 1969, the Cold War Space Race came to an end.

That most famous of days of the twentieth century was a high point for the US, which had been battling with Russia since the 1950s to be the leading force in space exploration. The communist superpower drew first blood, thanks to its successful launch of the first two satellites, Sputnik 1 and 2, but it didn't stay ahead for long. Five months later the US fought back with the launch of Explorer 1, before breaking new ground on 17 March 1958 with the launch of Vanguard 1 – the first satellite to be powered by solar cells.

This satellite, which is still orbiting the world today, features cells made from silicon. It is this form of solar technology that has been used on many of the proceeding satellites – but its ascendancy has not lasted to today, due to the development of the GaAs and III-V solar cells in 1970 by Zhores Alferov from the Ioffe Physico-Technical Institute of the USSR Academy of Sciences.

These compound semiconductor cells are superior to those based on silicon, by being more robust to moisture, radiation,

and ultraviolet light; boasting the highest efficiencies (solar-to-mechanical energy); and exhibiting extremely low degradation with temperature increases.

Thanks to these strengths, by 1990 GaAs had surpassed silicon as the most widely adopted solar technology in space, and today single and multi-junction III-V solar panels are considered the industry standard.

That is not to say, however, that III-V cells are faultless. Weaknesses include being rigid, heavy and limited in size, and having wafer costs around two hundred times those of silicon. The latter impediment has restricted their use to government-funded projects, mainly in space.

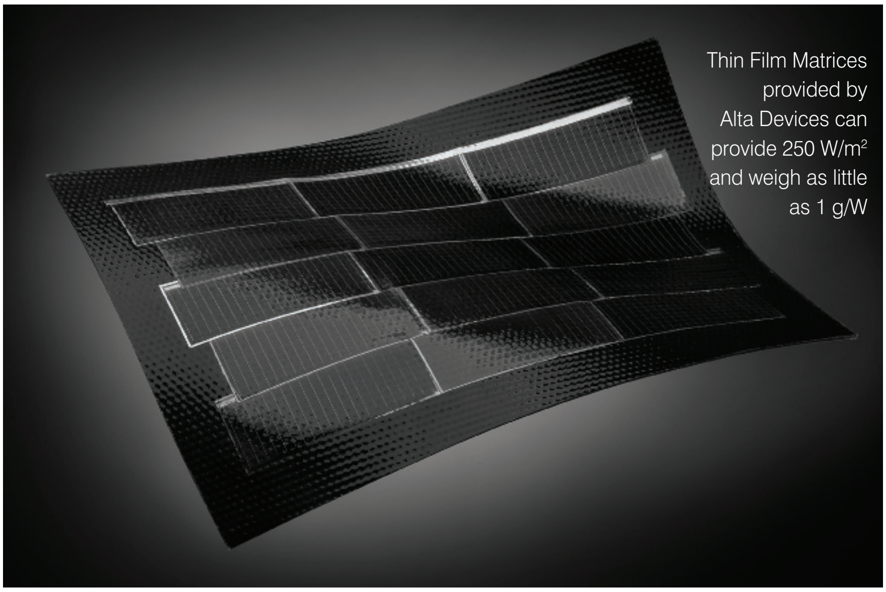
But what would be possible if GaAs cells were cheap, lightweight, flexible, and durable – and delivered all these attributes while maintaining a high efficiency?

At Alta Devices of Sunnyvale, California, we are working on turning this vision into a reality. The mission of our company, which was founded in 2008 by academics Harry Atwater of Caltech and Eli Yablonovitch of the University of California, Berkeley, is to bring mobile power to the masses. To succeed in this endeavor we have developed a process that allows us to grow and separate thin films of GaAs from the top of single crystal wafers, which can be reused, thereby slashing substrate costs.

Another strength of this process is the high efficiencies that can be realized – in 2011 we propelled the single-junction solar cell efficiency record to 28.8 percent. This is close to the theoretical limit, and surpasses the best silicon solar cells, which can offer an efficiency of up to 25 percent.

On top of this efficiency benefit, GaAs thin-film cells deliver additional advantages: They weigh less, and because they are flexible, they can wrap around curved surfaces.

Simply looking at the efficiency figures fails to provide a full appreciation of the superiority of GaAs cells over those made from silicon. Due to the higher bandgap of GaAs, electrons generated in the photovoltaic process are excited to higher energies, enabling higher aerial power densities. What's more, cells made from this binary alloy convert light into energy across the entire visible and into the near infrared spectrum, making them suited to not only the outdoors, but also cloudy, low light, and even indoor applications. Although a handful of silicon-based materials can provide power indoors, their efficiencies are almost three times lower than those of GaAs.



Thin Film Matrices provided by Alta Devices can provide 250 W/m^2 and weigh as little as 1 g/W

Our claim of the superiority of GaAs over silicon is backed up by independent studies conducted by the National Renewable Energy Laboratory (NREL). This investigation revealed that our GaAs solar cells produced more energy than those made from silicon when operated under the same conditions – and when conditions changed, due to an increase in temperature, the reduction in performance was much smaller.

The strengths of solar cells made from thin films of GaAs and other III-V materials will allow them to operate in new markets, rather than fight for use in large solar panels that line roofs and traverse the Western deserts of the US. Thanks to their high aerial power densities, these materials can thrive within the relatively untouched mobile markets. Their inherent properties, which are particularly suited to providing power indoors, would allow them to win sales in automotive, unmanned aerial system, portable power, wearable, smart phone, tablet, and Internet of Things (IoT) markets. It should even be possible to extend the battery life of low-power IoT and wearable devices indefinitely, by coupling thin-film GaAs solar cells with the latest energy-harvesting chips.

Cutting the cord with mobile solar technology is not just a benefit to those in developed nations – it could also make a big difference to the lives of those living in the poorer nations of the world. Here, the demand for devices that connect to the internet is rising fastest. Last year alone, while web usage on mobile devices increased 25 percent globally, it shot up by 40 percent in Africa, despite the vast majority of those living there having limited access to electricity. Traditional power grids cannot keep pace with this rising demand, but this gap can be plugged by smarter and cleaner solutions, such as thin-film GaAs solar technologies.

Given the abundance of gallium and arsenic, which are relatively inexpensive to extract and obtain, there is no reason why there cannot be a world filled with GaAs solar cells. And their cost should not hold back sales, thanks to the manufacturing processes that we have developed for mass production of highly efficient thin-film cells. So following decades of development and deployment on satellites, the time has now come for GaAs solar cells to come back to earth with a splash.

Alta Devices solar provides clean and renewable energy to Aston Martin Racing's FIA World Endurance Championship car without limits.

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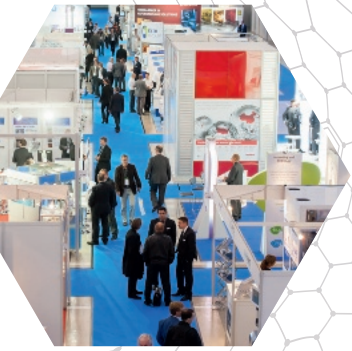

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CS Mantech shines a spotlight on GaN

Existing and emerging opportunities for GaN transistors and ways to make them even better lay at the heart of this year's CS Mantech.

BY RICHARD STEVENSON

SHORTLY AFTER the turn of the millennium, GaAs Mantech became CS Mantech. And hindsight shows that those behind the decision to rename the conference made a wise decision. While developments in GaAs devices and manufacturing technologies still feature heavily at this gathering, many of the talks are now devoted to advances in GaN.

That was certainly the case at this year's meeting, held from 18-21 May in Scottsdale, Arizona. At this conference some speakers showcased the tremendous performance that products made from GaN can offer, while others either highlighted new markets where this class of device can serve, or unveiled new approaches for either addressing weaknesses in reliability or taking breakdown voltages to new highs.

One area where GaN can make an impact is in mobile devices. These gadgets have transformed our lives, providing access to e-mail and the web when on the move – but by the end the day, we are often hunting around the house for a cable, so that we can re-charge the battery. A move to a wireless power supply for charging the mobile would be very welcome, and approaches involving GaN transistors are showing much promise, according to a paper delivered by Tatsuya Hosotani from Murata Manufacturing Company.

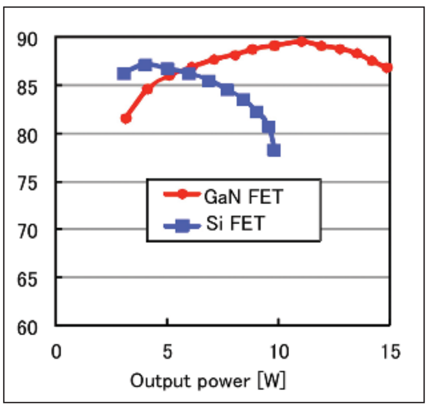

Figure 1 : For wireless power supplies, GaN FETs are more efficient than those made from silicon, and they are capable of transmitting more power. The y-axis is percent efficiency.

Hosotani and his co-workers started considering the use of GaN transistors for wireless power supply and wireless charging in 2009, and in Scottsdale he announced the results of experiments that showed a power conversion efficiency from the DC power source to the load, via RF transmission, of 89.5 percent (see Figure 1). The output power of this wireless power supply was 22.4 W.

The frequency selected for power is regulated, in order to minimise interference with mobile devices. There are industrial, scientific and medical (ISM) radio bands that have been allocated for these uses, rather than that of communication, and they exist at 6.78 MHz and 13.56 MHz. The Murata team have used the lower of these bands, building wireless power supplies

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Talks:

Plasma etch and deposition processes for GaN and SiC power semiconductor devices

Speaker: Chris Hodson, Product Manager Power Semiconductor and ICT devices, Oxford Instruments

Silicon Compatible GaN Power Electronics

Speaker: Professor Iain Thayne, Professor Ultrafast Systems (Electronic and Nanoscale Engineering) University of Glasgow

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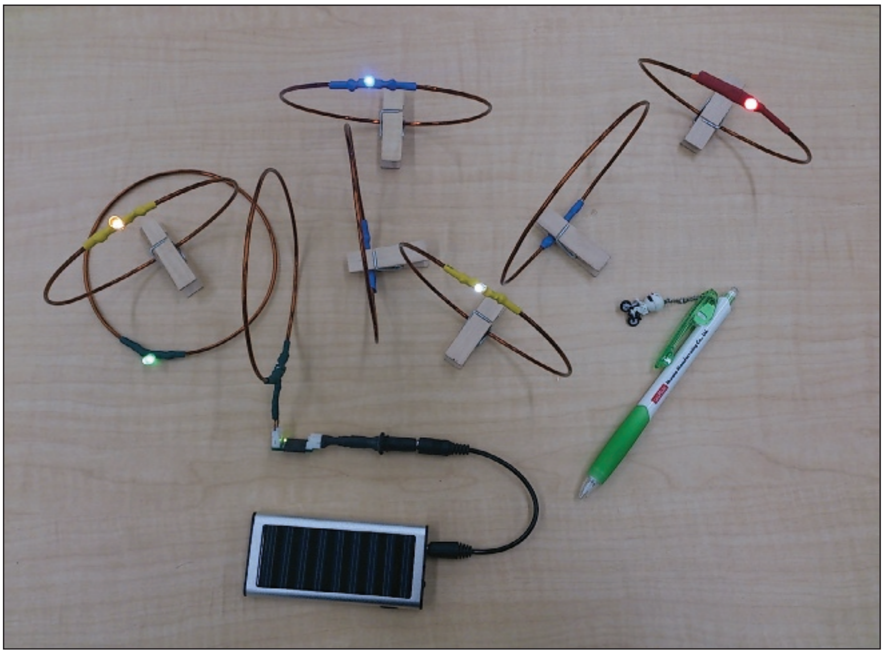


Measurements determined that GaN FETs could form a wireless power supply with a DC-RF-DC power efficiency of 89.5 percent. Operating at 6.78 MHz, this system produced an output power of 22.4 W.

with GaN FETs from EPC.

Inducing electromagnetic resonance transfers power. DC power is intermittently supplied to create a RF electromagnetic resonance field, which is transmitted and then converted back to a DC form. Note that this technology is not restricted to supplying power to mobiles and tablets, and could be used for small battery-powered electronic devices and communication cards.

Measurements of power conversion efficiency were made with a system featuring a single loop of copper wire with a diameter of 2 mm and a radius of 50 mm. With coils separated by 3 mm, an output voltage of 61.8 V and a supplied power of 22.4 W were realised at an input voltage of 18 V. In comparison, a system with silicon FETs produced an inferior efficiency of 87.1 percent, and due to the poor performance of this class of transistor at high frequencies, power supplied by this system was restricted to below 10 W.

"We will be able to get to even higher efficiencies by devising a new power conversion technique and by using new power compound semiconductor devices," explained Hosotani in an interview with *Compound Semiconductor*. He expects the first commercial wireless chargers incorporating GaN FETs to hit the market two or three years from now. To enable this, he and his co-workers will be developing power transmitting and receiving modules for various products.

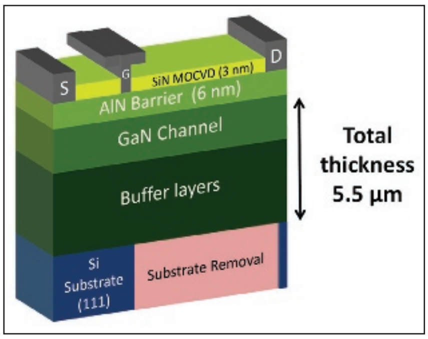


Figure 2: Partial removal of the silicon substrate can propel blocking voltages for the GaN HEMT to 2.3 kV.

To higher voltages

One of the weaknesses of the GaN-on-silicon HEMT is its relatively low breakdown voltage. To increase this, a team from the Institute of Electronics, Microelectronics and Nanotechnology in Villeneuve d'Ascq has developed a new device architecture that involves local substrate removal (see Figure 2). This modification to the design supresses parasitic substrate conduction, and holds the key to propelling blocking voltages to 2.3 kV.

"This is a record breakdown voltage," claimed the leader of this team, Farid Medjdoub, who pointed out that this record was realised with a barrier thickness below 10 nm. And even higher voltages are possible, with the team to soon publish a paper reporting a 3 kV AlGaN/GaN transistor.

The work described at CS Mantech involves 4-inch GaN-on-silicon epiwafers grown by EpiGaN. They feature a 5.5 µm-thick buffer, a GaN channel with an unspecified thickness, a 6 nm-thick AlN barrier, and a 3 nm-thick Si_3N_4 cap layer.

Device formation began with the addition of an ohmic contact formed from a Ti/Al/Ni/Au metal stack. This step involved removal of part of the SiN film. Following rapid thermal annealing of these contacts at 875 °C, devices were isolated by nitrogen implantation, before gates with a length of 1.5 µm were defined by electron-beam lithography. The gate metals, a pairing of nickel and gold, were deposited on top of the AlN layer by carefully etching the SiN cap with a low-power SF_6 plasma.

Thinning and polishing of the substrate to 200 µm followed, before wafers were loaded into an STS tool, where reactive ion etching removed silicon up to the buffer layer in the area around the drain of the transistor.

"It takes about 90 minutes to locally etch the 200 µm-thick silicon substrate," explained Medjdoub, who believes that the process is fully compatible with high-volume production, because backside-silicon deep etching is commonly used in industry.

The team compared the DC characteristics before and after substrate removal, considering 50 µm-wide devices with a 30 µm gate-drain spacing. At a gate-source voltage of 2 V, the DC output current density dropped from 0.55 A/mm to 0.45 A/mm after etching, due to degraded thermal dissipation within the trench. This also impacted the specific on-resistance, which climbed from 4.1 mΩcm² to 4.6 mΩcm² following local substrate removal.

Superior breakdown voltages stemming from substrate removal only occur at longer gate-drain distances (see Figure 3). When these contacts were 30 µm apart, the conventional device blocking voltage was around 1.6 kV, compared to 2.3 kV for a comparable device featuring substrate etching.

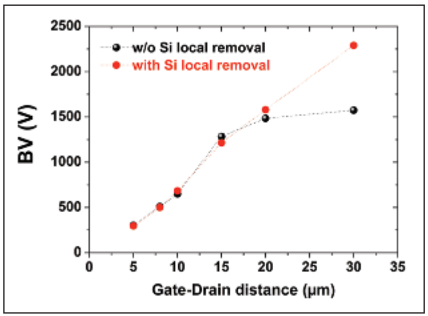


Figure 3: Benefits of higher blocking voltages are uncovered at greater gate-drain distances.

Adding field plates and dielectrics under the gate promises to take the performance of these devices to a new level. "This is definitely in our plan," said Medjdoub, who is aiming to include these refinements in a normally off transistor.

Cutting current collapse

One of the biggest weaknesses of the GaN HEMT is that it can suffer from current collapse: That is an increase in the on-resistance after the transistor is switched from the on to the off state. This is believed to originate from a trapping of electrons on the AlGaN surface.

Several ways have been proposed to address current collapse, including high-pressure, water-vapour annealing, which is an approach developed by a team from Nara Institute of Science and Technology, Japan. At this stage of research, the spokesman for this team, Joel Asubar, told *Compound Semiconductor* that they cannot be certain that their approach is the most successful one for addressing current collapse – but they are convinced that it is one of the simplest methods for doing so.

Evaluation of the high-pressure, water-vapour annealing process involved treating devices prior to SiN passivation (see Figure 4). GaN-on-SiC HEMTs featuring a 25 nm thick $Al_{0.2}Ga_{0.8}N$ barrier were subjected to annealing at 0.5 MPa for 30 minutes at temperatures of 200 °C, 300 °C and 400 °C.

Measurements revealed that the maximum current density for the device was nominally identical to that of a control sample, indicating that high-pressure water vapour-annealing did not induce any significant change in the DC operation of the device.

To represent current collapse quantitatively, the team evaluated the normalised dynamic ratio of the device. They defined this figure-of-merit as the ratio of the dynamic on-resistance to the static on-resistance. It tends to one when the device is subjected to longer pulses, which will allow more time for the detrapping of electrons – and greater recovery of the dynamic on-resistance (see Figure 5).

This result indicates the capability of addressing current collapse with high-pressure water vapour annealing, which is argued to be a process that is compatible with high-volume manufacturing. "All we need is a heater, high-purity deionized water and a chamber. These are all readily available in any semiconductor fabrication facility," said Asubar.

With work still at an early stage, the impact of the annealing process on HEMT performance is still under evaluation. "But at this point, we have not obtained any data suggesting high-pressure water vapour annealing degrades HEMT performance," claimed Asubar.

He and his co-workers are trying to understand why the annealing process cuts current collapse. Simulations that fit curves to data for the normalised dynamic ratio as a function of pulse length suggest that HEMTs have six trap levels with energies between 0.28 eV and 0.6 eV. However, this reduces to two traps at 0.28 eV and 0.37 eV after annealing. Meanwhile, X-ray photoelectron spectroscopy suggests that annealing leads to formation of an oxide layer, which is suitable for passivation and the filling up of near-surface nitrogen vacancies.

One of the next goals for the team is to determine if their annealing process impacts the long-term performance of devices. "Also, aiming for collapse-free operation, we have done preliminary work on combining high-pressure water-vapour annealing with field-plate approaches," revealed Asubar. "Our initial results are promising."

Perfecting the package

The higher powers produced by RF GaN devices have fuelled efforts to develop new packaging technologies that offer a low-cost, effective approach to thermal management. The traditional approach for housing of high-power RF components is to use metal-ceramic packages and assembly processes (see Figure 6). Products that result are reliable, consistent, and capable of dissipating heat, but production costs are very high and throughput limited.

"For a traditional multi-level package there is usually more cost in the package

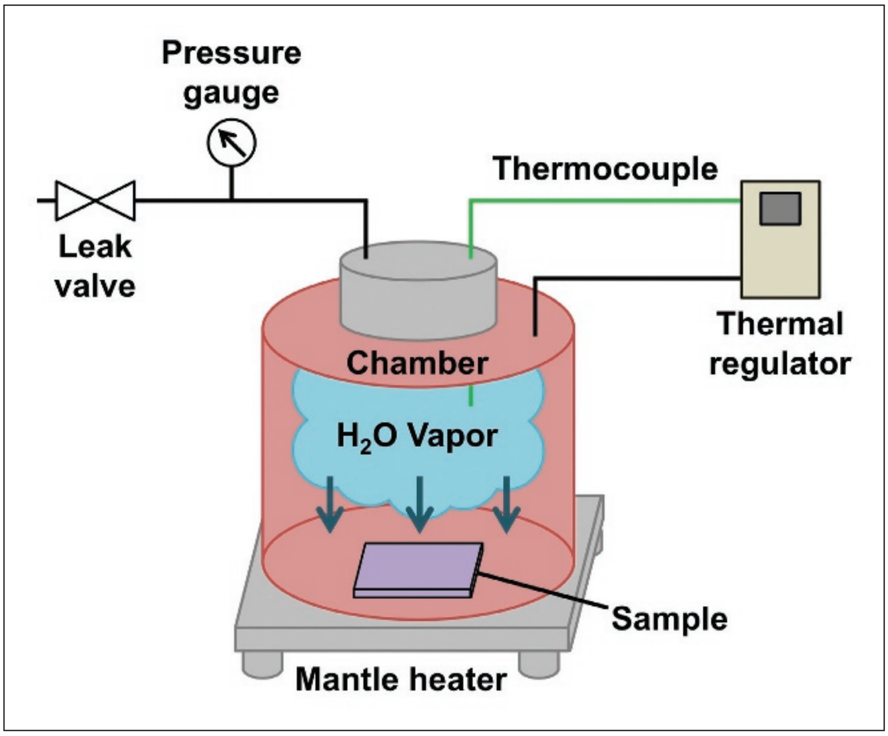


Figure 4: High pressure annealing in water vapour is able to cut current collapse in GaN HEMTs.

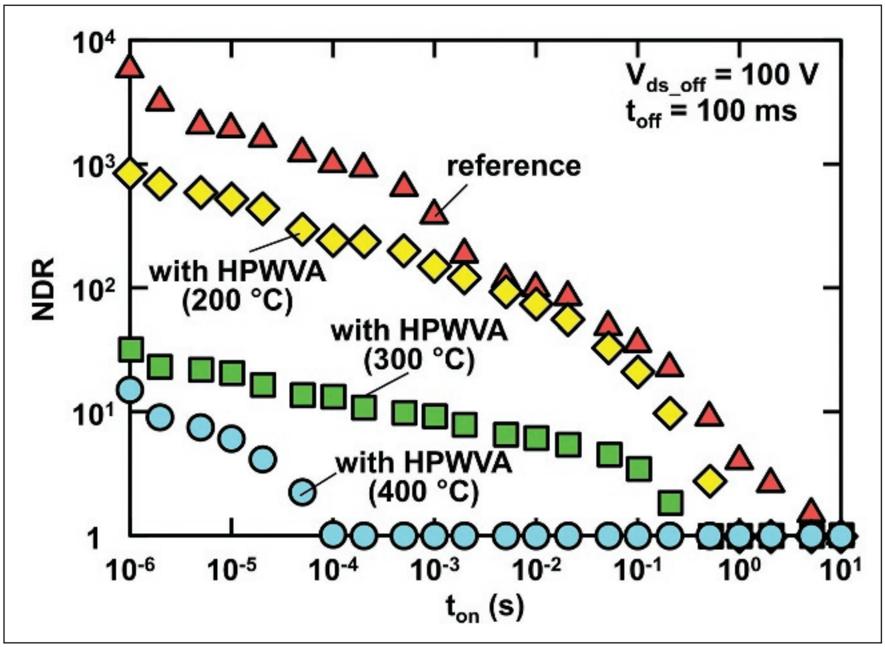


Figure 5: A high-pressure water-vapour anneal (HPWVA) reduces the normalised dynamic resistance, which is the ratio of dynamic on-resistance to static on-resistance. t_{ON} is the length of the applied pulses.

of a multi-level package, while adopting the plastic overmould assembly process.

"We have released products with this technology and are running regular volumes in production," explained Martin. These products can deliver a CW output of up to 200 W, while still operating below the maximum junction temperature for the device.

Development of this alternative packaging technology has involved selecting and qualifying mould compounds for the different package types and device technology. Traditional mould compounds for plastic parts have a glass transition temperature of 115 °C to 140 °C, and above that they transition from a hard to a rubbery state, which has a different thermal expansion coefficient, and can damage the device and the wire bonds. However, turning to new overmould materials can address this, because they have glass transition temperatures of 170 °C to 235 °C.

materials and assembly than the die, even for GaN. The range is from about 40 percent to 75 percent," explained Quinn Martin from MACOM Technology Solutions.

For this reason, there are times when die are packaged in a co-planar technology, which has the the source and pins at the same level – usually on the backside of the package. With that design, the part can be surface mounted onto a printed circuit board along with all the other components through a reflow process.

Plastic overmould parts are manufactured in this way, and they lead to significant cost savings compared to a metal-ceramic multi-level package. According to Quinn, the cost reduction is not just a few percent, but is measured in factors such as 1X, 2X, etc.

However, the downside of this approach is that for heat to get out of the device, it must first travel through the package and PCB before it reaches a better heatsink, the metal carrier (see Figure 7). The PCB is a terrible material for heat dissipation, with a thermal conductivity below 1 W/m-K, and this governs the poor thermal dissipation of the die.

Multi-level packages address this issue. The source and the pins are at different heights, so the electrical connections can be made through the leads at the top of the PCB, while the source rests on the heat sink near the bottom of the PCB. But the downside is the cost, due to the use of metal-ceramic air cavity packages.

To drive down costs, MACOM has produced a package that offers the best of both worlds: It has the thermal benefits

MACOM has also made advances in the material used to attach the die to the package. In air cavity packages, AuSi and AuSn eutectics are often used to bond the die to a metal flange. This provides a reliable, low-thermal-resistance connection. But for plastic packages, thermal conductivity is compromised by epoxy die, which is used because it is more compatible with the associated production equipment.

Improvements are possible by turning to new materials that incorporate gold, silver or copper particles in an epoxy/organic matrix. When properly cured, sintering results in a material capable of combining a strong bond with a thermal conductivity that can be higher than that of a eutectic and hit 200 W/m-K.

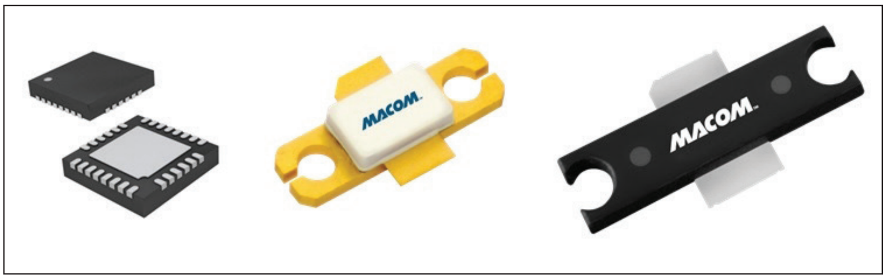


Figure 6: Co-planar (left) packages tend to feature plastic overmoulded parts that trim cost, but impair heat extraction when they are used in PCB circuits. Multi-level packages made from metals and ceramics address this, because the bottom of the package can be in contact with the carrier. However, this approach is expensive. Multi-level plastic overmould parts made by MACOM offer the best of both worlds, combining low cost with good thermal management.

High-frequency GaN

One company with a strong pedigree in high-frequency GaN amplifiers is Qorvo, a firm formed in early 2015 from the merger of TriQuint and RFMD. At this year's CS Mantech, it took the opportunity to discuss its 0.15 µm GaN MMIC technology for 2 GHz to 50 GHz power amplification that was originally developed at TriQuint's facility in Richardson, Texas. According to Qorvo, there are several companies that can supply GaN MMICs operating between 2 GHz and 20 GHz, but very few of them are offering production quantities at higher frequencies.

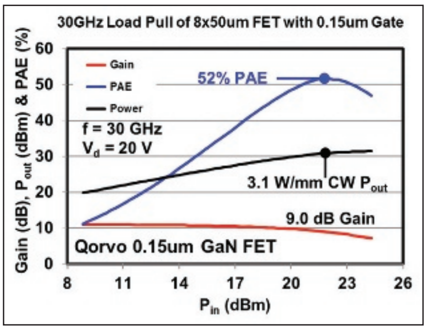


Figure 8: Loadpull measurements at 30 GHz on a pre-matched 8 x 50 μm device biased a 20 V.

Qorvo's AlGaN/GaN HEMT epiwafers are formed on 4-inch SiC and have a proprietary epitaxial structure that features a semi-insulating GaN layer for improved isolation, an undoped GaN channel layer and an AlGaN layer. The devices have ohmic source and drain contacts made from Ti/Al, an active area defined by etching a mesa, and an 0.15 μm gate created by electron-beam lithography and plasma etching of SiN. A source-connected field plate is added over the gate channel. "This is used to improve the building block transistor's power performance and maximum stable gain," said Ming-Yih Kao, Engineering Fellow at Qorvo.

Other components in the MMICs include TaN resistors and SiN capacitors. These are joined using three levels of metal interconnects, including a gold-plated airbridge. Following all this front-side processing, substrates are thinned to 100 μm, and backside via etching and metallisation for the backside ground plane of the MMIC is undertaken.

Measurements of device characteristics for the HEMTs indicate a maximum drain current of 1.15 mA/mm and a maximum transconductance of 425 mS/mm (see Figure 8 for the results of other measurements).

According to Kao, the Qorvo 0.15 μm QGaN15 process offers a higher transconductance, a smaller gate capacitance and a higher cut-off frequency compared to its QGaN25 process, which it has been using to make amplifiers in the S-band and X/Ku band for more than a decade.

Products made with the QGaN15 process include 4 W and 8 W amplifiers operating at 30 GHz. They produce a power-added-efficiency of more than 25 percent between 27 GHz and 31.GHz. And withmore products are in the pipeline, this portfolio is set to grow.

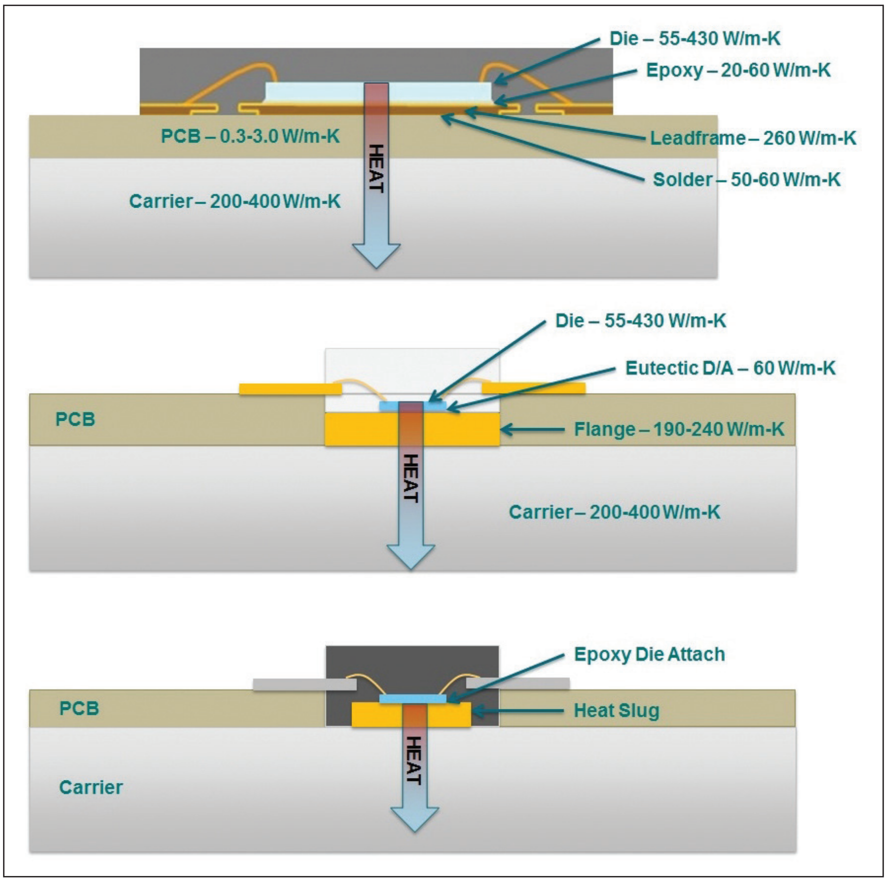
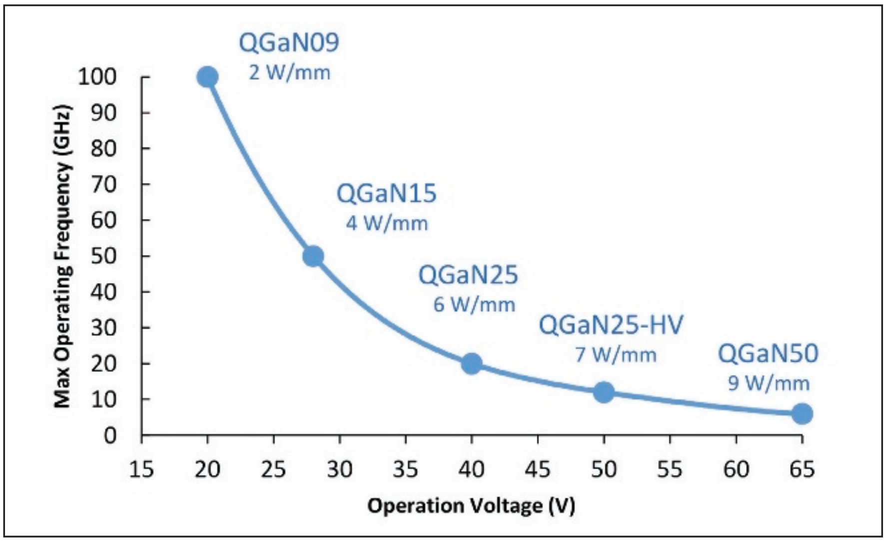


Figure 7. Heat extraction with co-planar parts is poor, due to the very low thermal conductivity of the PCB material (top). Turning to a multi-level part improves heat extraction (middle), and this can be aided by switching from a eutectic to an epoxy that features metal particles (bottom).



The portfolio of Qorvo GaN processes can cover various commercial and defence applications across a wide range of operating frequencies: QGaN15 up to 50 GHz; QGaN25 up to 25 GHz; QGaN25HV for higher operating voltages and up to 15 GHz; and QGaN50 for the highest operating voltages and up to 10 GHz operation.

This expansion of GaN products at Qorvo highlights the growing market for GaN devices. Whether they are RF, power devices, or those used for wireless power supplies, they are improving through refinements in manufacturing, the unveiling of superior chip architectures and the addressing of issues that hamper device performance, such as current collapse.

Lasers **light the road ahead**

Laser-pumped phosphors create more compact and efficient headlamps that double driver visibility

BY ABDELMALEK HANAFI AND HELMUT ERDL FROM BMW

TAKE YOUR CAR OUT AFTER SUNSET, and for every mile you go, you are about five times as likely to be involved in an accident as you would be when going for a drive during the day. Why? Well, it is partly that you are tired and are more likely to be hit by a drunk driver – but probably the biggest factor is that you don't get as good a view of the road ahead.

To try and improve visibility, while reducing the number of accidents, headlamp designers are building units that are not only more powerful – so that the driver can see further – but produce a better emission profile. The aim is to give a clear view of the road ahead, while not dazzling on-coming traffic, pedestrians and wildlife (see Figure 1).

If an emission profile is to meet the requirements for European low-beam lighting, it must generate a visibility of up to about 100 m along the driver's lane. Such a beam must also contain a narrow peak of very high luminous intensity, which is also termed an asymmetric hot-spot. Another feature is the cut-off line, incorporated to avoid blinding the on-coming traffic. In general, the different illumination profiles produced by a headlight must also conform to international regulations, a

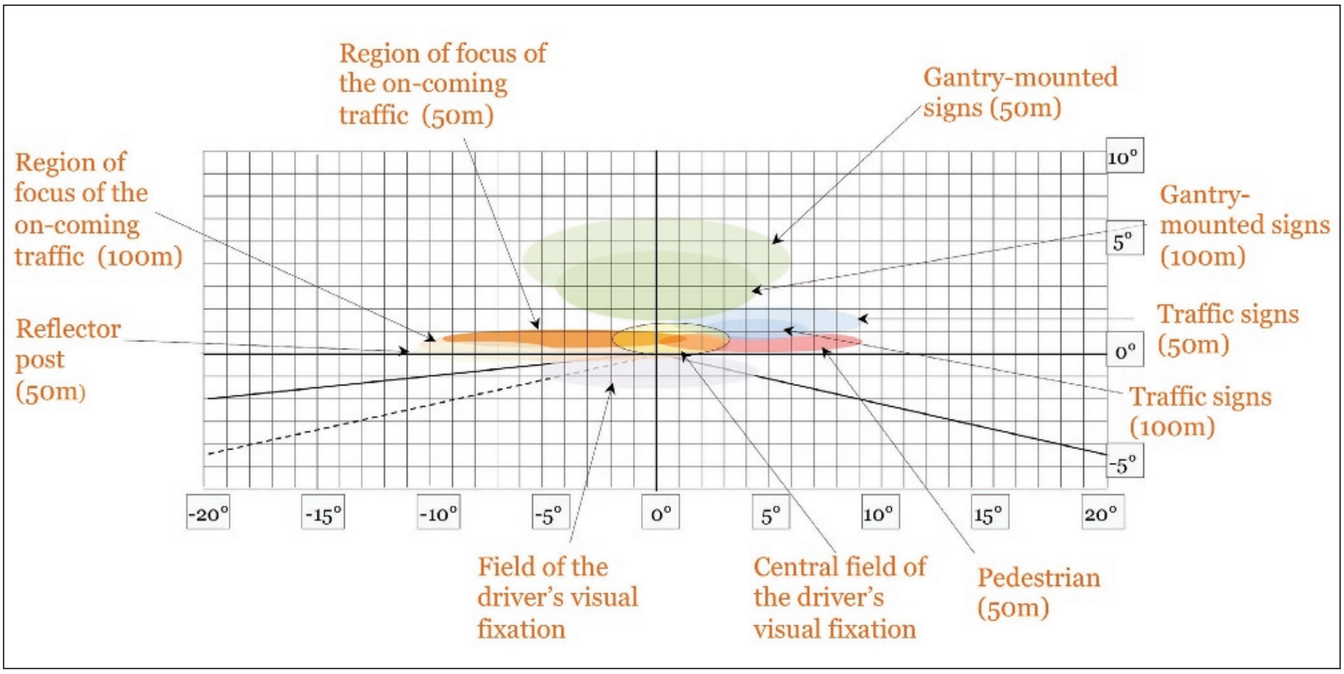


Figure 1. The illumination produced by the headlamp varies in intensity, so that it allows the driver to see road markings and pick out pedestrians, but avoids causing excessive glare to on-coming traffic and wild life. Taken from J. Damasky, "Lichttechnische Entwicklung von Anforderungen an Kraftfahrzeugscheinwerfer", Ph.D. Dissertation, University of Darmstadt (1995)

set of rules that also stipulate the characteristics of dynamic illumination patterns that can help the driver negotiate a winding road and spot pedestrians and animals (see Figure 2).

The light source

The capability of the headlight is governed by the light source. Ideally, it should be powerful enough to enable the driver to see a long way ahead, while being easy to house and package. The quality of the beam produced not only depends on the brightness and luminous flux of the source, but also on the likes of its spectral profile.

For most of the twentieth century, the incandescent bulb has been the only option for the light source in a headlamp. But in the last decades designers have been able to consider halogen and Xenon lamps, and more recently even solid-state sources.

At BMW, we integrated the first xenon-based illumination system into our cars in 1991. Compared to predecessors based on halogen bulbs, these headlamps generated more luminous flux

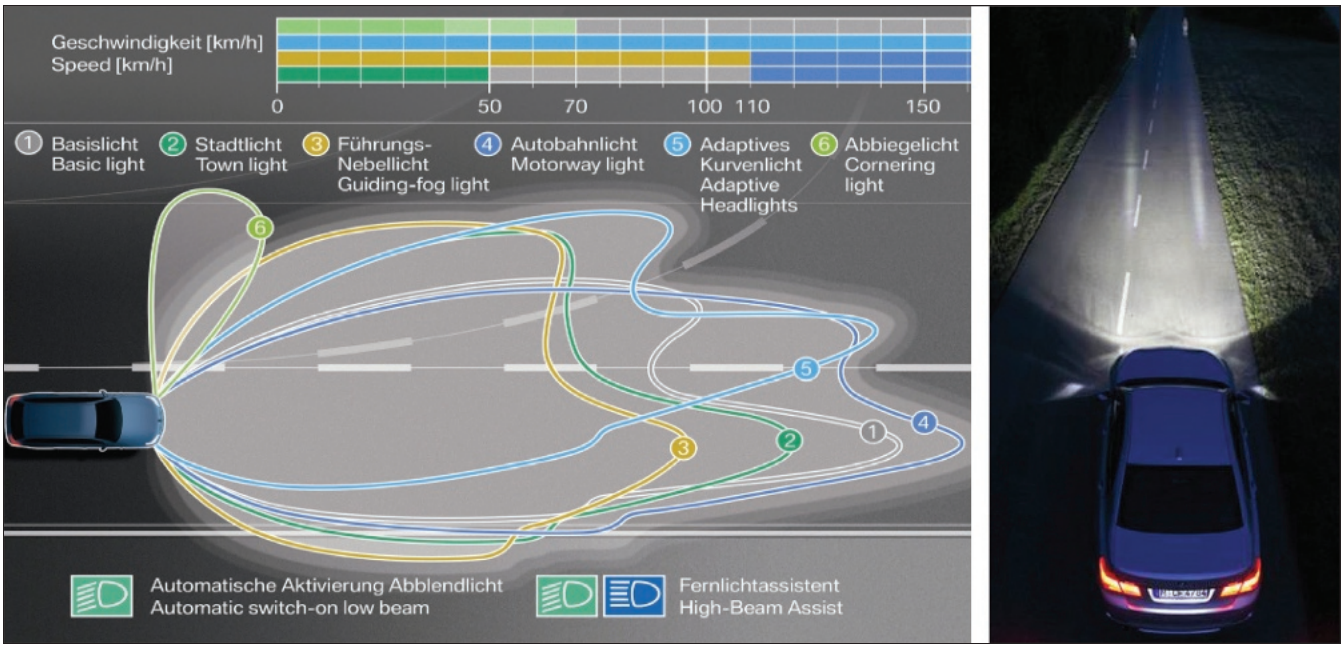


Figure 2. (a) Bird's-eye-view of several variable illumination patterns corresponding to the dynamic assisting functions (b) Marking lighting as a driver assistance lighting function: using a night-vision system, pedestrians and animals are detected, locate, targeted and automatically illuminated.

on the road, reduced power consumption and trimmed system dimensions. These headlamps even featured dynamic functions that improved driver visibility by adaptively illuminating selected parts on the road.

Recently, thanks to their compactness, many headlamp manufacturers have started to incorporate white, phosphor-converted LEDs into their designs. The small size and the particular emission profile of these high-power chips promise to concentrate light in certain angular areas, where enhanced visibility is needed. Another virtue of this solid-state source is that it unlocks greater freedom in styling, but these benefits must be weighed against two major weaknesses: Compared to the xenon source, the luminous flux from a chip is an order of magnitude lower, and the luminance is more than 50 percent less.

The luminous intensity of the asymmetric hot spot produced by the headlamp is proportional to the product of: the luminance of high-power white emitters; the aperture of the lighting module; and the efficiency associated with the collection of the flux produced by the source, to that illuminating the road. One way to increase the luminous intensity is to turn to a multi-module package. However, this increases the emitting area or leads to a reduction in the collection efficiency of the light flux. To realize the regulatory requirements of the luminous intensity on the distribution patterns (background and hotspot), multiple packages are needed, but this is detrimental to the geometry of the headlamp, which is relatively heavy and cumbersome.

LED-matrix systems address a higher variability on the distribution pattern. They feature arrays made from 80-100 individually addressable Lambertian white emitters per light-engine (see Figure 3). These systems take advantage of the instant switch on/off and dimming properties of the LEDs, and they provide a given light distribution pattern by partially overlapping several small light spots in the far-field. Even without the incorporation of additional mechanical actuators, these light engines can combine high-beam and low-beam capabilities with bending and swivelling light, and are capable of producing a glare-free high-beam. However, they do have an Achilles heel: The range of visibility is extremely limited by the limited luminous intensity of the LEDs.

At first glance, it would appear that increasing the number of LEDs in the matrix would address this shortcoming, while enabling the generation of free-patterned new dynamic light distributions, similar to those resulting from a video projector. But the requirements for such a LED-matrix light-engine are rather challenging. In addition to a higher luminous flux of the LED chips they include the need for a far-field resolution of 0.1°, a specification that corresponds to projecting a 5 cm diameter spot on a wall located at 25 m in the far field. To meet these requirements, if aberration-free secondary optics with a 60 mm focal length is used, the dimensions of the LED must be no more than 100 μm by 100 μm. But a typical phosphor-converted white LED is far bigger than this, having sides of 1 mm^2.

Another issue is the vast number of LEDs that are needed – for a field of view that is ±30° in the horizontal direction, and ±10° in the vertical, a matrix of 600 by 200 chips is required. This results in the requirement for a high power, active emitting display, which is 5 orders of intensity levels above the available technical solutions, realized by OLEDs. Despite these fundamental limitations, some semiconductor companies, car manufacturers and set-maker suppliers have been promoting this approach. However, they are compromising with the number of LEDs, using a matrix of just 1024 chips.

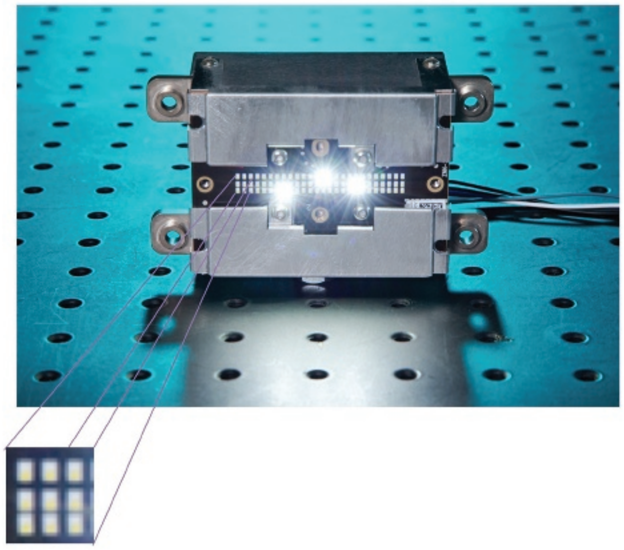


Figure 3. A matrix LED light-engine: up to 100 pixels; 130 lumen per LED (Source: Osram). Note that when this technology is used for making headlamps, each sub-set of chips is equipped with its secondary optics.

We question this approach, preferring to evaluate the requirements of vehicle lighting systems for both today and tomorrow, and based on this assessment, consider the options for the lighting source. Modern vehicle lighting systems are set to feature more lighting functions, such as dynamic driving assistance. However, incorporating this may make them bigger and heavier, while they should be heading in the opposite direction, getting smaller and lighter, to aid styling and trim energy consumption. This implies that to make better headlamps, there is a need to move on from the LED.

One of the lessons that can be learned from geometrical optics is that it is possible to reduce the size of the optical system,

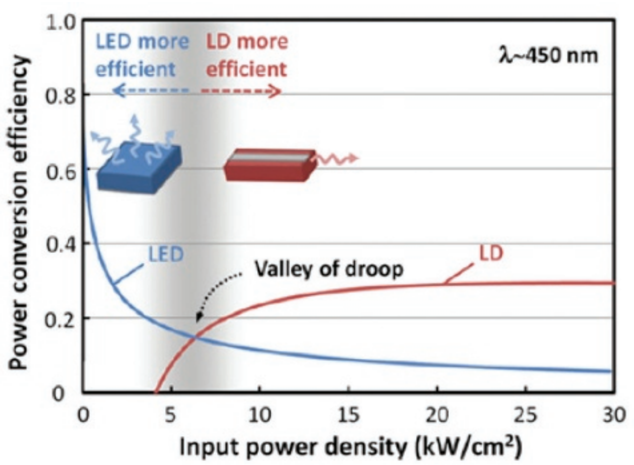


Figure 4. Droop causes the efficiency of the LED to rapidly decrease at high power densities. Such limitation is not observed in laser diodes. Taken from J. J. Wierer et. al. Laser Photonics Rev. **7** 963 (2013)

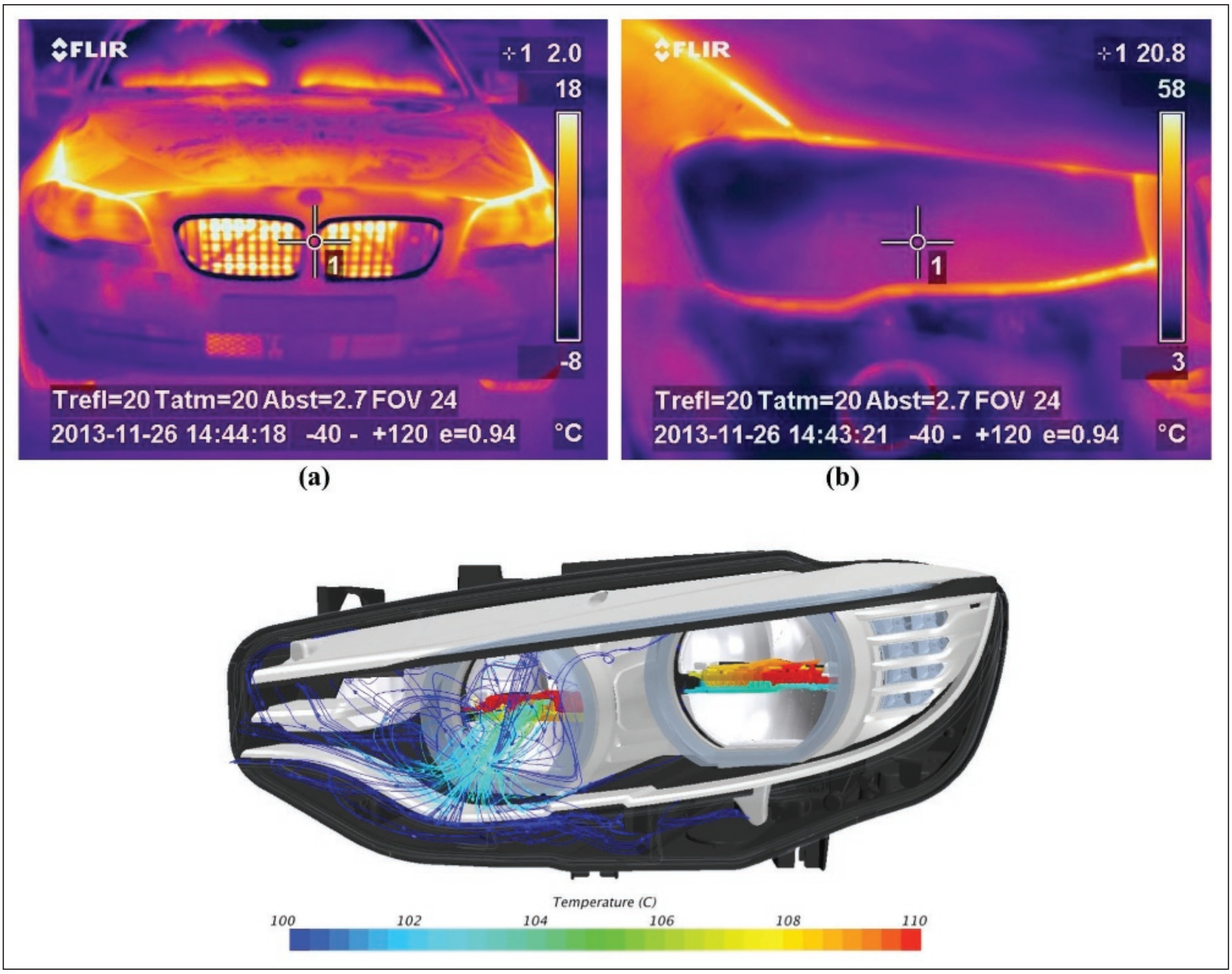


Figure 5. (a) Temperature distribution on the hood of the front of a BMW vehicle as the combustion engine is turned on. (b) Temperature distribution around a headlamp. (c) Temperatures inside an LED headlamp culminates at 110 °C.

so long as the light source is scaled down accordingly. The implication is that to make a better headlamp, a far, far brighter light source is needed. We have pursued this goal, directing efforts at creating a high-luminance white-light source that approaches a point source. This is a disruptive approach, because it moves away from trying to increase luminous flux, with the new target being an increase in luminance, or in other words, brightness.

Our approach to creating a very bright point source is to pump a remote, yellow-emitting phosphor with a high-power, multi-mode, blue edge-emitting laser diode. This class of laser is increasing in power, with a 3 W version recently available. The emission surface is just 30 μm by 4 μm, compared to 800 μm by 800 μm for a high-power LED, which equates to a factor of more than 5000. If one also accounts for the emitting cone and the optical power of the light-sources, the luminance of the laser diode is 500,000 times higher than that of the LED.

Another strength of the blue laser is its superior efficiency. As the current through the LED is cranked up its efficiency declines due to a mysterious malady known as droop. Its origin is controversial, but the principal cause is probably Auger recombination. Droop does not plague lasers, however, with increases in drive current causing increases in efficiency to a stable level (see Figure 4).

Encouragingly, the blue laser is getting ever more efficient. Operating at 25 °C, 1.7 W chips produce a wall-plug efficiency of 25 percent, while the more recently launched 3 W successors have an efficiency of 35 percent, and may soon hit 40 percent. Further improvement is expected, as more manufacturers release products that will primarily target the video projector market. As they compete with each other to deliver better-performing products, better sources should become available for illumination purposes.

This level of performance is promising, but if the laser is to be used in the headlamp, it must operate under rather harsh environmental conditions. Headlamps are near the combustion engine and the batteries, so the local temperature can hit 80 °C. And inside a headlamp it can be even higher – in the case of the LED, in here it can reach 110 °C, while inside the chip the junction temperature can be 150 °C (see Figure 5).

Fact is that high-power, multi-mode, blue laser diodes operate at lower junction temperatures than LEDs, with temperatures ranging from 90 °C to 110 °C. But even at these elevated temperatures, the performance is compromised, with a roll-over in performance at a case temperature of 70°C, occurring for a drive current of 2.3 A. So, if the laser is to deliver a performance that is good enough for use in a headlamp, it must be cooled.

Unfortunately, the commercial high-power blue laser diodes that are currently available are not designed to fulfil the automotive requirements, because they do not have an operating range spanning -40°C to 85°C. However, thanks to the remote-phosphor configuration, these chips can be prevented from overheating using the air flow around the headlamps to cool them as the vehicle moves. Using this approach the laser, which is driven in continuous-wave mode below the rollover current, is maintained below 60 °C (see Figure 6). This chip pumps a phosphor via a robust optical fibre (see Figure 7).

Armed with our new form of headlamp, we set our sights on extending the visibility range to the maximum tolerated by the European ECE regulations. This led to an illuminance of 1 lux at a distance of more than 600 m in front of the vehicle, realised by using the combination of an LED that generated a broad illumination pattern of 50 lux and quasi-collimated white light from a laser that generated a far-field spot of 290 lux (see Figure 8).

We estimate that the typical requirements for a light source that can deliver this level of performance are a peak brightness of more than 1000 cd/mm^2, an average brightness of more than 500 cd/mm^2 and a minimum luminous flux of 500 lumens.

There are also requirements for the phosphor, which has a conversion efficiency influenced by composition and temperature. If the phosphor gets too hot – this could result from heating by a laser spot size below 100 μm – it can quench luminescence.

To prevent this from happening, we house the phosphor in a reflective configuration that supports local cooling. The phosphor is about 100 μm-thick, has a radius of about 1 mm, and heat is efficiently dissipated through the thickness (not the radius) by carefully selecting the substrate so that it takes into account the coefficient of thermal expansion of the assembly. The emitting surface has a diameter of about 350 μm (full width at half maximum). In addition to aiding heat dissipation, this configuration allows recycling of back-scattered light from the phosphor, thanks to reflection at the phosphor-substrate interface.

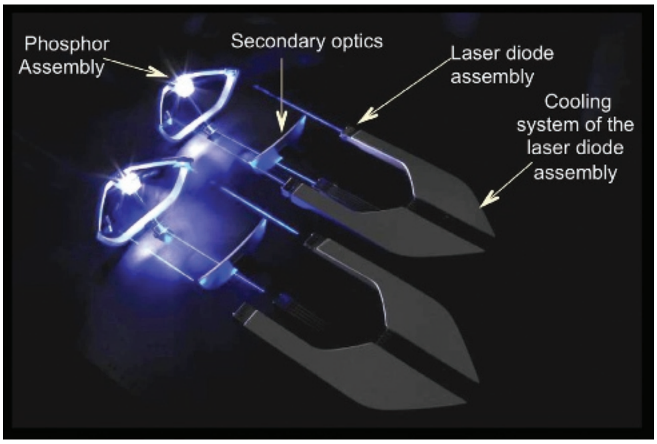


Figure 6. Experimental setup showing white light produced by two cerium-doped yttrium aluminum garnet (Ce:YAG) phosphor-chips in a remote position that are excited by high-power multimode 450 nm laser diodes (over 1W).

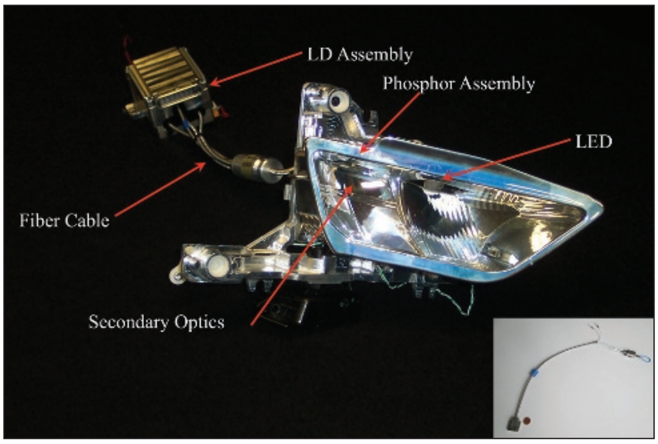


Figure 7. (a) First generation of laser diode-based light-engines composed of three 1 W laser diodes (b) BMW new generation of light-engines featuring compactness, cost-effectiveness and efficiency based on a single 3 W laser diode.

Requirements for the phosphor are not limited to exceeding a particular efficiency, and also include colour requirements defined by regulations. Optimising the phosphor involves not only the determination of the material composition, but also the selection of the right grain size, grain distribution and density, and the thickness of the phosphor chip. And of top of this, the package assembly must be designed to maximise the useful luminous flux. We have done this, realising a conversion efficiency of more than 300 lm/$W_{radiant}$ and a quenching temperature exceeding 220 °C. Operation in environments with temperature as high as 110 °C is possible with our phosphor assembly, which is located in the centre of the headlamp. The laser assembly is, however, positioned on the periphery of the headlamp, where a cooling mechanism can benefit from the air flow.

For our new form of headlight to be practical, its performance must be maintained over the lifetime of the vehicle – and this dictates a lifetime for the laser. Depending on the lighting functions under consideration, this chip will have to operate for between 2000 hours and 6000 hours. This is well below the lifetime of a commercial blue laser, which is typically 30,000 hours.

Safety issues?

Using lasers for headlamps may raise a few eyebrows, given that the light emanating from this high-luminance source can cause eye damage. To prevent this from happening, we took stringent measures to protect drivers, pedestrians and wildlife. The high-beam laser-light booster can only be used above a certain cruising speed – such as 40 km/hr – and following the activation of the main LED-generated high-beam. On-coming traffic is detected automatically a long way away with the high-beam laser-light booster, so it can be turned off well before the vehicle gets close.

The high-power laser diodes used as this point source in this headlight are classified as Class 4 high-power blue laser diodes,

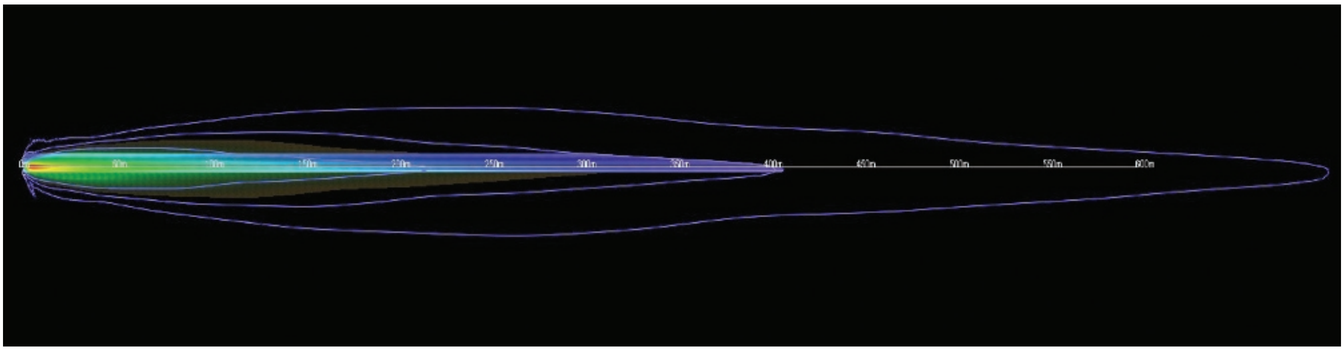


Figure 8. Bird's-eye-view of a light distribution, illustrating the extension of the visibility range to the maximum tolerated by the ECE regulations.

so the package must be constructed in a manner that prevents light from leakage out. To increase safety, this unit features monitoring photodiodes that detect failure modes of the laser diodes, phosphor and the optics in situations that include crashes and degradation-induced effects. If failure is detected, the booster is automatically switched off.

Following several years of development, last summer we released the first vehicles equipped with laser-based high-beams – these were incorporated into the BMW i8, a hybrid plug-in sports car that can go from stand still to 62 mph in just 4.4 s. A limited production run of a few thousand vehicles demonstrated the possibility of the technology, and gave us the chance to gauge the views of our customers.

Demand for the i8 has been very high, and has led us to plan for a release of a new BMW model that combines the laser-based, glare-free, high-beam and a marking light, which we refer to as a dynamic light spot. We will produce hundreds of thousands of this model of car.

Producing a far higher volume of cars with laser-based headlights has not been easy. Many suppliers lack experience with laser technology and the use of high-brightness, white-light sources. Such sources require optics with higher optical quality. However, we expect that this situation will change as our supplies embrace this new, superior technology for headlamps, and we start to incorporate it in all our upper-class premium vehicles and our compact-class premium ones.

This increase in the deployment of this technology must go hand-in-hand with its refinement, with new approaches needed that integrate the technology in a more compact housing, and enable more streamlined manufacturing.

Looking ahead, we can expect this new class of headlamp to evolve and incorporate new laser-based lighting functions. This includes driver-assistance dynamic lighting, which requires high brightness sources and high resolution in the far field, and would be possible with a laser scanning technology. Galvano scanners are bulky and too slow for illumination purposes in the automotive sector, but MEMS-based scanners are more promising: They are extremely compact, offer high scan frequencies, and are robust enough when integrated in the appropriate package. The primary challenge is to uncover an appropriate configuration and optimal driving method for combining the beam of a laser emitting more than 4 W with a MEMS-based scanning mirror, so the result is a high-quality, free-patterned illumination.

This is not the only option – there is also the combination of optical phase modulation technologies and laser diodes. By accurately controlling the phase of a beam, free patterning of light distributions is possible. Coded patterns could be programmed to create dynamic light distributions without the need for high scanning frequencies, and using a synchronized sequential red-green-blue-system would reduce the number of modulators to one.

While it is not clear which of these technologies will win in the end, laser-based headlights clearly have a great future. And by lighting up the road ahead far better than their predecessors, they should reduce the dangers of going out for a drive after dark.

Further reading

B.L. Hills Perception **9** 183 (1980)
W.N. Charman Ophthalmic Physiol. Opt. **17** 371 (1997)
O. Dross *et. al.* Proc. SPIE **5942** 126 (2005)
A. Cvetkovic *et. al.* Optics Express **14** 113014 (2006)
J. Jiao *et. al.* Proc. SPIE **5187** 234 (2004)
J. J. Wierer *et. al.* Laser Photonics Rev. **7** 963 (2013)
C. Weisbuch, "Droop in LEDs: Origin and Solutions", DOE SSL R&D Workshop – Tampa Jan. 28th, 2014.
§6.22.9.4, ECE Regulation N° 48 Rev 9

Putting CPV on rooftops

High-efficiency CPV could become a reality for rooftops by uniting microscale solar cells with a planar microtracking concentrator technology

BY JARED PRICE AND CHRIS GIEBINK FROM THE PENNSYLVANIA STATE UNIVERSITY AND XING SHENG AND JOHN ROGERS FROM THE UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

PROSPECTS for concentrating photovoltaics (CPV) are at an all-time high. Driven by a maturing industry and increasing emphasis on the value of high efficiency, the global installed capacity of CPV is forecast to triple to 1 GW over the next five years.

None of this capacity, however, will be installed on rooftops, which is where a significant proportion of solar panels are being deployed by the broader PV industry. Amidst this growing trend toward decentralized power generation, the conspicuous absence of rooftop CPV begs the question: Is CPV missing an opportunity?

Creating a viable CPV technology for rooftops is not trivial because it requires overcoming both practical and aesthetic challenges. While standard PV panels are compact and can mount flush with the roof, CPV modules are traditionally bulky, requiring a precision tracking system to orient each module toward the sun throughout the day.

These aspects are not problematic for ground-mounted systems where there is ample space to move and prevent shading. But on rooftops they are a non-starter: Space and structural support are limited, and there is a need to preserve aesthetic appeal, because few of us would want to have the equivalent of an array of mini satellite television dishes scattered across our roof.

A radically different CPV architecture is therefore needed, which must deliver the efficiency of a traditional system, but do so in the form factor of standard, fixed-panel PV.

Our team at Penn State University and the University of Illinois at Urbana-Champaign is making progress on this front by combining a translation-based tracking technology with microscale photovoltaic cells embedded inside the concentrator optic itself. The result is a quasi-static CPV panel less than 1 cm-thick that operates at fixed tilt with an imperceptible amount of

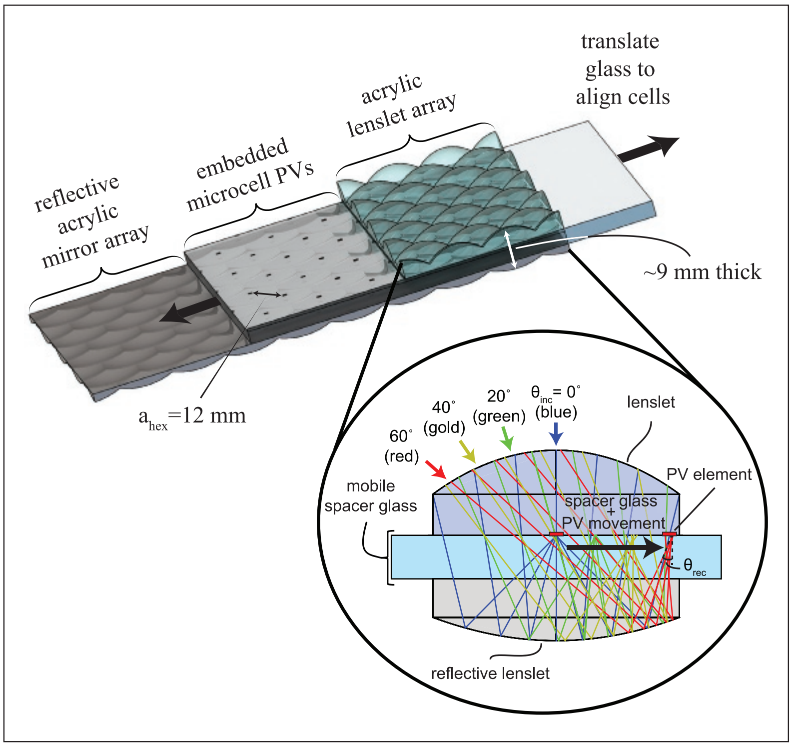


Figure 1. Moving the cells relative to the lens ensures that sunlight is concentrated on the device throughout the day.

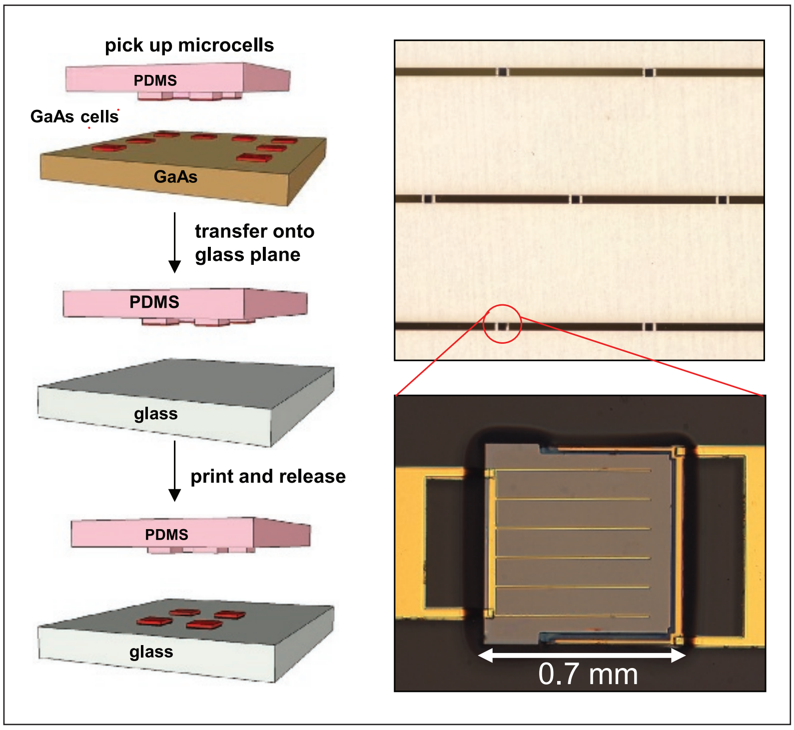


Figure 2. The transfer-printing process that is used to produce microcell arrays has a very high throughput

movement. Over the course of a sunny day, such a panel could deliver 50 percent more energy than a state-of-the-art silicon equivalent.

Embedded microtracking

To accomplish solar tracking without reorienting the panel, we have adopted a planar translation-based approach, with optics that remain fixed while PV cells slide laterally to follow the moving focal spot (see Figure 1).

This type of design is not a new idea. The performance of various forms of translational tracking have been explored before, but their utility has been limited by image field curvature, which degrades the focal spot in the solar cell plane for light incident at oblique angles beyond about 20°. This is a substantial drawback, because a latitude-tilted panel sees sunlight incident at angles of up to 60° over the course of 8 hours. Consequently, previous translational tracking schemes could only operate efficiently for a few hours each day.

We resolved this problem by adopting a folded optical path. With this configuration, light is refracted by a top lenslet, reflected by a bottom lenslet and finally focused on an intermediate plane – a sheet of glass patterned with a corresponding array of solar cells. The interfaces between this plane and those of the top and bottom lenslet arrays are lubricated by optical oil, which also serves to eliminate parasitic reflections.

Tracking is achieved by sliding the middle solar cell sheet laterally. Sunlight is focussed on cells that have an area of less than 1 mm^2, enabling the size of the associated lenslets and the thickness of the overall concentrator stack to be kept small. By employing this design, cells are embedded in a 'microtracking' panel that can accept light over a 120° full field of view, which corresponds to operation for more than 8 hours per day. Incoming radiation is focused by a factor of more than 200, and daily average optical losses are kept below 15 percent.

Microscale cells

The benefits of the microcells are more than just enabling a compact panel. Thanks to their small size, the power delivered to each of these cells is orders-of-magnitude lower than that impinging on a conventional CPV cell, which is typically around 1 cm^2 in size. This simplifies thermal management to such an extent that, according to our work and that of others, the cell does not require active cooling.

Another advantage of working with microcells is



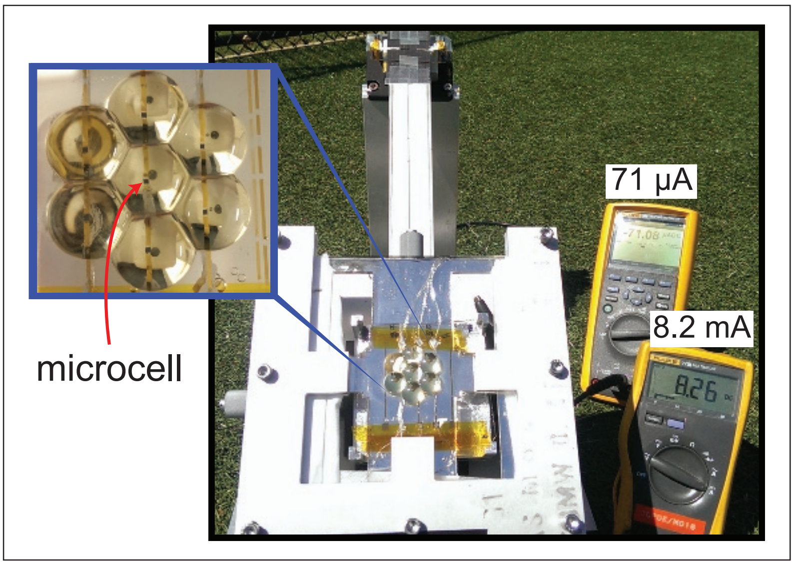


Figure 3. Outdoor testing of a small-scale prototype using three-dimensional-printed lenslet arrays.

that they have a lower series resistive loss. This leads to a more robust performance when the cell faces the inherent illumination non-uniformity of the microtracking concentrator focal spot.

Our fabrication of the microcell sheet begins with the growth of the device structure on a GaAs substrate by MOCVD. Inserted between the device stack and the substrate is a lattice-matched AlGaAs sacrificial layer, which is removed by wet etching to separate the cells from the substrate.

The resulting chips, which are only a few micrometers thick, are picked up with a soft elastomeric stamp and placed precisely on a glass (sliding middle sheet) substrate with a high-throughput process, known as micro-transfer printing. This process can print millions of cells per hour with a yield exceeding 99.5 percent while producing micrometre-scale placement accuracy (see Figure 2). Following transfer of the cells, metal interconnects are deposited to create a network that optimizes the power produced by the module.

We evaluated our microtracking design by fabricating a small-scale prototype incorporating seven, series-connected GaAs microcells. These were sandwiched between a pair of custom, 3D-printed, plastic lenslet arrays made by our collaborators at LUXeXcel, Inc.

Testing involved measurements in the lab, and then outdoors during several sunny days in central Pennsylvania, where the panels were held at a fixed tilt (see Figure 3). Despite a relatively large surface-form-error in the printed lenslets, for over 6 hours we could maintain a factor of 100-150 increase in the short-circuit current compared to that of an adjacent bare cell. Turning to commercial off-the-shelf planoconvex glass lenses improved the concentration factor to 200 suns and extended the operating time to 8 hours.

Taken together, these initial results have validated the basic microtracking concept and set the stage for testing at a larger scale. When this is carried out, we will improve the concentrator performance by optimizing the lenslet optics for higher concentration and by applying an anti-reflection coating to improve their optical efficiency.

To higher efficiencies

In addition to improving the optical performance of our concentrator system, we are also pursuing ultra-high efficiency cells by moving to quadruple junction, four-terminal devices. By transfer-printing different sub-cells on top of one another, we avoid the current- and lattice-matching issues that have challenged monolithic four-junction cells to date. This approach expands the range of feasible sub-cell materials and opens up the possibility of

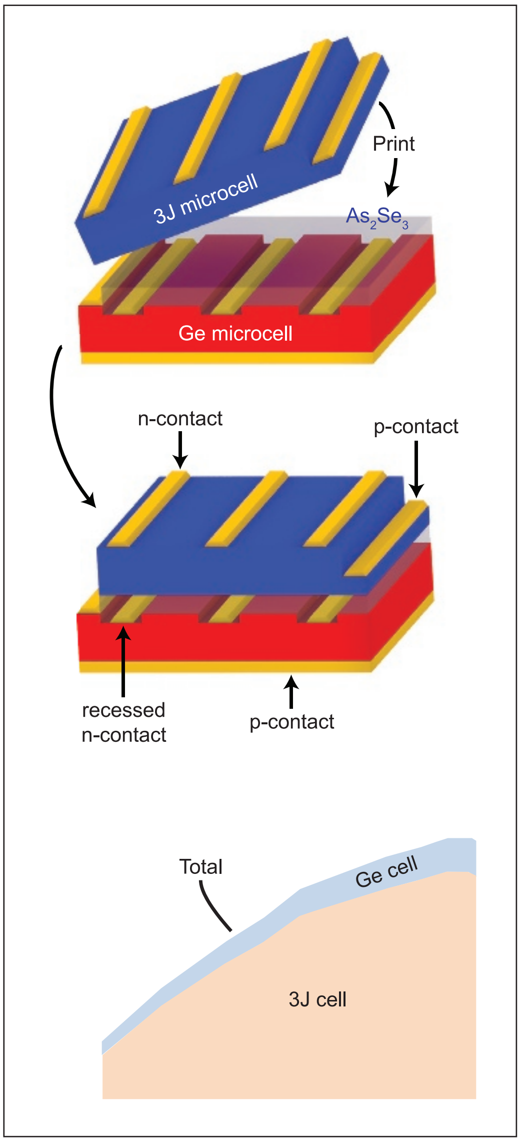


Figure 4. A mechanical assembly approach can create four-junction microcells that deliver a higher efficiency than their triple-junction predecessors at a range of concentrations.

increasing the number of junctions to five or more.

We have used transfer printing to combine a InGaP/GaAs/InGaAsNSb top cell with a germanium bottom cell. The resulting four-junction photovoltaic delivers a total efficiency of 44 percent at 1000 suns (see Figure 4). Extrapolating our concentrator performance together with these high efficiency cells suggests that a microtracking CPV panel could deliver 50 percent more energy over the course of a sunny day than a state-of-the-art silicon module of equivalent size.

Delivering high-performance is no guarantee of success for rooftop CPV – modules will also have to deliver long-term operational reliability, while retailing for a price that makes them competitive with existing PV panels. It is likely that the key to reliability will be environmentally-robust plastic or glass lenslet arrays, since all the cells, moving interfaces and lubricating oil are sealed and protected within the concentrator stack. Making meaningful cost projections at such an early development stage is tricky, but the combination of wafer recycling, high-throughput transfer printing and inexpensive injection-moulded optics indicates that the ingredients are there for a low-cost system.

It is important to emphasize that microtracking CPV complements – rather than competes with – conventional CPV. The latter is ideal in applications where space and movement are not constrained, while our microtracking approach opens up an opportunity to deliver a step-change in the efficiency in constrained-space rooftop and urban installations. This expands the number of markets that CPV can serve, and we hope that it will accelerate the broader adoption of this technology.

Further reading

Concentrated Photovoltaics (CPV), Update 2014 – Global Market Size, Competitive Landscape and Key Country Analysis to 2020. (GlobalData, Report No. GDAE1084MAR, 2014)
J.S. Price *et. al.* Nat. Commun. **6** 6223 (2015)
J.M. Hallas *et. al.* Appl. Optics **51** 6117 (2012)
F. Duerr *et. al.* Opt. Express **19** A207 (2011)
X. Sheng *et. al.* Nat. Mater. **13** 593 (2014)
J. Yoon *et. al.* Nature **465** 329 (2010)
K. Ghosal *et. al.* Compound Semiconductor **5** 34 (2014)

Europium propels the GaN LED into the red

Doping of GaN with europium enables a red LED to join forces with blue and green cousins and form a monolithic, full-colour chip

BY YASUFUMI FUJIWARA FROM OSAKA UNIVERSITY AND WOJCIECH JADWISIENCZAK AND FAIZ RAHMAN FROM OHIO UNIVERSITY

LEDs have a sensational set of attributes. These small, highly efficient and versatile chips are now serving myriad roles, from space illumination to communication, gas sensing and displays. And performance continues to improve, as manufacturers strive to increase efficiency and lower cost, while researchers in academia and industry develop new materials and architectures for next-generation devices.

Since the invention of the LED, one of the targets of researchers has been to extend emission to shorter and longer wavelengths. Historically, this has been realised by varying the composition of the alloys used for making these solid-state emitters, but more recently it has involved changes to the thickness or the stoichiometry of the quantum wells.

For a decade or more the latter technique – compositional tuning, also known as band gap engineering – has been adopted for extending the emission of III-nitride LEDs into the ultraviolet and towards the green. This approach has yielded much success, with several groups reporting deep UV and green III-N LEDs. What's more, green laser diodes have been developed and launched to market. These triumphs beg the question: Is it possible to push the emission even longer – perhaps all the way to the red and beyond?

The pay-off of developing a red III-nitride LED would be huge. Although red LEDs are already available with the AlInGaP system, forming this with the III-nitride system would allow all three primary colours to be integrated on the same chip. Such a device would revolutionise the display industry, and would also find deployment in applications requiring a compact, full-colour light source.

Producing a red-emitting III-nitride LED is far from trivial, however. Stretching emission to longer wavelengths requires an increase in the indium content of the quantum well, but this goes hand-in-hand with plummeting efficiencies that originate from deterioration in crystal quality and increased alloy segregation.

At the heart of the issue are opposing temperature requirements for the growth of indium-rich InGaN. Temperatures in the region of 1000 °C are needed to ensure the supply of sufficient nitrogen via the cracking of ammonia, while temperatures below 600 °C should be employed to prevent decomposition of the alloy.

However, armed with clever epitaxial growth techniques, it is possible to circumvent these problems. Trailblazing this approach has been Kazuhiro Ohkawa and colleagues at the Tokyo University of Science. In 2011, this team demonstrated that indium-rich InGaN can be deposited by altering the design of the MOCVD reactor: The substrate is held in a confined space, and ammonia flows by while heated to a higher temperature. These researchers also modified the design of the active region, doubling the number of quantum wells from five to ten. This enabled the epitaxial structure to relax, aiding indium incorporation.

These modifications to the growth and the architecture of the LED led to the fabrication of deep red LEDs. However, the output power of these 740 nm devices was only 2 μW. So one can conclude that a lowering of the growth temperature is not that promising an approach to making powerful red III-nitride LEDs.

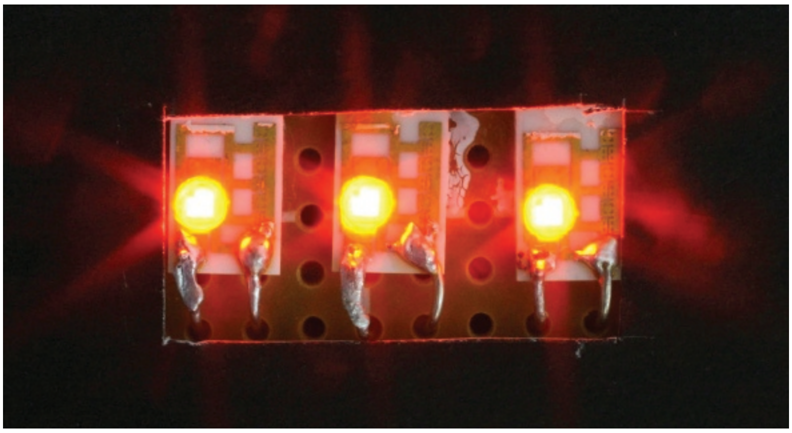


Figure 1. The first GaN-based red LED operating under current injection at room temperature. Europium-doped GaN is used as the active layer of the LED.

A team from Toshiba's Corporate Research and Development Centre has pioneered an alternative way forward that appears to have more potential. Their device featured thin AlGaN interlayers inside each GaN/InGaN quantum well, and it emitted 1.1 mW at 629 nm. Although this output is much, much higher than that from devices reported previously by other groups, it still falls short of a practical device, due to its low external quantum efficiency of around 2.9 percent.

Another approach, pursued by many groups, is to build LEDs based on nano-columns. This makes it far easier to incorporate indium, but the downsides are low device efficiency and complicated growth and fabrication procedures.

There is also a radically different approach to making red LEDs: Doping them with trivalent europium (Eu^{3+}). This ion is already widely used, providing a luminescent centre in red-emitting phosphors, such as europium-doped Y_2O_3 that is used in cathode ray tubes and plasma display panels. In these applications ions are doped in an insulator (host matrix), with red emission primarily resulting from charged particle and optical excitations.

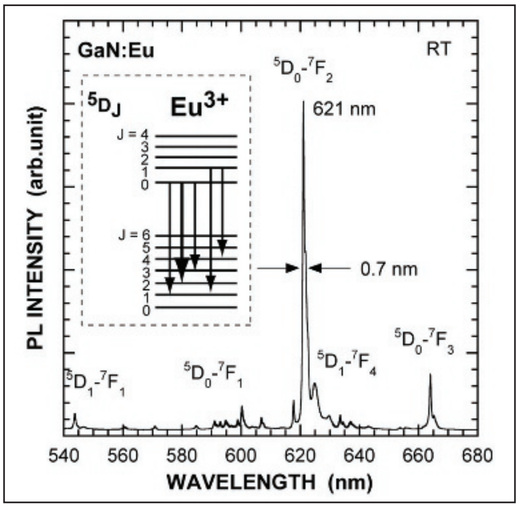


Figure 2. Photoluminescence from europium-doped GaN. Emission peaks are assigned as the intra-4*f* shell transitions in Eu^{3+} ions.

One of us, Yasufumi Fuijiwara from Osaka University, is broadly adopting this approach, but taking a slightly different tack by doping europium directly into the GaN. This method has much promise, because europium-doped GaN has excellent luminescence properties in the red spectral region, resulting from the specific optical properties of rare-earth elements. This includes a sharp, intense, temperature-independent emission peak associated with intra-4*f* shell transitions.

One of the downsides of rare-earth excitation is that it is very sensitive to energy mismatch between the host and the doped rare-earth ions. Consequently, care must be taken when selecting the bandgap of the host. As a general rule, wider bandgap materials are preferred, because they provide a greater number of energy migration channels for exciting rare-earth ions. In fact, due to significant physical and chemical differences between the rare-earth element and the host atom it replaces in a semiconductor – including variations in ionic radii and electronegativity – the rare-earth ions often have to be considered together with the gap level they generate in the host. This facilitates the 4*f*-shell core excitation and de-excitation processes. Typically, rare-earth elements incorporated in the semiconductor are in the (3+) charge state. The rare-earth ion loses all 5*d* and 6*s* electrons to form ionic bonds, and the partially-occupied $4f^n$-shell provides multiple electronic energy levels for energy migration. It is between these levels that radiative transitions can occur. When doping GaN with the rare-earth elements, optically active centres are formed that exhibit temperature-stable, narrow 'atomic-like' emission lines. The spectral position of these lines is defined by the spin-orbit splitting of electron states in the partially occupied 4*f* shell of the rare-earth-ion.

GaN is a great host because it combines a direct bandgap with a high level of optical activity, even when it features a high defect density that would quench emission in other technologically important, but smaller bandgap, III-V and II-VI compounds. Another strength of using III-nitrides is that there is weak thermal quenching of radiative emission produced by the optically active rare-earth ion.

When Eu^{3+} ions are incorporated into GaN, they are substituted for metallic cations (Ga^{3+}) and occupy sites with reduced symmetry. There is no contribution to the state energies from the odd-parity components of the crystal field, but electric dipole transitions between $4f^n$ states are present, due to the admixing of opposite-parity wavelengths into multiplets.

We are not the first group to fabricate europium-doped GaN layers. In the late 1990s and early 2000s, a group from the University of Tsukuba, another from the University of Cincinnati, and a partnership between researchers at Ohio University, Sandia National Laboratories and the Lawrence Berkley National laboratory all formed such structures by either MBE, or by implanting ions followed by a post-implantation thermal anneal. Optical excitation resulted in stimulated emission from the europium ions, and electroluminescence resulted from two different device architectures: europium-doped GaN grown on *p*-type silicon and caped with indium-tin oxide; and a metal-insulator-semiconductor structure with indium, europium-doped GaN, and an *n*-type silicon substrate.

These devices produced red emission, but only under very high voltages. For the device capped with indium-tin oxide, voltages as high as 46 V were employed – and this produced weak emission, due to the low efficiency of the impact excitation of Eu^{3+} ions by hot carriers. One option for reducing the operating voltage is to turn to a device architecture with a *p-n* junction, which can inject the current into an active layer and realise energy transfer from host excitations to Eu^{3+} ions. The team from Osaka University has used MOCVD to investigate atomically controlled doping of

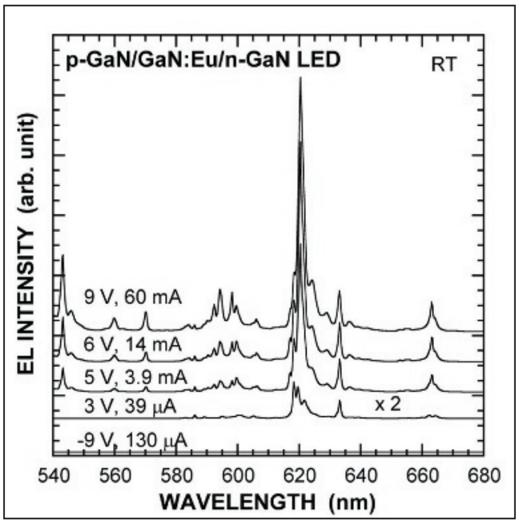


Figure 3. Electroluminescence of europium-doped GaN LED with different applied voltages.

rare-earth atoms in III-V semiconductors. They reported our initial success in 2009, when we grew europium-doped GaN layers with high crystalline quality, and demonstrated low-voltage, current-injected red emission from *p*-type GaN/GaN:Eu/*n*-type GaN LEDs (see Figure 1).

We have investigated room-temperature photoluminescence produced by the europium-doped GaN. Over the entire 2-inch wafer, bright red emission was produced, with peaks at 543 nm, 600 nm, 621 nm, 633 nm and 663 nm associated with the intra-4*f* shell $^5D_1$–$^7F_1$, $^5D_0$–$^7F_1$, $^5D_0$–$^7F_2$, $^5D_1$–$^7F_4$, and $^5D_0$–$^7F_3$ transitions, respectively (see Figure 2). The strongest of these peaks is at 621 nm, with a full-width-at-half-maximum of 1 nm. Note that there is no evidence for either band-edge emission, which would be expected at 361 nm for undoped GaN, or for defect-related blue/yellow band luminescence. This indicates that there is a very effective transfer of excitation energy from the GaN host to the Eu^{3+} ions that underpin the strong red luminescence.

Devices formed from europium-doped GaN, which otherwise have a structure that is similar to that of a blue LED, start emitting light at a forward voltage of just 3 V (see Figure 3). Similar to photoluminescence, the dominant emission peak occurs at 621 nm. A key observation is that under reverse bias, there is no electroluminescence – this implies that all the light generated when the device is under forward bias results from energy transfer from the host to the europium ions, with none stemming from impact excitation or ionisation of these species via hot carriers.

However, the emission produced by that generation of LED was very modest. At a 20 mA drive current, output power, integrated over the $^5D_0$–$^7F_2$ transition region around 621 nm, was just 1.3 μW, while the external quantum efficiency was 0.001 percent.

We have steadily increased the output of our LEDs by optimising growth conditions and device structures. Switching to growth at atmospheric pressure enhanced europium-specific emission, due to a combination of an increase in the number of optically active europium-ion centres, efficient energy transfer, and a further reduction of non-radiative processes in the GaN host. This propelled the output power integrated over the $^5D_0$–$^7F_2$ transition region to 17 μW at 20 mA; the corresponding efficiency was 0.04 percent.

Another lever to increasing LED output is to increase the thickness of the active layer. Power increases monotonically with active region thickness, due to increases in the number of europium ions, with a peak power at 20 mA of 50 μW for an LED with a 900 nm-thick active region. The corresponding external quantum efficiency for this emitter was 0.12 percent.

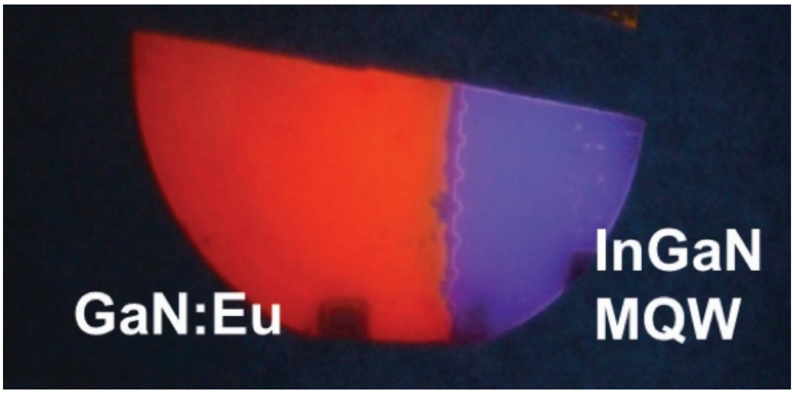


Figure 4. Monolithic integration of blue and red emitting regions on the same LED wafer.

Further improvements have followed, with output power increasing to 93 μW at 20 mA – this is the highest value ever reported. This output corresponds to an external quantum efficiency of 0.23 percent, putting this device in the same ballpark as green-emitting, commercially available nitrogen-doped GaP LEDs.

At lower injection currents, the LED operates at an even higher efficiency, suggesting that the number of optically active europium-doped ions may be a bottleneck. We know from a recent study of ours on europium luminescence that there are at least eight different kinds of europium luminescent centres with different local structures that can coexist, and that the energy transfer from the GaN host depends strongly on the local structures. Due to this insight, we have devoted much effort on the selective formation of luminescent centres with efficient energy transfer. This has involved co-doping europium with other impurities.

One of the promises of a red-emitting nitride LED is that it can be integrated with a blue and a green cousin on the same substrate to form a chip that emits all three primary colours. We have taken a significant step towards this by employing selective growth to form red and blue emitters side by side. Our hope is to follow this up with a full-colour monolithic red-green-blue chip that can be used for screens and projection displays. This will be superior to the hybrid LEDs of today, due to lower cost, easier system integration and much better colour mixing.

Further reading

B. Henderson *et. al.* Crystal-Field Engineering of Solid-State Laser Materials, Cambridge Studies in Modern Optics, Cambridge University Press 2000
Photonic Applications of Rare Earth Doped Materials, MRS Bulletin **24** (1999)
J. Heikenfeld *et. al.*Appl. Phys. Lett. **75** 1189 (1999)
S. Morishima *et. al.* Phys. Status Solidi A **176** 113 (1999)
H. J. Lozykowski *et. al.* Appl. Phys. Lett. **77** 767 (2000)
J. H. Park *et. al.* J. Appl. Phys. **98** 056108 (2005)
A. Nishikawa *et. al.* Appl. Phys. Express **2** 071004 (2009)
Y. Fujiwara *et. al.* Jpn. J. Appl. Phys. **53** 05FA13 (2014)

An insight into silicon PAs

A concise, multi-author treatise discusses issues relating to the efficiency, linearity and manufacturability of silicon power amplifiers

BY RICHARD STEVENSON

IT IS SAID that forewarned is forearmed. So on that basis, if you are a GaAs PA designer, it is worth your while to be aware of the capabilities of rival products based on silicon, given the interest that they are generating through the efforts of Peregrine and Qualcomm.

For engineers in that position, based on the title alone, it would be tempting to place an order for *Linearization and Efficiency Enhancement Techniques for Silicon Power Amplifiers*. This accessible book that has just been released retails for a price that is far from extortionate, and consists of six informative chapters covering important topics. But it may not meet the needs of every GaAs PA engineer.

Why? Well, each of the chapters is authored or co-authored by an expert – and while this approach ensures great coverage of several topics, the authors tend to write about their successes in a narrow field, resulting is a book that is far from comprehensive.

Illustrating this point is the coverage given to techniques for improving the linearity of silicon PAs so that they are not dramatically inferior to those based on GaAs. In this chapter, several methods are listed for increasing linearity, including envelope elimination and restoration, linear amplification with non-linear components, and the application of a constant amplitude locked loop universal modulator. However, only one approach is discussed in detail: Cartesian feedback with digital enhancement.

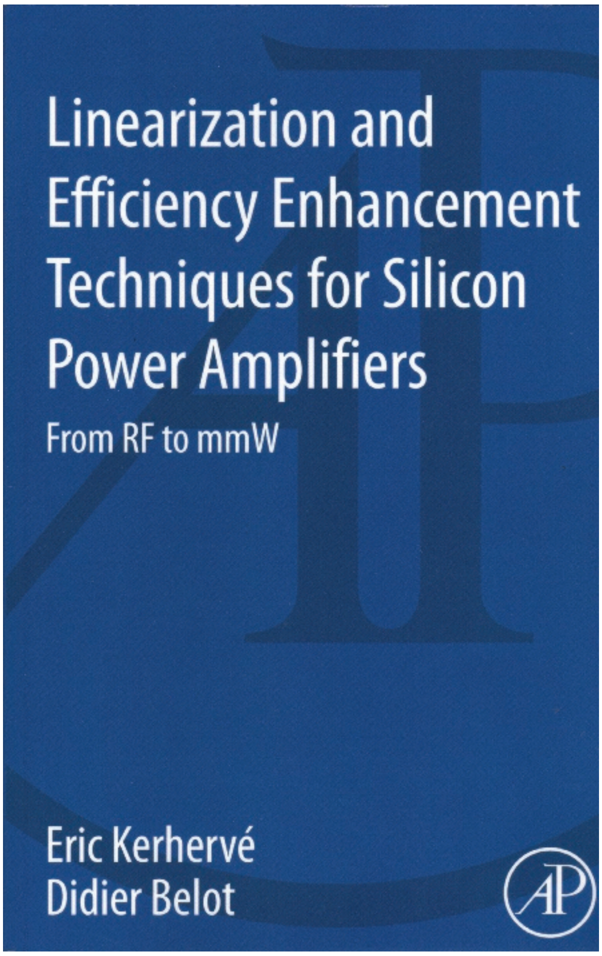
In this section of the book, as well as describing the increase in linearity, consideration is given to the increases in power consumption and total chip footprint that arise from the introduction of Cartesian feedback with digital enhancement. The feedback path consumes just over 20 percent of the total power, while the digital part takes up only 1 percent of the total area.

Efficiency verses linearity

A chapter that may help any RF engineer to look at the world in a different light is that entitled Transmitter Linearity and Energy Efficiency. It begins by asserting that those in marketing want the linearity of the amplifier

The proliferation of mobile devices is driving the development of silicon power amplifiers, which require techniques to improve efficiency and linearization in order to compete the incumbent GaAs devices.

and its efficiency to both be the 'first priority' – an impossible task, since physics dictates that gains in one area must come at the expense of deterioration in the other.



Linearization and Efficiency Enhancement Techniques for Silicon Power Amplifiers has just come out in press. It is published by Academic Press and retails for £42.99.

The radical solution offered to the reader is that instead of starting with a linear circuit and making it more efficient, one should start with a circuit exceling in energy efficiency, and try to make it more linear.

This approach is applied to the construction of an amplifier that is capable of serving different data transmission technologies. One of the most demanding of these is WCDMA, which has output power requirements down to -50 dBm. Such low powers are not accessible when operating the amplifier in compression-mode, which allows for high efficiency, but cannot reach such low powers. The solution is to supplement this mode of operation with p-mode, a configuration where the output power depends on both the input power and the power supply.

In addition to excellent linearity, these compression-mode transmitters feature several inherent stabilities that are important for fast design, consistent manufacture and long-term performance.

Great performance is of little practical value, however, unless it goes hand-in-hand with reliability. This is discussed in another chapter, where the point is made that using nanometre CMOS technologies for PA design brings major challenges, some of which have not been encountered before. These include thermal effects, metal interconnect electromigration, time-dependent dielectric breakdown, hot carrier injection and electrostatic discharge.

Towards the terahertz

Although most chapters in the book consider amplification at frequencies associated with mobile communication, two look at devices operating at higher frequencies.

For frequencies of tens of gigahertz, the efficiency of power amplifiers in transmitter systems with a high peak-to-average power ratio can be quite low. To increase efficiency, engineers may turn to a Doherty amplifier. This was introduced in 1936 by the American electrical engineer William Doherty, and it combines a main amplifier, working in either class AB or class B mode, with a peaking amplifier. The latter operates in class C mode, and only makes a contribution at high input powers.

To date, there are only a couple of reports of Doherty amplifiers fabricated with silicon technologies. In 2008, the first millimetre-wave Doherty amplifier implemented in 130 nm CMOS technology was announced, which operated with an efficiency of 3 percent at 60 GHz; while in 2014 a report emerged of a Doherty amplifier formed with 45 nm silicon-on-insulator CMOS technology operating at 21 percent efficiency.

Even higher frequencies are covered in the final chapter of the book, which considers amplification in the terahertz domain. In this arena, silicon devices are severely limited by their cut-off frequency and breakdown voltages, but the use of multiplier chains and a 0.13 μm SiGe HBT process has enabled output powers of -3 dBm at 325 GHz and – 29 dBm at 825 GHz. However, this approach has drawbacks, such as very high DC power consumption and very low chip surface efficiency, so there is a preference for fundamental frequency oscillators.

The good news for the developers of silicon amplifiers is that the transistors are improving. Maximum oscillation frequencies are now reaching 500 GHz, while a target of 700 GHz is being pursued in the EU-funded DOTSEVEN project that will finish in 2016. This is helping to improve the results obtained with CMOS technologies. One highlight is a 65 nm technology used to form a three-stage amplifier that delivers an output power of up to 6.3 dBm at 150 GHz.

In this last chapter, III-V technologies are discussed – and arguably, it would be absurd not to mention them, given their far higher oscillation frequencies, plus their ability to form amplifiers delivering gain at frequencies that silicon-based technologies cannot yet reach. This is a rare mention of the compounds, however, so if you are looking for a detailed comparison of silicon and III-V technologies, you must search elsewhere. But if you want an insight into several ways to improve the capability of silicon RF amplifiers, this could be the book for you.

Scrutinising growth

Reflection anisotropy spectroscopy exposes defects and anti-phase domains that can destroy the performance of III-V- on-silicon devices

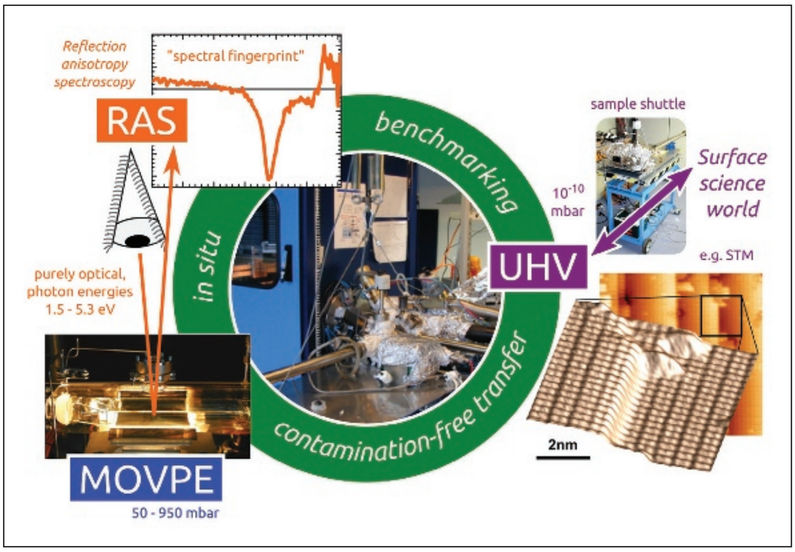
BY OLIVER SUPPLIE, SEBASTIAN BRUECKNER, MATTHIAS M. MAY AND THOMAS HANNAPPEL FROM TU ILMENAU

WHETHER IT IS MULTI-JUNCTION PHOTOVOLTAICS, microelectronics or photonics, the integration of III-Vs with silicon offers the best of both worlds. Armed with this combination, one can harness the sensational characteristics of the compounds while accessing the size and lower cost of silicon. But how should one go about doing this?

When it comes to the selection of the growth technology, the number one candidate has to be MOCVD. Its high-volume capability is highlighted by its use in the production of myriad LEDs, while its suitability for growing III-Vs on silicon is already showing encouraging signs. However, to accelerate progress in this field, it is essential that engineers gain a better understanding of the growth of these III-V-on-silicon heterostructures, including the complex physico-chemical processes and interface formations. This knowledge should make it easier to grow these challenging epistructures.

One way to get this insight is to use optical spectroscopy to study epitaxial growth. This allows *in-situ* monitoring of interface formations and growth processes on the atomic scale in the vapour phase conditions used for deposition.

There are several forms of optical spectroscopy to choose from, including a technique known as reflection anisotropy spectroscopy. This is tough to understand, and it is not easy to employ it for analysis. However, those that are willing to make the effort are well rewarded. In fact, the information gathered by this approach is so rich that it would be reprehensible not to utilize it.



The experimental approach of the team at TU Illmenau consists of *in-situ* monitoring of the MOCVD processes (Aixtron AIX-200) with reflection anisotropy spectroscopy (Laytec EpiRAS-200) and a contamination-free MOCVD-to-UHV transfer for benchmarking of the *in-situ* signals to surface science techniques in UHV, such as STM (Specs Aarhus 150).

One of the distinguishing features of reflection anisotropy spectroscopy is that, unlike many reflection measurements, differences in reflection are measured along two mutually perpendicular crystal directions. This gives this form of spectroscopy tremendous atomic-scale sensitivity to the surfaces and the interfaces of cubic crystals – and particularly those with the (100) orientation. However, making good use of the spectra requires an understanding of their origin – and this means combining the physico-chemically complex environment of MOCVD with the world of interfacial science, usually based on ultra-high vacuum periphery. Fortunately, these two can be linked by a dedicated, contamination-free transfer system.

Our team from the Technical University of Illmenau, Germany, focuses on the benchmarking

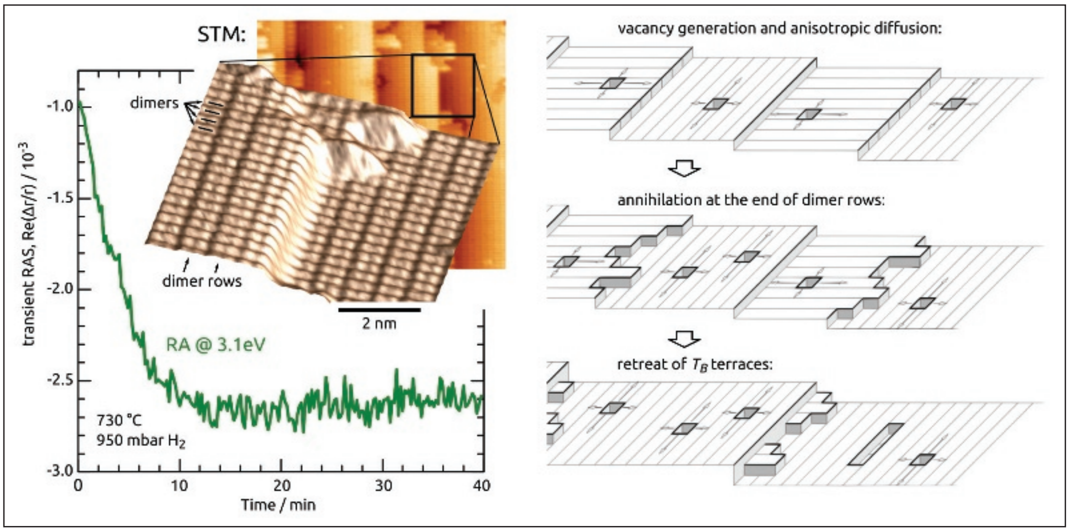


Figure 1. Transient reflection anisotropy spectra during the formation of an almost single-domain silicon (100)-(1x2) surface. The inset shows the scanning tunnelling microscopy image of such a surface. The sketch at the right illustrates the formation process consisting of silicon vacancy generation, anisotropic diffusion and annihilation at the end of the dimer rows.

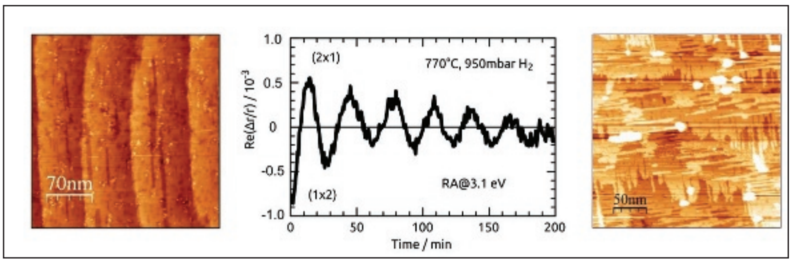
of *in-situ* reflection anisotropy spectra. This involves using all the tools available in high-end analytics, including low-energy electron diffraction (LEED), scanning tunnelling microscopy (STM), Fourier-transform infrared spectroscopy (FTIR) and photoelectron spectroscopies (PES).

One of our strengths is that we can bridge the gap of more than ten orders of magnitude in pressure within a matter of seconds. We realise this with a mobile, ultra-high vacuum shuttle that enables us to access essentially any UHV chamber – this could be in our labs, or at remote locations such as synchrotron facilities. With the *in-situ* signature, we can carry the atomic scale information, together with the reflection anisotropy spectrometer, from one laboratory to the next. As this form of spectroscopy is also applicable in ultra-high vacuum environments, we can determine whether surfaces remain intact after further analysis.

Silicon surfaces

We can showcase the benefits of our approach by recounting the success that we have had with growth on the silicon (100) surface. Deposition of III-Vs on this substrate can induce defects during preparation and III-V nucleation. These imperfections are a major impediment to the performance of optoelectronic devices, because they are responsible for non-radiative recombination.

Figure 2. Transient reflection anisotropy spectra during layer-by-layer removal at silicon (100). The left scanning tunnelling microscopy image shows a preferential (1x2)-type surface with elongated silicon vacancy islands. The right scanning tunnelling microscopy image shows frayed step edges at a two-domain surface after longer annealing.



Another issue with the growth of III-Vs on silicon (100) is that it can lead to antiphase disorder, caused by oddly numbered atomic step heights at the substrate surface, where silicon dimers on adjacent terraces are mutually perpendicular.

The goods news, however, is that the monohydride silicon (100) surface exhibits a characteristic reflection anisotropy spectroscopy signal that is related to the silicon dimers – and the intensity of this signal corresponds to the number of parallel-aligned dimers. Reflection anisotropy spectroscopy is able to provide an *in-situ* quantification of the majority dimer orientation, and by selecting the photon energy of that signal during surface preparation, it is possible to employ process conditions that produce single-domain surfaces.

We have observed a transient reflection anisotropy signal during annealing of silicon (100) with a 2° misorientation towards [011]. Conditions for this were 730 °C in a hydrogen gas environment held at 950 mbar. We observed a strengthening of the intensity of this signal, due to an increase in the proportion of the surface exhibiting the (1x2) surface rearrangement, as confirmed by LEED, FTIR and STM.

There is an activation energy associated with this surface reconstruction, according to *in-situ* measurements at different temperatures – and this is consistent with chemical interfacial reactions induced by hydrogen. The conclusion to draw from this is that kinetically controlled surface etching processes are taking place, via the formation of SiH_x species.

Combining these findings with STM and *in-situ* hydrogen desorption studies reveals that the generation of silicon vacancies should be blamed on continuous adsorption and desorption of hydrogen. These vacancies are mobile, moving preferentially along dimer rows, where they annihilate at step edges. This causes a retreat of the (2x1) domains, with only small residuals left at the step edges, as verified by STM images (see the inset of Figure 1).

Our studies with transient reflection anisotropy spectroscopy have uncovered process conditions that lead to domain imbalances with ratios as high as 85:15. Such a surface is able to highly suppress antiphase disorder within the very first III-V epilayers. What's more, we can quantify that imbalance in-situ, allowing us to adjust the conditions before we start to nucleate III-Vs.

On larger terraces we have performed analogous experiments. This study includes almost exactly oriented silicon (100), where we observe a completely different behaviour: The reflection anisotropy spectroscopy transient oscillates, with constant period and decreasing intensity. From STM and LEED measurements, we know that a flip of the sign of the signal implies a rotation of the preferential silicon dimer orientation. So what we are witnessing is a periodic change from (1x2) to (2x1) domains.

This situation arises due to layer-by-layer removal of silicon atoms. It is believed to occur when vacancies group to vacancy islands (see Figure 2) – and once they reach a certain size, vacancies may also be created within the vacancy island, such as at the subjacent layer. The continuation of this process accounts for the oscillation of this signal, which gets weaker as more and more residuals are left over to leave a two-domain surface with frayed step edges (see Figure 2).

Adding III-Vs

When it comes to the growth of III-Vs on silicon, most surfaces that might be suitable for growth have characteristic reflection anisotropy spectra. This is certainly true for GaP, which can be grown pseudomorphically on silicon (100). Although this III-V might not be used to build a device, single-domain GaP/silicon (100) surfaces – where complications arising from the polar-on-non-polar transition between a III-V epilayer and a group IV substrate are already solved – are a great starting point for a transition to other III-Vs.

Reflection anisotropy spectroscopy offers an insight into the entire process, from silicon preparation to GaP nucleation and formation of a surface of this material (see Figure 3). We can monitor signals providing information about the atomic order at the surface and the thickness of the epilayer and heterointerface. This data allows optimization of each process step, and holds the key to the formation of very flat, single-domain quasi-substrates. According to *ex-situ* atomic force microscopy measurements, the roughness of this surface, evaluated in terms of root-mean-square roughness, is typically in the range of a few Angstrom.

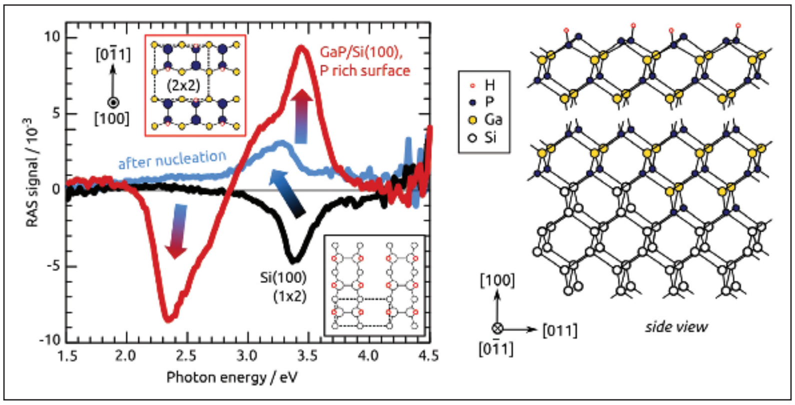


Figure 3. Reflection anisotropy spectra of silicon (100) (black), after pulsed GaP nucleation and of the final phosphor-rich GaP/silicon (100) surface of 0.04 µm-thick single-domain epilayer. The insets indicate a top view of the surface reconstruction of silicon (100) and GaP/ silicon (100), respectively. The ball-and-stick model on the right hand side sketches the layer stack for a double-layer step at the silicon surface assuming abrupt interfaces.

Preparing these well-defined, sharp interfaces is highly beneficial. It improves the performance of many classes of device, including those that feature tunnel junctions; and it allows the construction of structures incorporating III-Vs on either germanium or silicon. For example, reflection anisotropy spectroscopy allows control of the preparation of single-domain vicinal germanium (100) surfaces.

Development of quadruple-junction cells, which are taking efficiencies to new highs, have also been aided by reflection anisotropy spectroscopy. This technique has helped to develop, on InP (100), a photovoltaic tandem subcell that is optimized to absorb the infrared part of the solar spectrum within a four-junction cell.

It is clear that reflection anisotropy spectroscopy can play a major role in assisting the epitaxial growth of III-Vs, silicon, and germanium. Once spectra are established, it is easy to refer to them when growing challenging structures. They are undoubtedly proving indispensable for the growth of III-Vs on silicon, which involves competition between thermodynamic driving forces and kinetically limiting interfacial reactions such as adsorption, desorption and etching reactions that lead to a highly complex, interfering preparation scenario.

Further reading

D.E. Aspnes *et. al.* Phys. Rev. Lett. **54** 1956 (1985)
S. Brückner *et. al.* Phys. Rev. B **86** 1953101 (2012)
S. Brückner *et. al.* New J. Phys. **15** 1130491 (2013)
T. Hannappel *et. al.* Rev. Sci. Instrum. **75** 1297 (2004)
O. Supplie *et. al.* J. Phys. Chem. Lett. **6** 464 (2015)
O. Supplie *et. al.* Phys. Rev. B **90** 235301 (2014)

AlN Schottky barrier diode makes its debut

HVPE growth enables the fabrication of Schottky barrier diodes with a bandgap of 6.1 eV

A PARTNERSHIP between researchers in Japan and the US is claiming to have fabricated the first vertical Schottky barrier diodes made from AlN.

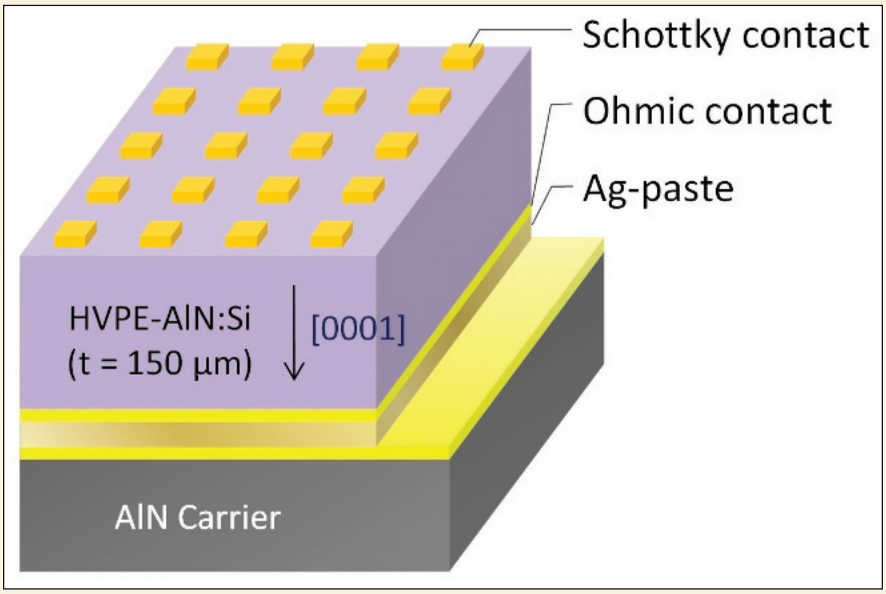
These devices promise to deliver a superior performance to existing wide bandgap devices, due to their much higher bandgap that leads to a far higher electric breakdown field. The bandgap of AlN is 6.1 eV, and it has a breakdown electric field of 11.7 MV/cm, compared to 5.6 MV/cm for diamond, 3.3 MV/cm for GaN and between 2.0 MV/cm and 2.4 MV/cm for SiC.

Up until now, unlocking the potential of AlN Schottky barrier diodes has been held back by the lack of a suitable, native substrate. Electronic devices such as diodes require *n*-type conductivity, and this has been realised previously by either using oxygen impurities or nitrogen vacancies – or by turning to growth of films by MOCVD, which allows silicon doping, but film thicknesses tends to be less than 1 μm. A more suitable approach is to deposit films using a faster deposition technique, HVPE. This is the approach taken by the Japan-US collaboration, which involves researchers from Tsukuba Research Laboratories, Fuji Electric Company, Tokyo University of Agriculture and Technology, HexaTech and North Carolina State University.

Members of this team produced substrates by growing, via HVPE at 1450 °C, silicon-doped AlN layers up to 250 μm-thick on chemically mechanically polished aluminium-polar surfaces. These surfaces were produced on highly insulating, 15 mm-diameter AlN(0001) substrates that had been formed by physical vapour transport (PVT). Growth of the AlN proceeded at 25 μm/hr, with quartz fragments placed on the susceptor providing a silicon dopant source.

Devices were formed by chemical-mechanical polishing of the surface of the epilayer of AlN, and removal of the PVT-grown substrate to leave a 150 μm-thick piece of freestanding AlN. Schottky contacts with dimensions of 270 μm by 270 μm were created by depositing 20 nm of nickel and 50 nm of gold on the N-polar surface.

X-ray diffraction offered an insight into the crystal quality of the free-standing AlN. Narrow peaks in the spectra indicated that the crystal quality is comparable to that of the PVT-grown AlN.



HVPE enabled the growth of silicon-doped AlN substrates that were used to form Schottky barrier diodes.

Secondary ion mass spectrometry revealed the dopants and the impurity levels in the HVPE-grown substrate. "The silicon concentration was 3×10^{17} cm^{-3}, and carbon and oxygen were below the detection limit," explains Toru Kinoshita from Tsukuba Research Laboratories.

To determine the electrical properties of the silicon-doped AlN, the team also grew a thinner film that would avoid a measurement error caused by thickness inhomogeneity. Measurements on the resulting 32 μm-thick film at 300K revealed a net electron concentration of 2.4×10^{14} cm^{-3}, a mobility of 115 cm^2 V^{-1}s^{-1}, and a resistivity of 2.3×10^2 Ω cm.

Compared to an AlN film grown by MOCVD, which had a similar silicon-doping concentration, the HVPE-film had a lower mobility. This might be surprising, since the HVPE-grown material had a dislocation density that is lower by four orders of magnitude – but it is plagued by a high total defect concentration, which the team blames for the low mobility.

Kinoshita and co-workers have studied the electrical properties of the device after gluing the substrate onto an AlN carrier with silver paste.

Measured at 298 K, the Schottky barrier diode had a turn-on voltage of 2.2 V, a series resistance of 3.5×10^6 Ω, and an ideality factor of 7.9. Using a thermionic emission model and electrical data at various temperatures, the researchers estimated a barrier height for this device of 1.1 eV at 298 K.

The researchers believe that damage is present at the interface between the Schottky contact and the HVPE-grown AlN, resulting from mechanical polishing. This is to blame for the high ideality factor and the large difference between the barrier height and the turn-on voltage.

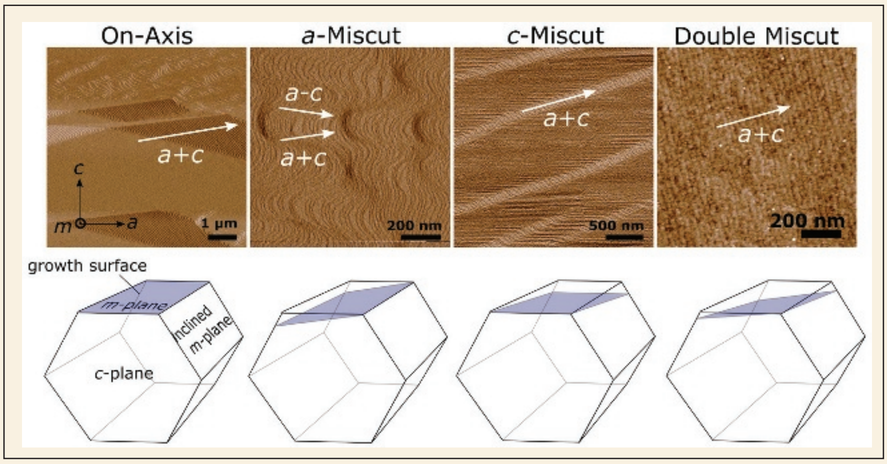
T. Kinoshita *et. al.* Appl. Phys Express **8** 061003 (2015)

Double miscut substrates yield superior quantum wells

Narrower, longer emission results from growth on m-plane substrates with a second miscut

RESEARCHERS at the University of California, Santa Barbara (USCB), have improved the characteristics of *m*-plane InGaN quantum wells by growing these heterostructures on substrates that are miscut in two directions.

The superior quantum wells promise to improve the performance of *m*-plane laser diodes. These devices have an inherent advantage over the more conventional *c*-plane lasers, which are held back by internal electric fields that hamper radiative recombination. However, the *m*-plane variants suffer from a broad linewidth that lowers the peak power in the spontaneous emission spectrum.



Atomic force microscopy images expose the superior growth of heterostructures on *m*-plane substrates that have a miscut in two directions.

The West-coast team have shown that it is possible to address this by turning to double miscut substrates – they are miscut along the *a*- and *c*-directions. Quantum wells formed on this foundation, which is provided by the Mitsubishi Chemical Company, produce improved spontaneous emission characteristics.

Interest in miscut substrates for *m*-plane growth is not new. As far back as 2007 researchers from UCSB were reporting results on substrates with a -1° miscut in the *c*-direction. That platform for growth supresses the formation of hillocks that would occur on on-axis, *m*-plane substrates.

Compared to *c*-plane substrates, single miscut *m*-plane variants exhibit a low indium uptake and lead to quantum wells with a broad luminescence linewidth. Both of these weaknesses hamper the fabrication of high-performance lasers: Broad luminescence distributes carriers over many non-lasing optical modes, leading to a lower peak power and peak gain; and a reduction in indium uptake has to be compensated for by lowering the growth temperature – and this degrades the crystal quality of the heterostructure.

A previous study by UCSB found that quantum wells grown on substrates that are -1° miscut in the *c*-direction have a striated morphology, with striated regions exhibiting emission at longer wavelengths. These striations are formed from a diagonal stepflow, with a directional component along the *a*- and *c*-axis that led to increased indium content.

This observation encouraged growth of quantum wells on double-miscut substrates. This latest study involved co-loading substrates into an MOCVD reactor that had either a miscut of -1° in the *c*-direction or two miscuts: either a miscut of 1.49° in the *c*-direction and a miscut of 2.10° in the *a*-direction; or a miscut of 0.21° in the *c*-direction and 0.51° in the *a*-direction.

On all these substrates the researchers grew a range of LED and laser stuctures at 1100 °C. They featured one to three wells with widths of 4 nm to 12 nm, separated by quantum barriers with widths of 8 nm to 16 nm.

Atomic force microscopy images of the heterostructures grown on the double miscut substrates revealed stable step-flow growth, with straight edges and a constant terrace width.

The researchers performed on-wafer electroluminescence measurements on many of the heterostructures, using 0.1 mm^2 indium *p*-type contacts and *n*-contacts formed by soldering indium to the wafer edge. LEDs with a double miscut of 1.49° in the *c*-direction and a miscut of 2.10° in the *a*-direction produced longer emission wavelengths for fluorescence, phtotoluminecence and electroluminescence. For the latter, the emission peak of an LED red-shifted by 38 nm compared to that formed on a miscut of -1° in the *c*-direction, thanks to higher indium uptake.

Another strength of the double-miscut substrates is narrower emission. Electroluminescence of laser diode structures revealed a full-width at half maximum of 30.5 nm for a structure grown on a substrate with a miscut of 1.49° in the *c*-direction and a miscut of 2.10° in the *a*-direction. This is 14.4 nm narrower than that for a laser on a substrate with a miscut of -1° in the *c*-direction.

The team told *Compound Semiconductor* that they are now planning to make lasers. They are currently developing epitaxial and processing steps, and will soon compare the performance of lasers grown on different miscuts.

L. Kuritzky *et. al.* Appl. Phys. Express **8** 061002 (2015)

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