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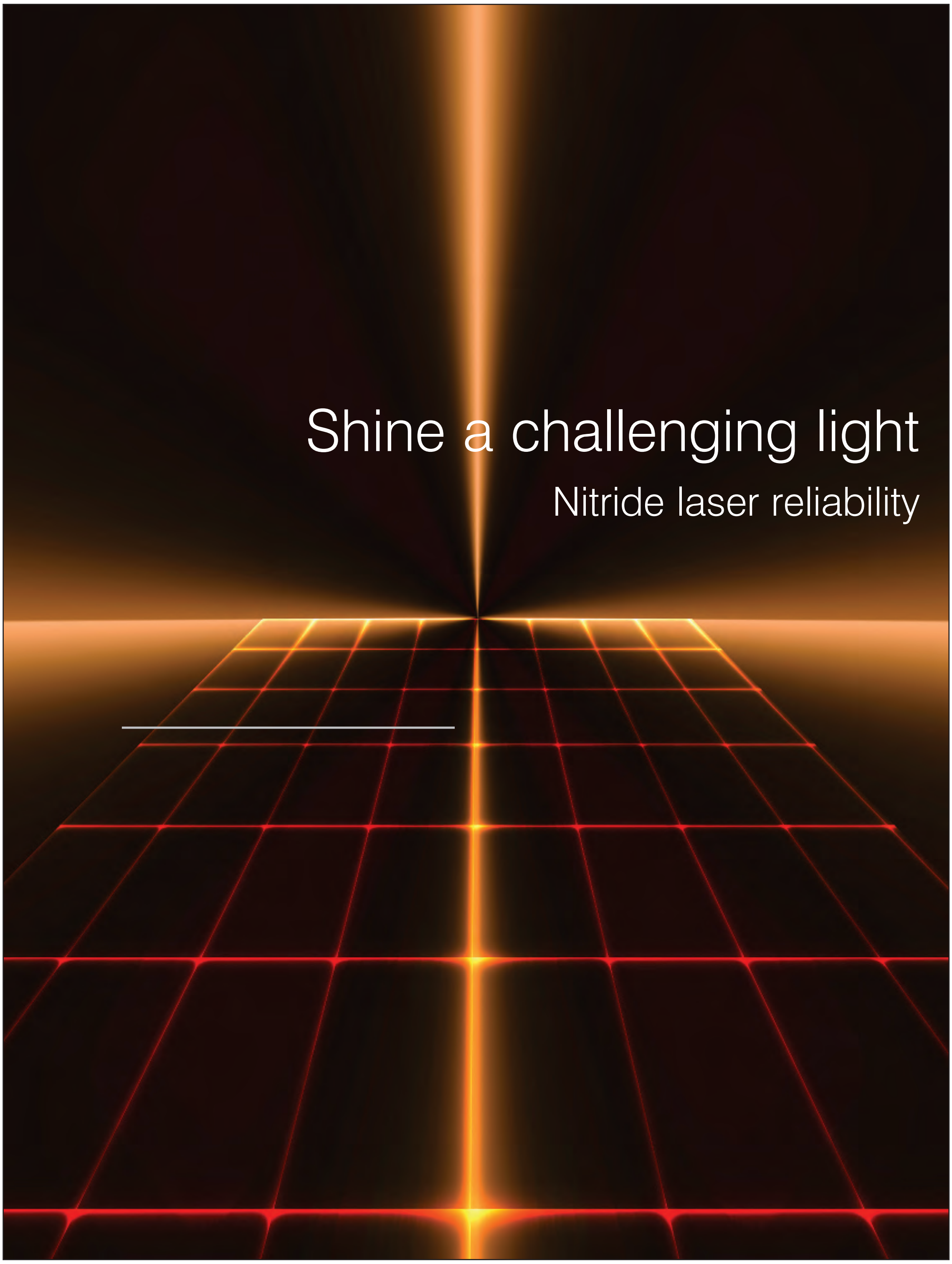

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III-V logic

Where will we be in 2015? My guess is that by then LED light bulbs will be more than just a novelty, concentrating photovoltaics based on III-V triple junction cells will be seeing some hefty deployments and compound semiconductors will be starting to play a role in helping to maintain the march of Moore's Law.

The notion that the compounds could soon replace silicon CMOS is sure to raise a few eyebrows. But it's not that outrageous an idea. After all, the International Technology Roadmap for Semiconductors is advocating the use of new materials for the 11 nm node that will be rolled out in 2015, and III-Vs are topping the short list.

If compounds are to make an impact in four years time, substantial progress has to be made at the research level right now. And that seems to be happening.

Any CMOS successor must be built on silicon – that industry is far too conservative to have it any other way. So processes will have to be devised that not only overcome the differences in lattice constant between III-Vs and silicon, but also differences in polarity. And these processes will need to place two types of transistor on the substrate – probably one made from III-Vs and the other from germanium – to realize devices that are either good at transporting electrons or holes.

At the International Electron Devices Meeting at the end of 2010 Sematech showed one way to do this, producing n-type transistors with a very tight spread of characteristics on 200 mm silicon (see Compound Semiconductor, January/February 2011, p12).

One downside of this approach was that a buffer was far too thick. In addition, deposition of the III-Vs was over the entire substrate rather than localized areas.

Researchers in Europe that include a team from imec have addressed both these issues by forming trenches in the silicon substrate and filling them up with a thin layer of germanium, followed by a thicker one of InP. If the trenches have a concave bottom and the germanium surface is treated to take on a particularly morphology, it is possible to form high-quality InP material on the orientation of silicon that is churned through the foundries today (see p.12 of this issue).

In the last few months imec's engineers have formed transistors from this material. Initial results are not great, with the devices suffering from high leakage currents. But the researchers have plans to tackle this and help to make a good case for III-V logic. By 2015, their efforts could be paying dividends.

Richard Stevenson PhD
Consultant Editor

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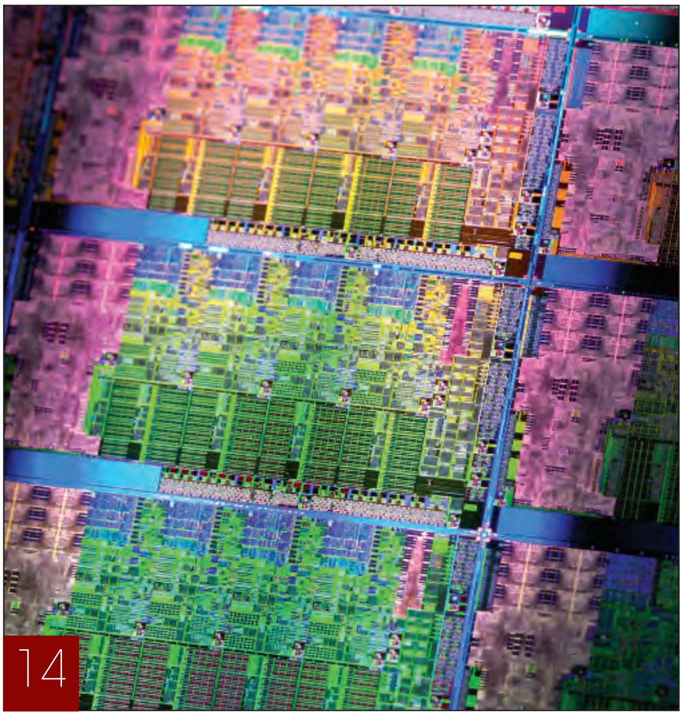
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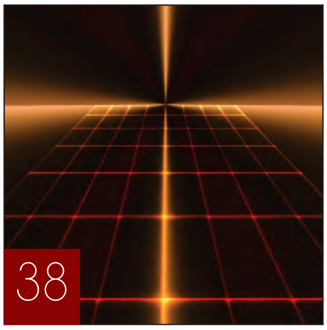
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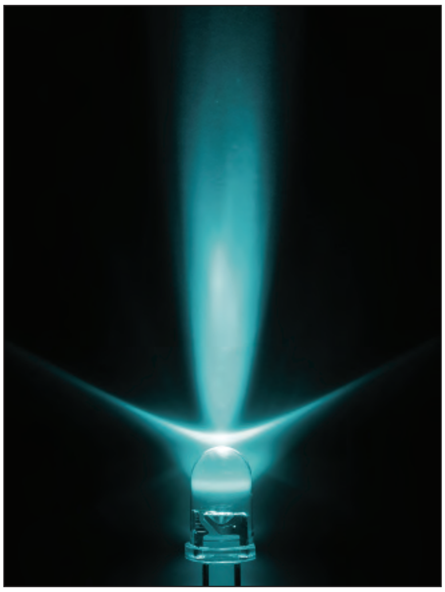
Lumileds Leads LED Lighting to "Freedom From Binning"



PHILIPS LUMILEDS have announced an industry breakthrough that is claimed to relieve luminaire manufacturers' and lighting designers' concerns over white light consistency and uniformity.

With Philips Lumileds vision for Freedom From Binning, white LUXEON emitters will be so uniform and consistent that there will be no colour bin selections. Buyers of the new LEDs, initially released at CCTs of 2700K and 3000K with others to follow, will receive LUXEON LEDs that are already tested and binned at real-world operating conditions so that their performance for colour, light output, and efficacy are already known. Lumileds will proliferate Freedom From Binning through new product introductions this year and into the future.

"At random, I can lay a thousand of these new LUXEONs in a straight line and the consistency and colour quality from LED to LED will be as good or better as what you would see with many of the bulbs in use today, said Michael Holt, CEO of Philips Lumileds. "The lighting industry has yearned for quality of light, simplicity of design, and more efficient light sources in mass quantities and reasonable costs that enable solutions that improve on what's possible with conventional lamps. By combining our unique TFFC and Lumiramic phosphor technologies with new manufacturing capabilities that allow us to 'hot' test and colour bin, Philips Lumileds' Freedom From Binning is charting a new course for the LED manufacturing industry to follow and moving us ever closer to the lighting industry."

The lighting community will want to look at LED performance information in a new way as a result of these advancements. Although typical datasheets present data for LEDs at 25°C, it's well know that the actual operating temperature is closer to 85°C (sometimes higher) and that the performance numbers reported are essentially overstated.

LUXEON products that offer Freedom From Binning are tested at 85°C so that the actual colour point and performance numbers are known.
"We sacrifice the marketing value of higher lumen and efficacy numbers for accuracy and confidence," said Holt. "We can calculate performance at lower temperatures but that would defeat the point and potentially mislead." Most datasheets from LED manufacturers include the information required to understand performance at elevated temperatures and the industry is able to make real-world comparisons between products.

Philips Lumileds will release its first product to feature Freedom From Binning this week at Strategies in Light. Colour selections will consist simply of a CCT designation, centred on the black body curve at hot (real-world) conditions. As new LUXEON products are introduced for the lighting industry, Philips Lumileds will expand its Freedom From Binning program.

Cree LED Lamp Raises the Bar for Colour Rendering

CREE has announced commercial availability of the LBR-30 LED lamp, aimed at replacing energy-wasting incandescent lamps commonly used in tracks, commercial and residential recessed downlights. Powered by Cree TrueWhite Technology, the lamp delivers beautiful, warm-white light with what the firm says, offers unrivalled colour accuracy and efficiency.

"We were highly impressed with the installation of LBR-30 lamps in our Pittsburgh, Pa. LEED Gold designed location," said Andrew Dunmire, AIA, LEED AP, VP of design and construction at Eat'n Park Restaurants, a restaurant chain with 75 locations throughout Pennsylvania, Eastern Ohio, and Northern West Virginia.
"The lamps truly brought our space to life by highlighting the vibrant walls and furnishings, while the reduced energy use,

compared to the incandescents, saves us every month on ongoing operating expenses – enabling us to achieve our sustainable design objectives."

Thanks to its high colour rendering index (CRI) of 94, the LBR-30 lamp is optimised for applications where high colour accuracy is essential, including restaurants, retail stores, groceries and museums. It delivers 600 lumens, equivalent to a 60 watt incandescent BR30, while using only 12 watts of input power. The lamp is designed to last 50,000 hours in open fixtures, which can provide merchants like Eat'n Park additional savings from reduced relamping and maintenance costs.

"The LBR-30 lamp's superior blend of incandescent-like colour and efficacy delivers a true no-compromise solution for both general and accent lighting," said David Turner, Cree director of marketing, LED Lighting. "This high-performance, retrofit lamp quickly installs into track or recessed fixtures and is available in flood or wide flood distributions, giving customers the flexibility to choose the most appropriate solution for their lighting needs."
The Cree LBR-30 is sold through Cree LED Lighting sales channels and is currently shipping in volume.

Worldwide LED Market Doubled in 2010

THE worldwide high-brightness (HB) LED market leaped from $5.6 billion in 2009 to $10.8 billion in 2010, a growth rate of 93%, according to market research firm Strategies Unlimited. LCD monitor and TV backlights led the growth spurt, followed by mobile display applications. Ten companies accounted for more than 75% of the HB-LED market. Strategies Unlimited arrived at these figures after analysing market demand as well as the supply-side activity of more than 40 HB-LED component suppliers.

The rank order, by revenue, of the top 10 suppliers in the HB-LED market in 2010 is:

1. Nichia
2. Samsung LED
3. Osram Opto Semiconductors
4. Philips Lumileds Lighting
5. Seoul Semiconductor
6. LG Innotek
7. Cree
8. Sharp
9. TG
10. Everlight

Several paths led to this impressive growth. Samsung LED, Seoul Semiconductor, and LG Innotek rode the boom in the LCD TV and monitor backlight market. Osram rode the rise of the Chinese HB-LED market, especially in the automobile sector. Lumiled's success in high-power backlight products, cell phone flash, and architectural lighting contributed to much of its success. Cree's dedicated focus on lighting ensured its continued strong position in the solid-state lighting revolution. Chinese LED suppliers captured 2 % of the market.

While LCD backlights accounted for the largest part of the jump in HB-LED revenue in 2010, mobile applications were also significant contributors. In particular, the large rise in PC notebook sales and the penetration rate for notebook backlights doubled HB-LED revenue over 2009.

Strategies Unlimited expects television and monitor backlights to conitnue to be a strong engine for growth in the next two years and flatten out in 2013. The overall forecast CAGR is more than 16% from 2010–2015. LED luminaire design, not performance, was the primary concern for the lighting market in 2010.

HB-LED component revenue for lighting was $890 million in 2010. Solid-state lighting will become the key market driver in 2014 because of the worldwide focus on energy efficiency and the phase-out of incandescent bulbs. The forecast CAGR for HB-LED components for lighting from 2010–2015 is 39%.

Sulfurcell achieves 12.6% efficiency

SULFURCELL, a producer of CIGS/CIGSe thin-film solar modules has announced TÜV Rheinland, a provider of product safety and quality certification, has confirmed the 12.6% efficiency of the company's full-scale 0.8m2 94W thin-film photovoltaic (PV) module.

The high efficiency module thin-film solar module modules will begin shipping to customers in Q3 of 2011. Since producing and shipping its first modules to customers in 2005, Sulfurcell has successfully commercialised on a mass scale, ramping-up its production capacity to 35 MW.

Sulfurcell distinguishes itself by developing comprehensive solutions for the BIPV, solar construction and commercial rooftop sectors. The company is currently setting up a network of partner installers and integrators in North America.

"We are delighted Sulfurcell has achieved such momentum over the last year, with major supply agreements, financing, and now validation of our 12.6% efficiency CIGS modules," said Nikolaus Meyer, CEO of Sulfurcell. "With our high-efficiency modules hitting the market in a matter of months, we imagine 2011 will be another year of success for Sulfurcell."

Osram Multi ChipLEDs Produce Picture-Perfect Images

OSRAM says displays using its LEDs produced using Thinfilm or ThinGaN technology raise image quality to new levels. Due to their small footprint, they remain undetected by observers through the black LED housing.

An LED developed by Osram Opto Semiconductors ensures brilliant colours and sharp contrasts. Osram says its Multi ChipLEDs used in the new FormoLight display are the smallest RGB LED on the market. The compact size permits a special image format. In this display for interior use, the LEDs are not used as backlighting hidden from observers as in LCD appliances, but are visible on the surface.

"Information has to be presented clearly in every respect. This concerns not only the concept of visualisation, but also the technical reproduction. Excellent image quality is needed, which is easier to realise thanks to the advantages of LEDs, such as their directional characteristics and light quality", explains Sven Weber of Osram Opto.

The FormoLight display thus impresses with rich colours, sharp contours and depth of field, showing high-quality images rich in contrast. Convincing from every angle, Multi ChipLEDs produce a homogenous image from every perspective. This homogeneity is based on two principles.

On the one hand, LEDs can be packed very closely because of their compact size; distance between pixels can be as little as 2mm. On the other, the special casting material ensures a perfect colour mix.

Ubilux selects Aixtron for GaN LEDs

Aixtron SE has a new MOCVD reactor order from existing customer Ubilux of Tainan County, Taiwan. The order is for two Aixtron CRIUS II deposition systems in the 55x2-inch configuration which will be used to expand the company's production capacity for GaN-based HB LEDs.

Ubilux placed the order in the fourth quarter of 2010 and the systems will be delivered in the first quarter of 2011. A local Aixtron support team will commission the new reactors at the state of the art clean-room facilities housed in the Ubilux headquarters in the Southern Taiwan Science Park.

President Henry Chen from Ubilux comments, "This is our first CRIUS II system purchase order. After Aixtron launched its new MOCVD systems, Ubilux was very glad to acquire them. Once we had finalised our expansion plans, we approached Aixtron´s local representatives who sorted out the deal with us."

"Ubilux already has several CRIUS systems for GaN applications as well as a G3 system for GaAsInP application. We are impressed with these systems' performance and we trust Aixtron technology. Over the years, we have built up an excellent relationship with the company so we were interested in acquiring the newest systems for our further expansion plans. I expect these will be a perfect match to our requirements," he continues.

Christian Geng, General Manager Aixtron Taiwan adds, "A feature of the Taiwan MOCVD community is the high number of the most advanced technology Aixtron systems that are being used for the mass production of UHB-LEDs. Our support and field service is available 24 hours a day to guarantee customers receive the support they need by phone or on-site. In fact last year, the Aixtron Taiwanese support team handled over 1,800 installations, upgrades, and customer support requests."

ISCAS Orders Two Aixtron MOCVD Tools for GaN Device Growth

AIXTRON SE has a new order for MOCVD reactors from existing customer, the Institute of Semiconductors Chinese Academy of Sciences (ISCAS).

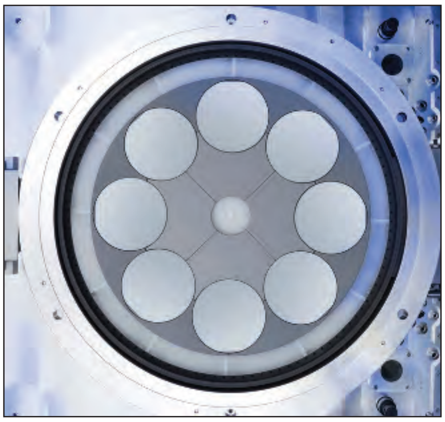
The order comprises one AIX 200/4 in the 3x2-inch wafer configuration and one AIX 2600G3 IC in the 8x3-inch wafer configuration.

The Beijing, PR China based institute placed the order during the third quarter of 2010 and following delivery in the second quarter of 2011, the systems will be used for production of electronic devices and red LEDs. The local Aixtron support team will commission the new reactors in a dedicated facility.

A spokesperson commented, "This is a repeat order for us and over half a decade we have formed a good long-term relationship with the Aixtron group. We are convinced that these Aixtron systems will help us to achieve a very high standard of results for R&D in these key technology areas. We have been impressed in initial trials how effectively and easy it has been to scale up device processes from our existing deposition systems to the new Aixtron systems."

"Our relationship with Aixtron began way back in 2003 when ISCAS expanded its R&D capabilities installing a state-of-the-art Close Coupled Showerhead (CCS) MOCVD reactor. That 3x2-inch reactor enabled us to grow high quality GaN on sapphire layers on 4-inch wafers as well as GaN on Silicon primarily for the development of short-wavelength laser diodes and UV photo-detector based devices."

The Institute of Semiconductors was among the first institutions/universities in China, authorised to offer master and doctoral degrees and to introduce postdoctoral



research stations. Currently, it runs three postdoctoral stations, four doctoral and five master programs.

It has made great and significant contributions to developing Chinese semiconductor science and technology and is expected to make many more splendid achievements in the future.

EV Expands Portfolio with Mask Aligner for HB-LED Production

EV GROUP has revealed the latest addition to its portfolio of products created to optimise the manufacture of high-brightness light-emitting diodes (HB-LEDs), compound semiconductors and power electronics. The new EVG620HBL fully automated mask alignment system builds on EVG's mask aligner platform, adding a high-intensity ultraviolet (UV) light source and five cassette stations. The firm says this is significantly more than competitive offerings and will enable continuous fabrication of devices. As a result, the EVG620HBL delivers throughput of up to 165 six-inch wafers per hour (up to 220 wafers per hour in first print mode) with high alignment accuracy and yield.

According to market research firm Global Information, global consumption of high brightness LEDs (HB-LEDs) will continue to grow at a rapid pace over the next decade, from $10.09 billion in 2010 to $46.05 billion in 2020. Key drivers will include explosive growth in solid-state and general lighting applications, as well as signage, professional displays, and stationary (non-vehicle) signals. To meet this increased demand, HB-LED manufacturers must quickly ramp up to higher production capacity, as well as optimise their manufacturing processes to ensure the highest yields.

This elevates the need for automated manufacturing solutions with the lowest cost of ownership. As with its dedicated EVG560HBL automated wafer-bonding system, introduced last July, EVG developed the EVG620HBL aligner to address these needs. EVG is not new to this market; its bonders and mask aligners are being deployed by four of the top five major HB-LED manufacturers. Building on this success, the company created the 620HBL in response to customer demand for a mask alignment system dedicated to meeting these devices' yield and throughput requirements. Another key feature of the EVG620HBL is the availability of special recipe-controlled microscopes whose illumination spectrum is optimized to ensure the best pattern contrast with various wafer and layer materials, including such advanced substrate materials as sapphire, SiC, AlN, metal and ceramic.

"Our ongoing R&D efforts and focus on innovation in equipment manufacturing and process engineering are enabling EVG to consistently deliver the state-of-the-art, high-volume manufacturing solutions that our customers expect," stated Paul Lindner, EV Group's executive technology director.

"Just last month, a HB-LED manufacturers ordered an EVG560HBL bonder, and the EVG620HBL is the latest result of our ongoing efforts around enabling HB-LED manufacturers to develop more efficient, cost-effective and higher yielding devices."

We look forward to making further inroads with this latest offering, which also features high-accuracy handling and alignment of fragile or warped wafers."

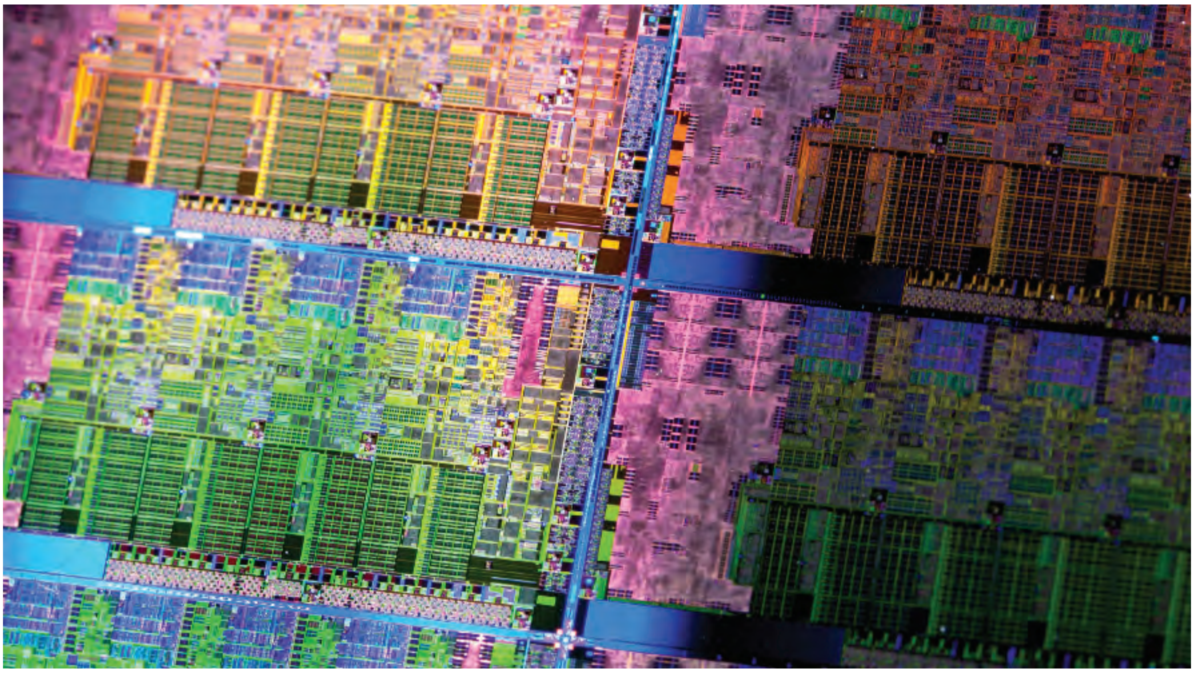
IMEC prepares the ground for III-V transistors on silicon

One option for maintaining the march of Moore's Law is to build the pairing of III-V and germanium transistors on silicon. Depositing compound semiconductors on silicon in a selective manner is tricky, but researchers at imec have shown that it is possible to do this on 200 mm on-axis wafers by forming concave trenches in the material, before filling them with a little germanium and topping them up with InP. **Richard Stevenson reports.**

It is getting harder and harder to squeeze more performance from silicon CMOS transistors. Back in the twentieth century improvements were possible by simply slashing the size of the silicon device and its silicon dioxide gate. But more recently gains have hinged on the introduction of exotic materials such as HfO_2, which prevents an unacceptable hike in leakage currents, and the insertion of a SiGe layer to speed the passage of electrons from source to drain.

Even more radical changes to the transistor architecture are on the horizon. According to the International Technology Roadmap for Semiconductors, transistor manufacture at the 11nm node, which is scheduled for 2015, will require the introduction of a new set of materials to replace silicon. III-Vs are high on the short list. If compound semiconductors are to make an impact, two tremendous obstacles must be overcome. The first is to find a pair of materials – one for the channel and another for gate – that can form a high-quality interface and prevent high leakage currents. The other challenge is to develop processes that can form III-V layers in a well-defined region on silicon substrates, so that this composite wafer could be processed in silicon foundries to yield transistors using conventional process flows and conventional toolsets.

One institution that has a rich history of developing a successor to silicon CMOS and has recently been addressing both of these challenges is imec of Leuven, Belgium. Since 2007 it has been involved in 'Dual Logic', a project with a total budget of € 9.1 million. The primary aim of the programme is to develop transistors for logic ICs on silicon substrates that are suitable for the 22 nm node and below, and feature a germanium channel for p-type transistors



and a III-V channel for n-type equivalents – both forms of device are needed to replicate silicon CMOS processors. imec has played a leading role in this project. One of its major achievements, aside from its work on germanium pMOSFETs, has been the development of processes that can form high-quality InP on selected regions of silicon substrates with the on-axis orientation used in today's CMOS foundries. This accomplishment has required the development of techniques that form trenches with a well-defined concave base and growth processes that can fill them up with high-quality InP.

The team of imec researchers began by developing InP-on-silicon processes on 6° off-cut, 200 mm silicon substrates in a 300 mm-compatible Crius MOCVD epi-reactor, built by Aixtron to be compatible with state-of-the-art silicon foundry specifications (see Figure 1 for an overview of the process). Subsequently, it has transferred this technology to exactly orientated silicon (001), because it views this format as the only one acceptable to that industry. "The silicon CMOS industry is about the most conservative industry you can think of," explains Matty Caymax, head of the imec team. He points out that switching to this more common format delivered additional benefits. Growth processes on off-cut wafers led to issues of crystal quality and surface morphology that depended on trench orientation, which were avoided when using on-axis silicon.

Side-stepping anti-phase domains

Hetero-epitaxy of III-Vs on any orientation of silicon is challenging. Accommodating lattice-mismatch between the two materials is one issue. However, this is overshadowed by problems that stem from depositing a polar material on a non-polar one. Unless the surface of silicon is carefully prepared, anti-phase domains form that plague the epitaxial layer.

"The main issue with anti-phase domain boundaries is the fact that they lead to bonds like gallium-gallium and arsenic-arsenic bonds, which are rather metallic in nature" explains Caymax. "This gives you problems if you want to use these materials for electrical applications – the devices would simply short-circuit."

Caymax and his co-workers initially addressed this problem by inserting a thin germanium layer in the trenches of 6° off-cut silicon. This germanium layer, which is sandwiched between silicon and InP, was treated so that all the atomic steps were two atoms high. Later,

Left: Intel continues to push the capability of silicon CMOS. It has just released second-generation Intel Core i7, i5 and i3 desktop processors that are manufactured with a 32 nm process technology featuring second-generation high-k metal gate transistors. How much more can be squeezed from silicon CMOS is unclear, but Intel, like imec, is looking at III-Vs to extend the march of Moore's Law. Credit: Intel

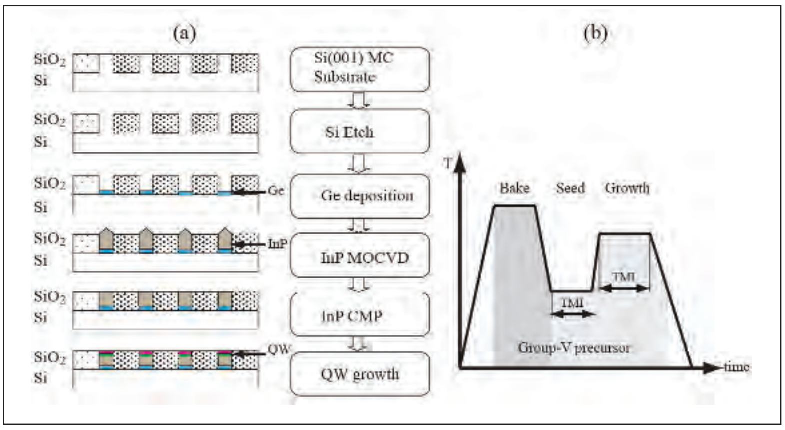


Figure 1 (a) imec's process flow for InP and InGaAs channel growth in silicon wafers with shallow trench isolation (b)The processes and temperatures used for InP growth

engineers replicated this landscape in the concave trenches in on-axis silicon. Substantially reducing the density of anti-phase boundaries is not the only benefit of inserting a thin layer of germanium between silicon and InP. Germanium also acts a bridge between the two materials because its lattice constant is almost half way between that of silicon and InP. In addition, the germanium layer reduces the 'thermal budget' (the combination of high-temperatures and the length of heating time) for the pre-epi bake. A lower thermal budget is desirable, because it cuts unwanted dopant diffusion.

Digging out the trenches

The trenches that imec's engineers make in the silicon substrates can have widths ranging from 20 nm to 100 μm, lengths that are an order of magnitude larger, and depths of a few hundred nanometers. They are created in wafers with the standard isolation structures known as shallow trench isolation, which are routinely used in the CMOS chip manufacturing industry. This isolation structure consists of a patterned SiO_2 capping layer that can laterally isolate devices. This approach allows a straightforward and elegant integration of compound semiconductor materials in a standard manufacturing process flow as used in silicon foundries.

At imec, engineers apply a standard wet clean to the wafers, dip them in hydrofluoric acid to remove native oxide and insert them into an ASM-Epsilon 2000 reactor where they are baked in hydrogen gas at 850 °C. In this chamber trenches are dug out in between the SiO_2 structures by etching these silicon areas in hydrogen chloride vapour at 850°C and a pressure of 10 Torr. Before the wafers are removed, a 30-75 nm-thick layer of germanium is added at atmospheric pressure and a typical growth temperature of 450 °C.

To optimise the temperature for growing the InP seed layer, imec's engineers compared the quality of material grown at 390 °C, 420 °C and 450 °C on 6° off-cut wafers (see Figure 2). At the lowest temperature the growth proceeds by what is known as the vapour-liquid-solid regime. According to the researchers at imec, it is likely that tertiarybutylphosphine (TBP) does not decompose at 390 °C, but trimethylindium does and it

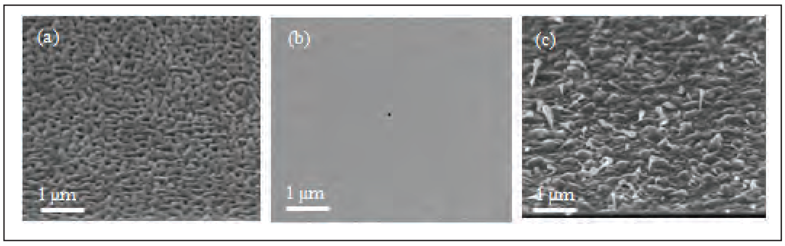


Figure 2. There is a fairly narrow temperature window for growth of InP. (a) at 390°C it seems that only trimethylindium decomposes, forming metallic indium on the germanium surface. Catalytic decomposition of TBP then occurs on the indium droplet to create whiskers. (c) at 450°C large islands form of the surface, probably due to a high indium mobility. (b) at 420°C both these issues are avoided, and a relatively smooth seed layer of InP can be deposited

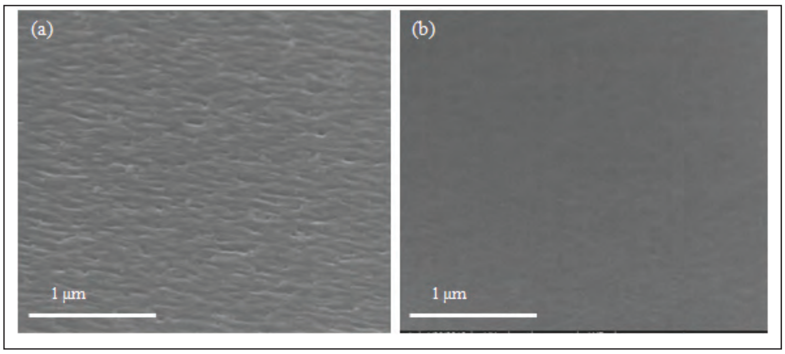


Figure 3 Switching from tertiarybutylphosphine to tertiarybutylarsine improves the quality of the InP layer

forms metallic indium on the germanium surface. Catalytic decomposition of TBP then occurs on the indium droplet to create whiskers. At 450 °C, large islands form on the surface, probably resulting from an indium mobility that is too high. But at 420 °C both these issues are avoided, and it is possible to grow a relatively smooth seed layer of InP.

Further improvements in the smoothness of this seed layer on off-cut silicon are possible by switching the gas used for the pre-epi bake from the pairing of hydrogen and TBP to hydrogen and tertiarybutylarsine (TBAs) (see Figure 3). This benefit, which has been observed before by several other groups, indicates that the quality of III-V growth is high when arsenic atoms provide a full-monolayer coverage of the germanium surface.

After the seed is deposited, the researchers ramp the temperature of the off-cut substrates to 610 °C over a five-minute interval that does not involve any growth of InP. This bake that takes place under a constant TBP pressure may anneal out some of the point defects and provide additional smoothening of the surface, thanks to indium migration. Engineers then deposit an InP bulk layer, using a higher growth rate than the seed. The quality of this material is improved by inserting a GaAs layer just 5 nm thick after the 420 °C bake in TBAs. The imec team have studied the quality of the InP in these trenches. In the trenches along the [110] direction it is possible to trap threading dislocations by employing an aspect ratio of more than two – if it is less than that, stacking faults and threading dislocations are seen in InP at the top of the trench. In contrast, in $[1\bar{1}0]$ windows in the surface, even if the aspect ratio is greater than two, stacking faults that originate at the side walls permeate through all the InP material.

On the level

It is possible to banish these issues related to the trench direction by turning to on-axis substrates. Modifying the trench geometry and employing similar growth processes can realise this - the only major difference to the process for the of-axis silicon is dropping the insertion of the GaAs layer. The key to success on this cut of silicon is to over-etch this material during the hydrogen chloride vapour phase etch to create a concave trench.

When germanium is deposited, it initially follows the underlying surface. However, when two adjacent facets interact due to the different material growth rates on different planes, the surface of the germanium film becomes smoother and its curve is not as pronounced as that at the silicon-germanium interface. imec's engineers realize a relatively uniform step density on this germanium buffer by baking the wafer at 700 °C. At this elevated temperature the step formation energy approaches zero and the top of the germanium film becomes rounded and continuous. In addition, many single atomic steps on the curved germanium surface are converted into a smaller number of double steps. Applying this approach to the growth of InP in a 200 nm wide trench has produced encouraging results. Cross-sectional transmission electron microscopy images reveal the absence of anti-phase domains in InP, which forms a flat, uniform layer along the complete length of the trench (see Figure 4). The dislocation density in the InP layer is far lower near the surface, thanks to the 'extended defect necking effect'.

Off the level

When imec's engineers set out to develop a selective area growth process for InP-on-silicon, they hoped to devise a technology that could fill the trenches precisely to the top of the oxide surface.

"We found that this is really challenging," admits Caymax. "We have loading effects: The growth rate and composition changes, influenced by the geometry. When you have smaller windows the growth rate goes up, when you have larger windows the growth rate goes down, and the best approach is to make sure that all the indium phosphide areas grow outside your oxide."

To process such a wafer into devices, everything that sits outside the trenches must be ground away. One way to do this is chemical mechanical polishing, a technique that can ensure a smooth surface across the entire wafer. "The good thing is that chemical-mechanical polishing has become an accepted step in silicon processing," says Caymax. After the CMP step, the wafers are loaded again into the MOCVD tool to top off the InP layer with the desired multiple layer stack that will form the channel of a quantum-well MOSFET. He and his team have processed some wafers with this approach, and last October they started to make their first devices. The good news is that these devices have showed transistor characteristics, but the downside is that they suffer from very high leakage currents. "We are working right now with solutions to cope with this leakage problem, one of which is the use of semi-insulating InP, which will hopefully block this leakage current," says Caymax.

In terms of devices, it is clearly early days for the imec team. But the lack of transistor success to date should not overshadow the important contribution that this European institute has made to building III-V transistors on silicon: developing a novel technology to deposit high-quality InP, selectively, onto on-axis silicon wafers.

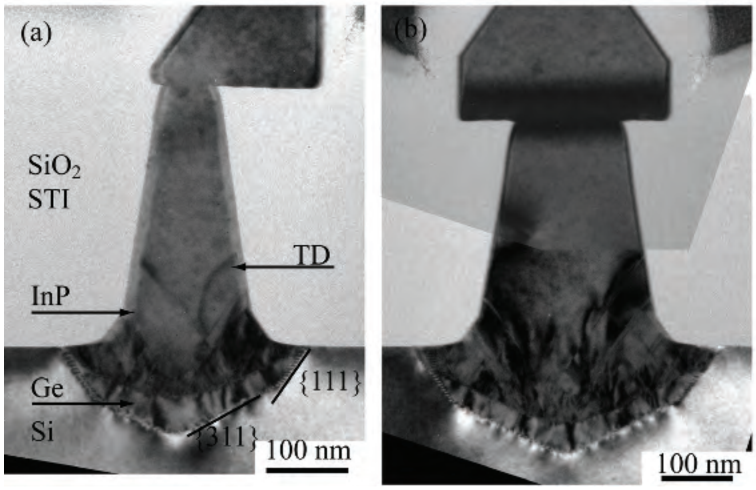


Figure 4. Transmission electron microscopy images of InP grown in trenches 10 nm (a) and 200 nm (b) wide reveal how threading dislocations are confined in the bottom of the trenches

Further reading
G. Wang et al. J. Electrochem. Soc. **157** H1023 (2010)
G. Wang et al. Appl. Phys. Lett. **97** 121913 (2010)

CSEurope www.cseurope.net
22nd March 2011 Frankfurt, Germany

What next for the Compound Semiconductor Industry?

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

Klaus H. Ploog

Pioneer of Molecular Beam Epitaxy (MBE) Keynote Speaker

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

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

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

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

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

Dr. Petteri Uusimaa

President, Modulight

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

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

Jan-Gustav Werthen, Ph.D.

Senior Director, Photovoltaics
JDSU

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

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

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

Jeff Shealy

Division Vice President
RFMD

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

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

Dr Otto Berger

Corporate Advanced Technology Director
TriQuint Semiconductor, Inc

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

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

Marc Rocchi

CEO, OMMIC

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

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

Alexander Bachmann

Marketing Engineer
OSRAM Opto Semiconductors GmbH

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

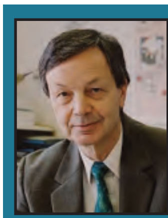
After the studies in physics, Alexander Bachmann worked on the development of electrically pumped vertical-cavity surface-emitting laser diodes at the Walter Schottky Institut of the Technical University of Munich. Emitting in the near- to mid-infrared spectral region, these devices are perfect light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

Dr. Michael Fiebig

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

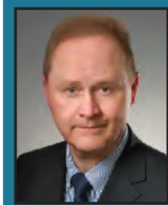
Topic: What are the success factors for the deployment of Solid State Lighting?

Dr. Michael Fiebig gained his PhD in Physics at the University of Hanover in 1998. During his doctoral thesis



Klaus H. Ploog

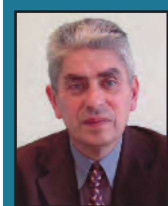
Dr Petteri Uusimaa



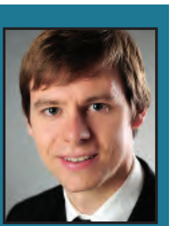
Jan-Gustav Werthen, Ph.D

Jeff Shealy

Dr Otto Berger



Marc Rocchi


Alexander Bachmann


Dr. Michael Fiebig


Dr Markus Behet


Dr. Ulf Meiners


Mark Murphy


Dr. Phillipe Roussel

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

Dr. Markus Behet

Europe Business Development Manager
Dow Corning Compound Semiconductor

Topic: SiC Advances for Power Electronic Applications

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

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

Dr. Ulf Meiners

Chief Technical Officer, UMS

Mark Murphy

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

Ulf Meiners received the Ph.D. in physics from the Technische Universität Munich, Germany and has been working in the compound semiconductor domain since more than 20 years.

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

Dr. Philippe Roussel

Project manager Power Electronics and Compound Semiconductors
Yole Développement

Topic: GaN power electronics: Market forecasts and industry status

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

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

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

Scott Parker

Executive Vice President Sales and Marcom
Oclaro, Inc

Topic: Future Proofing Networks with 100 Gigabit Optics

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

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

Dr. Ertugrul Sönmez
Business Development
MicroGaN GmbH

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

Ertugrul received his Diplom-Ingenieur degrees in electrical engineering from University of Ulm, in 1998. In 1998, he joined the department of Electron Devices and Circuits as a member of the scientific staff, earning the Doktor-Ingenieur degree in 2007. His main fields of research were compact silicon bipolar transistor modeling and analog RF MMIC design at 24GHz. He has authored and co-authored more than 40 publications and conference contributions. In March 2005, he joint ATMEL Germany GmbH in Heilbronn as Marketing Manager, to be responsible for the world wide UWB RFID product line. In June 2005, he joined TES Electronic Solutions GmbH in Stuttgart, a service provider of ATMEL Germany GmbH. His main activities were to lead the ultra wide band MMIC design.

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

Roy Blunt
SEMI International Compound Standards

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

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

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

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

Dr Mike Cooke
Chief Technology Officer
Oxford Instruments Plasma Technology

Topic: Batch and single wafer processing strategies for HBLEDs

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

Dr. Thomas Uhrmann
Business Development Manager
EV Group (EVG)

Topic: Engineered Substrates for future compound semiconductor devices

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

Uhrmann holds an engineering degree in mechatronics from the University of Applied Sciences in Regensburg and a PhD in microelectronics from Vienna University of Technology.

Uhrmann authored and co-authored several papers on semiconductor diode structures, micro or nanomagnetism and related areas.

Mike Czerniak
Product Marketing Manager, Exhaust Gas Management
Edwards

Topic: GaN - meeting emissions regulations

Mike Czerniak received his PhD at Manchester University, and started as a scientist at Philips' UK laboratories before moving to its fab in Nijmegen, working on compound semiconductor applications.

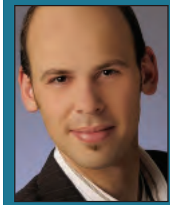
He was in marketing at Cambridge Instruments and VG Semicon; he is now the product marketing manager of the Exhaust Gas Management Division of Edwards, Clevedon, North Somerset BS21 6TH, UK

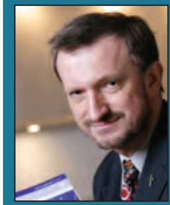

Scott Parker

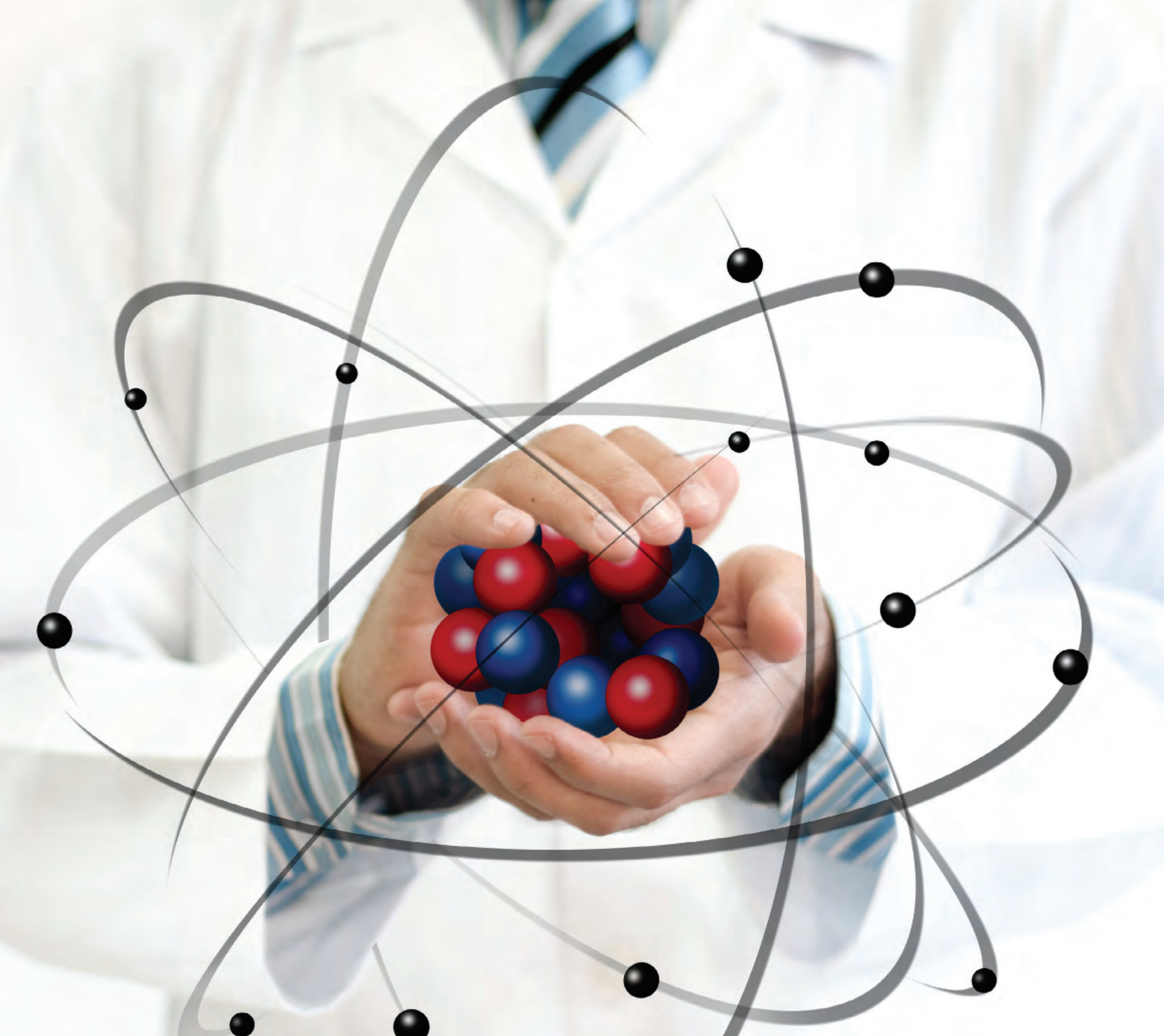

Dr. Ertugrul Sönmez


Roy Blunt


Dr. Mike Cooke


Dr. Thomas Uhrmann


Mike Czerniak



Nanomaster offers a different take on MOCVD

Process engineers put down nitride films by cranking MOCVD reactors up to 1100°C and cracking ammonia and metal precursor molecules on the substrate. But this type of growth can be performed at far lower temperatures to create epitaxial films with minimal hydrogen by switching to a table-top Nanomaster tool that employs an RF source to split nitrogen gas into a plasma. **Richard Stevenson talks to Nanomaster's CEO, Birol Kuyel,** about the pros and cons of this alternative growth technology.

Q What kick-started your development of a plasma-assisted MOCVD tool?

A I met Hae-Won Seo, a professor in the department of physics and astronomy at the University of Arkansas at Little Rock. She was just getting a new appointment, had limited funds, and wanted to replicate the clumsy, big MOCVD systems that she had seen or worked with in Taiwan.

For the money she had, she couldn't buy or do anything with those systems. So I proposed that we could do something table-top. The temperature will not be as high, but at these lower temperatures she could still do MOCVD because we could provide her with plasma enhancement. With her funding we designed and built the system, delivering it in September 2008.

Q Your interest in plasma-assisted growth of nitride films goes back a long way, doesn't it?

A Yes, I have 30 year-old patents for silicon nitride deposition from AT&T Bell Labs. At that time it was difficult to get the stochiometry and other properties of silicon nitride uniform throughout the film simultaneously. But we found that by activating nitrogen in a separate chamber, you could control the stochiometry independent of the composition and other physical parameters, like thickness, density and so on. Those experiments were done with nitrogen rather than ammonia.

So I had a similar expectation from gallium nitride - that plasma enhancement could help incorporate nitrogen at lower temperatures than is possible by the pyrolitic way that is widely used today.

Q What are the benefits of growing nitride films by plasma-assisted MOCVD?

A Nitrogen has some metastable states with long lifetimes, and plasma enhancement of nitrogen allows you to lower deposition temperatures. Reducing the temperature wherever you can is important, because higher temperature reactors are more difficult to build and require longer times to cool.

Another benefit is using nitrogen instead of ammonia. Then you don't need the hydrogen source. Hydrogen is not a good thing in these films, whether its silicon nitride or gallium nitride. It forms a vacany, making an intermediate state that will interfere with the proper operation of the device. In fact, in my earlier silicon nitrogen work, hydrogen would even migrate from the capping material to the gate area and cause threshold shifts. Plasma-enhancement gives you an opportunity to reduce the hydrogen content and the temperature at which the films can be grown.

Q Are there other benefits to using nitrogen gas, rather than ammonia, for the nitrogen source?

A Yes, it has big impact on running costs. Dealing with ammonia requires process abatement. In the case of nitrogen, you don't have that.

Q Are you the only manufacturer of a plasma-enhanced MOCVD tool?

A Yes. I think there is some work in Japan and Australia, but I don't know the nature of this work. I'd like to know more, but I have not run into any detailed information.

Q What were the big challenges in making your first tabletop MOCVD tool?

A The most difficult part was designing everything to work together - putting everything into one system was very, very complicated. Our customer wanted features and upgrades, so we made the tool flexible for that – making it possible to inject liquids directly into the chamber. That adds to the complexity of the small volume inside the plasma source. Vacuum technology, plasma technology and delivering liquid precursors - we had done that before with a number of different systems. The small volume was a big challenge. In this small volume interactions between heater plate and plasma can take place. However, the heater plate can be powered from outside, making it possible to maintain the plasma in isolation.

Q Could your describe the gas flows in your reactor?

A We designed our own showerhead plasma source. Some of the gases go through the showerhead and some of them through a gas ring put in the downstream of the plasma source. Fitting all of this in a small volume was a nightmare. We did that and built a system that is PC controlled. A person doesn't have to do anything manually. This system also has a turbo-molecular pump. Unlike other systems where you have pressures only going to milliTorrs, with this system you can go to the 10^{-6} to 10^{-7} range. So it

Nanomaster's plasma-enhanced MOCVD tool is capable of producing nitrides with very low levels of hydrogen impurities

CORPORATE PARTNERSHIP

To become a Corporate Partner, and be in Compound Semiconductor, contact Shehzad Munshi
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is incredibly clean. All the turbo molecular pump heaters, chambers, power supply and RF connections are in the table-top cabinet.

Q Does the cabinet accommodate absolutely everything?

A We provided bubblers for our first customer. But the volume of some of the bubblers was too big for their applications and it also required filling at their location. They went to different bubblers and chillers, and all that assembly went down on the floor. The only other thing outside the cabinet is the mechanical pump.

Q Is it possible to put *in-situ* monitoring equipment into your reactors?

A Yes, we don't have any limitations in terms of chamber size. What's more, there is no limitation in this geometry for diagnostics compared to any other tool. Although you have a plasma source on top, you can always have a small area where you can look at the surface through an optical window. It is also possible to do optical thickness measurements at oblique angles, and for temperature uniformity, you can put a pyrometer into the chamber. It important to remember that the substrate is not rotating. In that sense, all the measurements will be even easier.

Q Today you are offering two tools: the NMC-3000, which accommodates a 2-inch wafer, and the NMC-4000, which can hold a 6-inch wafer. Both of these are intended for R&D work. If they were scaled, would they be suitable for high-volume manufacture?

A The way that the machine operates currently is to put down thin films at slow rates. Manufacturing applications need more throughput and higher deposition rates. That would require operating at higher pressures, which is counter-productive, because plasmas like to operate at pressures in the sub-Torr range. If you go to 10 Torrs or 100 Torrs, like you do in an industrial machine, you may not be able to enhance with the plasma. So the window where plasma enhancement may be applicable is not as broad as all applications of MOCVD. However, it may that for a subset of certain MOCVD applications, where you may get certain benefits, you might comprise on throughout for quality.

Q Do you have any plans to develop a multi-wafer tool?

A What we would like to do – and this requires the availability of funds – is to build a cluster tool using an NMC-4000. A number of tools, served with a robotic load-lock, could be run in parallel to reach production levels of throughput.

Q What are you short term goals?

A Six months down the road we will have a lot more information because our demonstration system will be complete by then. Then we will try MOCVD at much higher pressures. Today, you can grow clean, uniform, high-quality films, but the rates are low. They can be enhanced by special design of the plasma source.

We will also be able to obtain uniformity data for our tool. I wouldn't expect any problems with that because the plasma source, the chamber and heating system are all much larger than the substrate size. And there is a perfect circle of symmetry in our chamber.

Growing InN nanorods by plasma-enhanced MOCVD

Hae-Won Seo's research team at the University of Arkansas at Little Rock, in partnership with researchers at National Sun Yat-Sen University, Taiwan, have employed the Nanomaster plasma-enhanced MOCVD tool for the growth of InN nanorods. These nanostructures have interesting characteristics, including strong quantum confinement and very high surface-to-volume ratio, but their growth is challenging. If the growth temperature is 500 °C or more decomposition of InN occurs, but switching to lower temperatures tends to increase the density of defects and dislocations in the crystal, leading to high carrier concentrations. The US-Taiwanese partnership addressed this issue with a MOCVD-based technique that employs a 50 W, 13.9 MHz nitrogen plasma, a flow ratio of nitrogen to indium of 6000:1 and base and chamber pressures of 5×10^{-6} Torr and 2×10^{-1} Torr, respectively. Turning to this approach led to an optimum growth temperature of 500 °C, which enabled the growth of high-quality InN nanorods on silicon (111) substrates.

Scanning electron microscopy revealed that the nanorods are straight, have a diameter of 90-120 nm, are typically 3.2-3.5 μm in length, and are uniformly dispersed on the substrate with an areal density of $3\text{-}5 \times 10^{7}$ cm^{-2}. The researchers have also studied the photoluminescence spectra produced by their nanorods at a range of temperatures between 7K and 160 K. At the lowest temperature, the full-width half maximum of the photoluminescence peak is just 27 meV. The narrow peak is claimed to be indicative of a high material quality and a low intrinsic carrier concentration.

The work of the researchers is reported in detail in *J. Nanosci. Nanotechnol.* **10** 6783 (2010)

Birol Kuyel is president and CEO of Nanomaster. He has a broad portfolio of expertise, including high-temperature plasma physics, Si_3N_4 film deposition and characterisation, X-ray and deep UV source development. He has been awarded 9 patents and published numerous papers.

Conductive polymers offer charge dissipation in GaN and ZnO sample processing

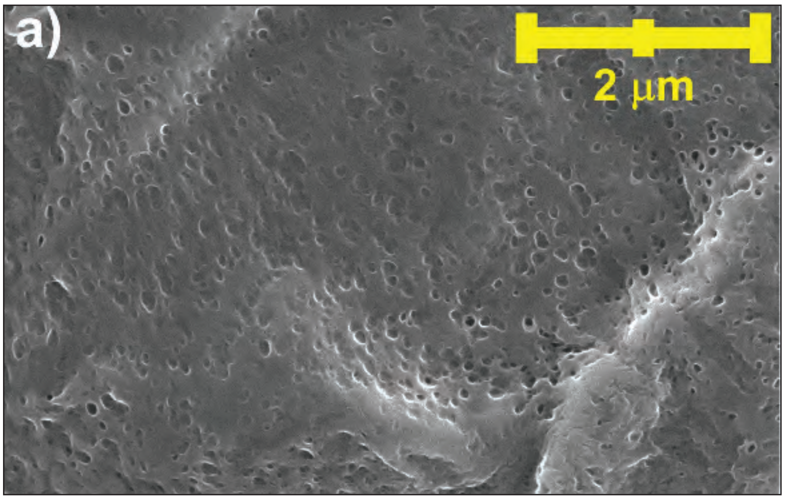
Conducting polymers such as polythiophenes promise to replace metallic films for charge dissipation in semiconductor processing. This switch should provide ease of use and deliver results of unprecedented quality, say **Rafal Dylewicz and Faiz Rahman from the University of Glasgow, UK.**

Creating structures in semiconductor materials is fundamental to making all semiconductor devices. A wide variety of process techniques are employed to craft various types of surface features. Several of these rely on the use of charged particles – electrons or ions – for their operation. Such processes include ion-based etching, electron-beam lithography and focused ion-beam techniques. Both electron-beam lithography and FIB techniques can be used for patterning semiconductor surfaces and are widely used in both research and industry.

A direct side effect of any such technique is charge accumulation, which results in sample charging. While conductive substrates tend to lose accumulated charge quickly, less conductive substrates tend to keep their charge and the resulting electric field causes problems during sample processing.

It is customary to coat vulnerable substrates with a thin layer of a suitable metal in order to obtain a high conductivity surface layer capable of effective charge dissipation. Both the deposition and the subsequent removal of such metallic charge dissipation films is an added complication. This is especially true when samples need to be processed further and the metallic film needs to be removed. This happens, for instance, when samples are merely observed using scanning electron microscopes (SEMs) before undergoing further processing.

Our group at the University of Glasgow, UK, has been exploring the use of conducting organic polymers for replacing metallic charge dissipation layers. Such materials offer convenience in both application and subsequent removal of electrically conducting thin films. Examples of potential polymers include polyaniline, polythiophenes and polyfluorenes. The ability of thin polythiophene layers, in particular, to dissipate



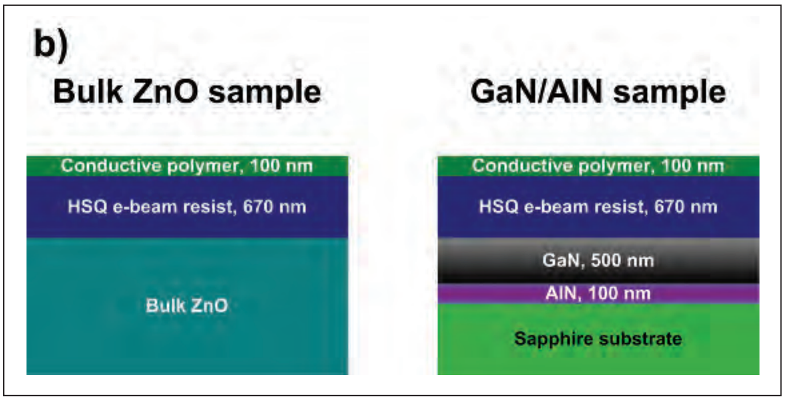


Fig. 1. PSS:PEDOT conductive polymer used for an advanced micro- and nano-fabrication processes: a) scanning electron microscope investigation of a polymer surface, after spin-coating deposition; b) schematic presentation of ZnO and GaN samples used in the experiment, where HSQ e-beam resist was further patterned by electron-beam lithography

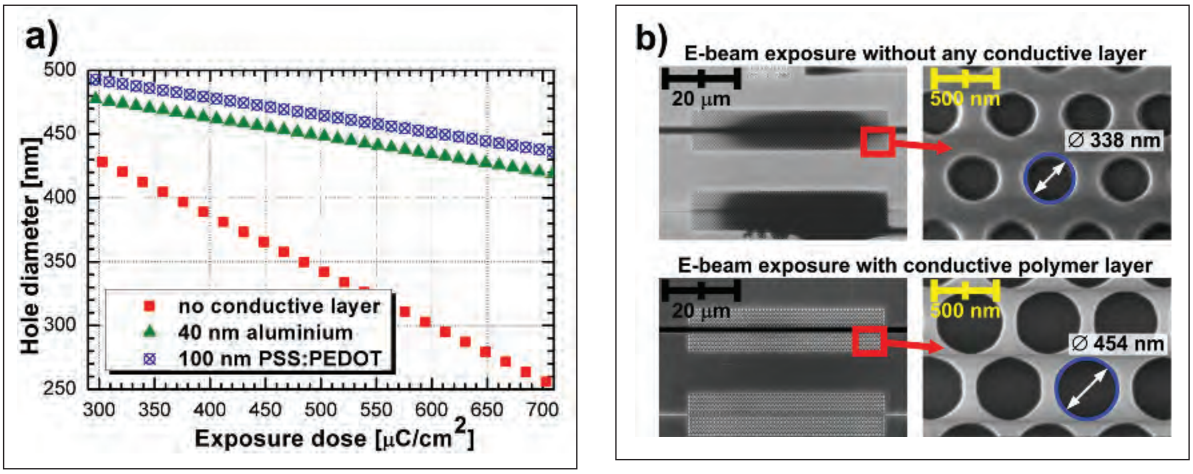


Fig. 2. Results of electron-beam lithography on bulk ZnO samples: a) linear approximation of measured hole diameter as a function of exposure dose, for three investigated cases; b) SEM micrographs of a photonic crystal lattice fabricated in HSQ resist on bulk ZnO, for an exposure without any electron dissipation layer (top) and an exposure with 100-nm-thick PSS:PEDOT layer used (bottom).

accumulated charge in electron-beam lithography process on wide bandgap semiconductors has been the subject of much of our recent investigations. Wide bandgap semiconductors such as SiC, ZnO and GaN are important members of the compound semiconductor family, so their processing is of vital importance to both researchers and industrial engineers.

Our work has focused on ZnO and GaN, typical wide bandgap semiconductors that display low surface conductivity. The aim of this work was to create dense periodic nano-patterns in hydrogen silsesquioxane (HSQ) negative type e-beam resist, so that passive photonic devices could be fabricated in these semiconductors by a subsequent dry etch process. We used a commercially available 2.5 percent water-based dispersion of poly(2,3-dihydrothieno-1,4-dioxin)-poly(styrenesulfonate), i.e. PEDOT:PSS from Sigma-Aldrich. The high electrical conductivity and good oxidation resistance of these polymer films make them suitable for electromagnetic shielding and noise suppression applications.

The optical transmission spectrum of the polythiophene film deposited on a float glass substrate reveals a featureless transmission curve. The polymer film, therefore, possesses high transparency throughout the visible spectrum and even into the near-IR and near-UV regions. In addition, values of extinction coefficient for a thin polythiophene film are negligible in a wide range of wavelengths, including the visible light spectrum, as experimentally determined with the use of a rotating analyzer ellipsometer. The optical transparency of polythiophene charge dissipation layers makes it easy to see the sample surface and perform any alignment operations required to align patterns relative to pre-existing device features.

Electron-beam lithography

Our process is simple, inexpensive and can be used with any wide bandgap semiconductor or dielectric material. However, it is described here in the context of electron-beam lithography exposure of dense and high-resolution patterns in hydrogen silsesquioxane (HSQ) negative type resist deposited on bulk ZnO and GaN/AlN-on-sapphire substrates.

Both scanning electron microscope inspection and electron-beam lithography patterning of ZnO and GaN face difficulties because these materials are not able to efficiently dissipate the charge that accumulates during such processes. Consequently it is common practice to perform e-beam lithography of wide bandgap semiconductors with a thin conducting metal layer, usually aluminium or gold, deposited on top of the e-beam resist.

The aim of the work was to create dense periodic nano-patterns in hydrogen silsesquioxane (HSQ) negative type e-beam resist, so that passive photonic devices could be fabricated in these semiconductors by a subsequent dry etch process

Furthermore, the processing of ZnO is difficult due to the fact that it is an amphoteric oxide, and is thus easily attacked by both acids and bases – typically used for the removal of metal films.

Use of conducting organic polymers in place of metallic films does not involve any special resist preparation steps. Processing involves spin-coating of a conductive polymer (PSS:PEDOT) on top of a HSQ-coated sample, electron-beam writing of dense patterns in the resist, removal of the PSS:PEDOT layer and, finally, development of the exposed HSQ e-beam resist. A layer of PEDOT:PSS polymer, spin-coated on a glass cover-slip, was investigated with a Hitachi S4700 scanning electron microscope at a moderate accelerating voltage of 5 kV, without any additional sputter-coated conductive layer. It is seen in Figure 1a that PSS:PEDOT appears to form a porous film, which contributes to the ease of its removal with water. A schematic diagram showing the use of commercially available PEDOT:PSS conductive polymer to dissipate charge in electron-beam lithography, for both bulk ZnO and epitaxial GaN/AlN/sapphire samples, is shown in Figure 1b.

Comparison of the experimental results for the ZnO sample appears in Figure 2. The fabricated nano-patterns included a 50 µm x 10 µm area of W1 (one row of holes removed) and W3 (three rows of holes removed) photonic crystal (PhC) waveguides with a triangular lattice of holes (periodicity of 550 nm, designed hole diameter of 440 nm). Numerical data in Figure 2a include three different cases, where no electron dissipation layer, a 40-nm-thick aluminium layer and a 100-nm-thick conductive polymer layer were used on top of the HSQ resist. Thus, conventional aluminium and the proposed polymer approach were compared and good agreement between these results is reported, whilst the new method considerably simplifies sample processing.

Scanning electron microscope observations of the resulting photonic crystal patterns, exposed with the same dose of 474 $\mu C/cm^2$ are shown in Figure 2b at two different magnifications of 2k and 70k. For pure HSQ resist without a charge dissipation layer (Figure 2b, top) severe overexposure of the PhC pattern was observed. Despite properly defined holes on the edges of an array, the middle part of the PhC lattice exhibited signs of a strong proximity effect, which is indicated by a decrease in SEM observation contrast. When a conductive polymer layer was used sharply defined holes were obtained within highly uniform photonic crystal lattices, as additionally indicated by high contrast SEM micrographs (Figure 2b, bottom).

After sample processing, the spin-coated conducting polymer may be easily removed due to its solubility in water, which makes it a perfect solution for the processing of amphoteric oxide samples, such as ZnO. GaN processing also benefits from the use of a polymer dissipation layer due to the extended exposure range and the avoidance of dense pattern overexposure in HSQ. The use of PEDOT:PSS coating, therefore, makes e-beam processing of ZnO and GaN sample much simpler, quicker, and less expensive.

Glasgow University cloister arches

This benefit is, of course, not limited to just these two semiconductors but may be extended to the processing of other semiconductors and dielectric materials. Although not described here, our work shows that FIB-based processing can also similarly benefit from the application of conducting polymers.

● *The authors would like to thank the technical staff of the James Watt Nanofabrication Centre and the Kelvin Nanocharacterisation Centre at the University of Glasgow, United Kingdom. They would also like to thank Szymon Lis (Wroclaw University of Technology, Poland) for ellipsometer measurements.*

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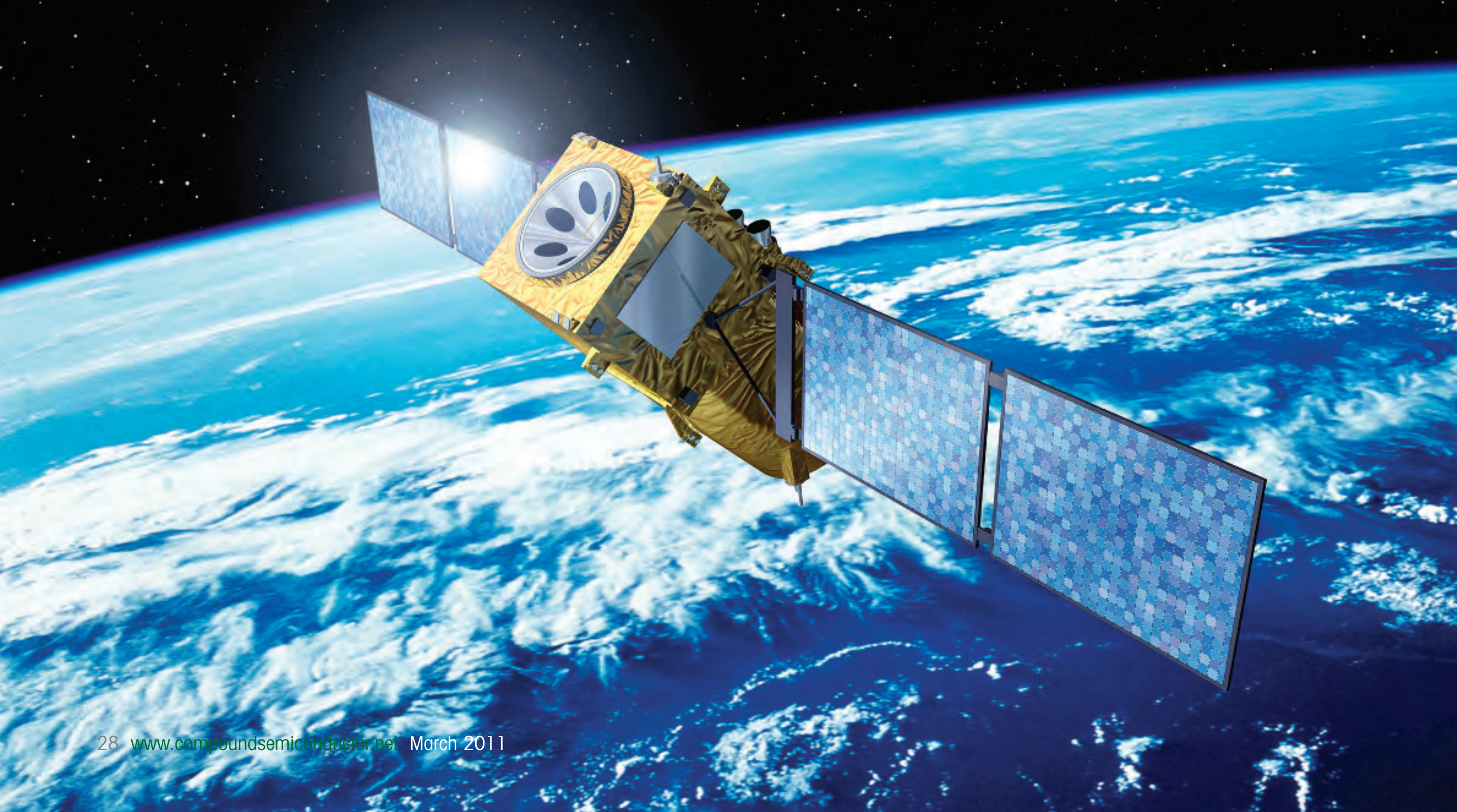
Electroluminescence exposes individual performances in multi-junction cells

Conventional multi-junction cell measurements only yield the characteristics of the entire device. In stark contrast, a novel electroluminescence approach can probe far deeper, extracting the current-voltage curves for individual sub-cells that hold the key to optimising the overall conversion efficiency, say the technique's pioneers, **Raymond Hoheisel, Sebastian Rönsch, Frank Dimroth and Andreas Bett from the Fraunhofer Institute for Solar Energy Systems and Helmut Nesswetter and Claus Zimmermann from EADS Astrium.**



Conversion efficiency is the key characteristic for solar cells. Increase this and photovoltaic installations become more attractive because fewer cells are needed to generate a given power. This makes the installation more affordable and also reduces the amount of space required for the photovoltaic system.

The most efficient solar cells utilize a very high proportion of the sun's radiation, which spans a spectral range extending from the ultraviolet to mid-infrared. To capture this radiation and convert it to electrical power effectively photovoltaics employ a collection of sub-cells designed to operate in different spectral ranges. In these devices several p-n junctions made of semiconductors with different bandgap energies are stacked on top of each other.

One way to optimise the overall efficiency of these multi-junction devices is to first characterise each sub-cell, and then optimise its contribution to the overall performance. Extracting this information is far from easy, but our partnership between the Fraunhofer Institute for Solar Energy Systems and EADS Astrium has pioneered a technique that can do just this, based on electroluminescence (EL) measurements. Today, no other technique can yield the information that is garnered by this approach.

We have used this EL technique to investigate multi-junction solar cells made of the semiconductors GaInP, GaInAs and germanium, which together can yield record efficiencies of more than 42 percent under concentrated sunlight. Our technique is not restricted to this class of device and can also be applied to multi-junction cells based on organic materials, silicon and chalcopyrites.

The monolithically stacked, triple-junction photovoltaic cells that we are studying power satellites and generate electricity on earth, where they are deployed in systems that use mirrors or lenses to focus light by a factor of several hundred. For both these applications, characterizing individual sub-cells not only aids device development – it also enables qualification testing during processing (see Figure 1)

Lateral and vertical characterization

Our EL technique involves forward biasing of the solar cell so that it operates as a light-emitting device. Each sub-cell has a different bandgap, so emits a different range of wavelengths (see Figure 2).

Left: The ADM-Aeolus mission satellite orbiting the Earth. On board of this spacecraft, III-V GaInP/GaInAs/germanium multi-junction solar cells power both communication systems and diverse scientific experiments Credit: ESA

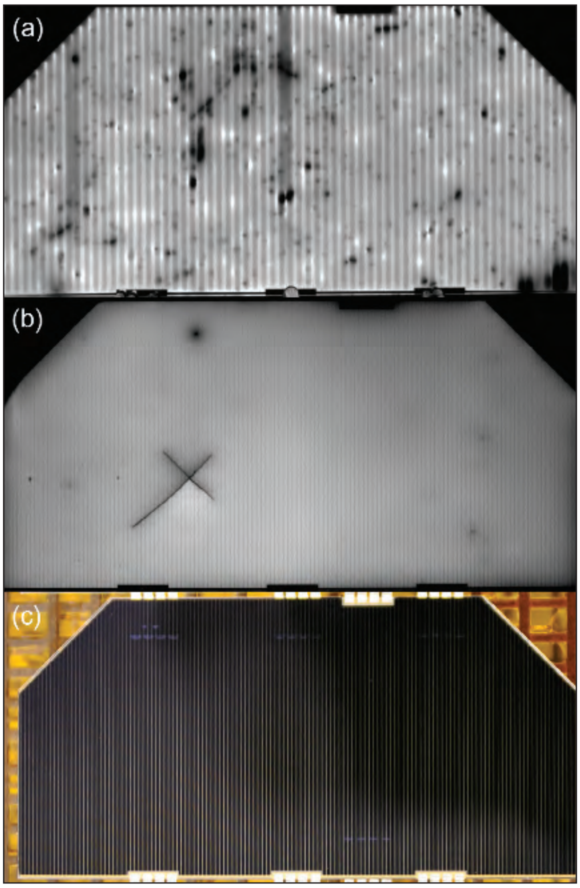


Figure 1: (a) GaInP top cell EL image of an 8 x4 cm^2 triple junction space solar cell showing lateral inhomogeneities and (b) GaInAs middle cell EL image of a mechanically damaged cell. None of this information is accessible by (c) a standard optical inspection

EL-emission can be detected in different ways. By recording the EL intensity distribution with a CCD sensor it is possible to expose lateral inhomogenities, a particularly important consideration in large space solar cells. Inserting output filters before the detector can select single sub-cell performance, allowing crystal defects that act as shunting paths to be detected, even if they only affect one particular sub-cell. It is also possible to use this approach to provide qualitative quality control, because this technique can expose material issues, such as cracks (see Figure 1b). In comparison, standard optical inspection reveals none of the lateral and vertical information accessible via EL-characterization (see Figure 1c). Even more detailed characterization of the cells can be realized by recording the EL-images of all of the sub-cells at a range of injection current densities.

Extracting cell I-V curves

The EL technique that we are pioneering also yields additional, incredible valuable information – the current-voltage curves of individual sub-cells, information that can drive improvements in multi-junction device performance and enable the introduction of dedicated in-line inspection procedures.

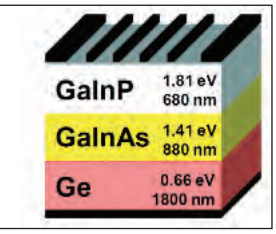


Figure 2: Schematic of a GaInP/GaInAs/germanium lattice matched triple-junction solar cell. The bandgap energies and emitting wavelengths of each subcell are indicated

Current-voltage curves for individual sub-cells cannot be accessed with a sun-simulator because the cells are monolithically connected in series and metal contacts are only on the front and back sides of the device (see Figure 2). The sun-simulator is limited to characterising the current-voltage curve of the triple-junction, and can also extract values for the short-circuit current, the open-circuit voltage, the fill factor and the efficiency of the entire device.

The foundations of our EL technique are theoretical developments detailed in two landmark papers. Uwe Rau from Forschungszentrum Jülich wrote one of these; the lead author for the other was Rau's colleague Thomas Kirchartz. Co-authors on this paper were Rau; Anke Helbig and Jürgen H. Werner from the Institute for Physical Electronics, Stuttgart; and Martin Hermle and Andreas Bett (an author of this feature) who both work at the Fraunhofer Institute for Solar Energy Systems (see *Further Reading* for paper references).

One cornerstone of this theoretical work is the so-called reciprocity relation. By measuring the spectrally resolved electroluminescence signal and the external quantum efficiency for each sub-cell, it is possible to access its dark current-voltage and illuminated current-voltage characteristics.

We have adopted this approach to study a $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As$/germanium lattice-matched triple-junction cell, extracting information that can be used to predict the power performance of this photovoltaic device under realistic operation conditions.

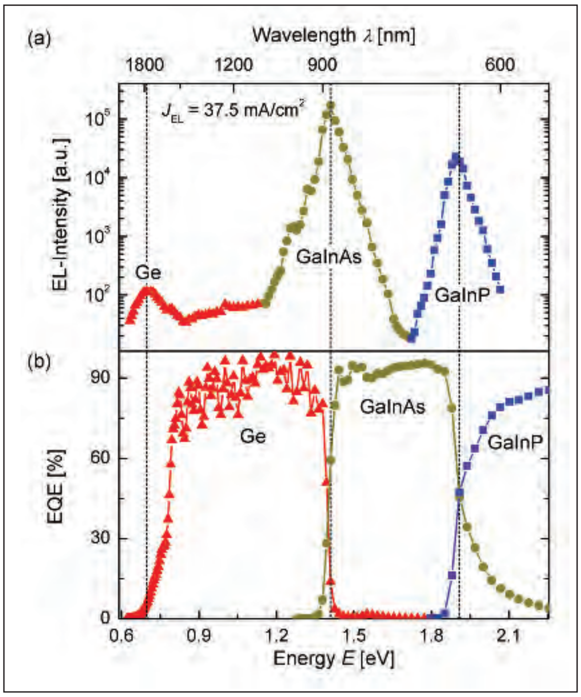
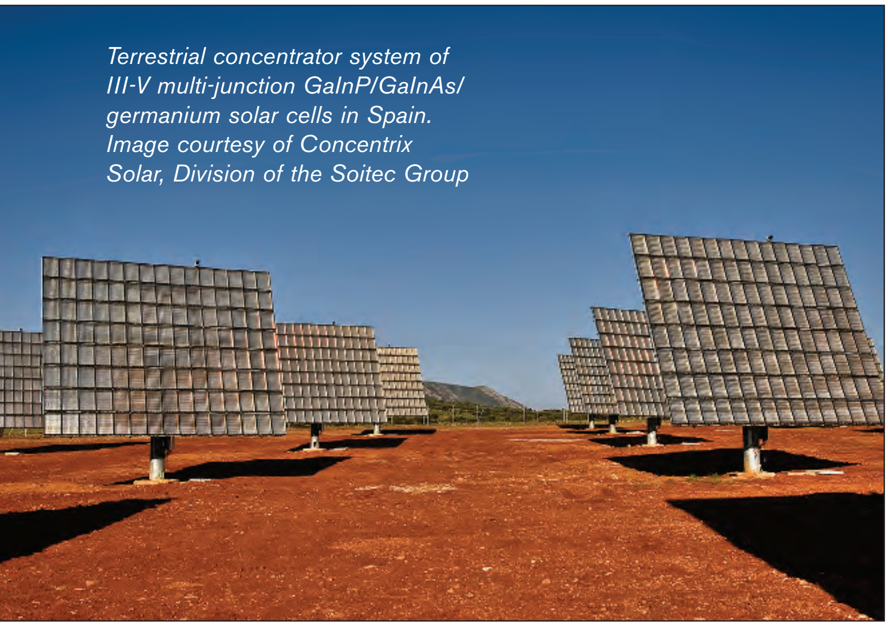


Figure 3: (a) Spectrally resolved EL spectrum at a constant injection current-density of 37.5 mA/cm² and (b) external quantum efficiency (EQE) of a 2x2 cm² lattice-matched $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As$/germanium triple-junction solar cell. Each EL peak is related to one of the sub-cells. The three EL peaks emerge at the same energy as the declining slope of the corresponding EQE because both are related to the band gap energy of the sub-cell



Terrestrial concentrator system of III-V multi-junction GaInP/GaInAs/germanium solar cells in Spain. Image courtesy of Concentrix Solar, Division of the Soitec Group

The spectral reciprocity relation connects the intensity of the EL signal with the energy of an emitted photon, the internal voltage of the sub-cell and the external quantum efficiency of the sub-cell. This efficiency depends on the black body photon flux, which is described by Planck's formula.

The first step is to measure the EL at a range of injection current densities when no light is incident on the cells. Once this is complete, the external quantum efficiency for each of the sub-cells is measured (see Figure 3). By applying the spectral reciprocity relation, the voltage of each sub-cell can then be calculated as a function of the dark-current density – this provides the dark current-voltage characteristics for each sub-cell.

Once the 'dark' current-voltage characteristics of the respective sub-cells are known, the illuminated current-voltage characteristics of individual sub-cells and of the whole multi-junction device can be easily calculated for any desired spectral condition using superposition principles.

Our studies have shown that there is excellent agreement between the resulting current-voltage curves derived by EL-analysis and those yielded by a sun-simulator (see Figure 4). This figure illustrates the great strength of the EL-characterization technique: In addition to predicting the combined current-voltage characteristics of the multi-junction solar cell, it reveals, in detail, all sub-cell current-voltage characteristics, including fill-factors and absolute voltage properties.

In principle, it is possible to derive the current-voltage curves under any spectrum of interest with our approach. These curves are extracted by inserting values for the photocurrent density of each sub-cell, which can be found by integrating the measured quantum efficiency with the new spectral operation condition. Based on the resulting current-voltage curves it is possible to estimate the performance, efficiency and fill factor – both at the sub-cell and multi-junction level – under the desired spectral operation condition of interest (see Figure 5). Catering for resistance effects is easy, too.

Our development of the EL technique has shown that it has a great deal to offer to both developers and manufacturers of multi-junctions cells. It provides qualitative and semi-quantitative information on lateral and vertical inhomogeneities, making this approach an attractive technique for fast in-line inspection during the cell growth process and module assembly. In addition, our EL technique is unique in being able to yield detailed information concerning the current-voltage curves of individual sub-cells, which hold the key to precise device improvement. What's more, fill-factor behaviour and the efficiency under arbitrary illumination conditions can be determined by our novel approach, aiding long-term energy harvesting analysis.

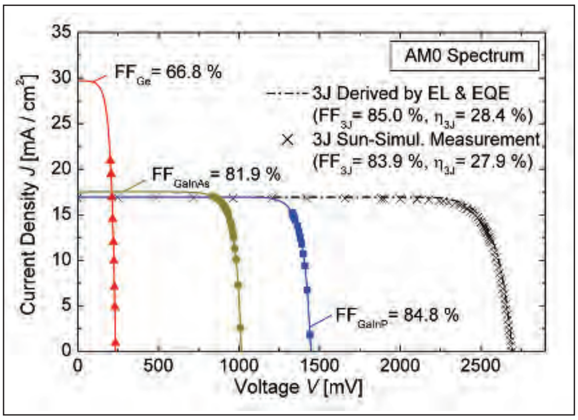


Figure 4: I-V characteristics with fill factor (FF) and efficiency (η) of the sub-cells and the triple-junction solar cell (3J) under AM0 illumination conditions. The plot includes also the directly measured I-V curve of the triple-junction solar cell (3J) by a sun simulator

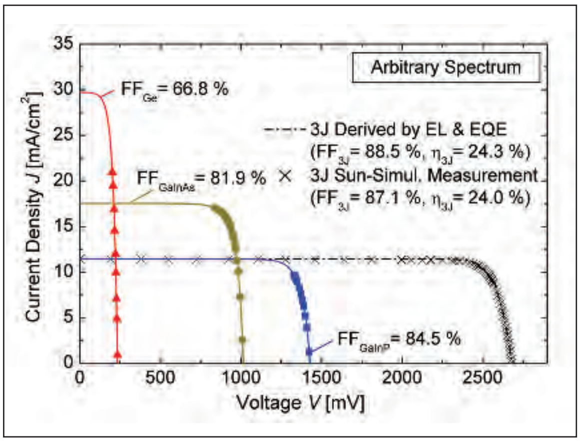


Figure 5: I-V characteristics with fill factor (FF) and efficiency (η) of the subcells and the triple-junction solar cell (3J) under illumination conditions with reduced illumination in the absorption range of the top cell. The plot includes also the directly measured I-V curve of the triple-junction cell (3J) by a sun simulator.

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Tuning the triple-junction

Extracting the very best performance from a triple junction photovoltaic demands optimisation of the absorption edge of every sub-cell. Incorporating quantum wells into the cells can realise this, while allowing the device to be tailored for the spectral conditions where it will be deployed, say **QuantaSol's Keith Barnham, Alison Dobbin, Matt Lumb and Tom Tibbits.**

Photovoltaic installations are going up and up. Despite the sharp downturn in the global economy, deployments continue to rise at an exponential rate in many countries, according to a recent report from the International Energy Agency's Photovoltaic Power Systems Programme. Germany continues to lead the way in photovoltaic deployment thanks in part to the success of its feed-in tariff program, and in 2009 it installed nearly 4 GW. Now its recipe for success is being adopted by several other countries, including the UK, through the introduction of their own market stimulation packages.

Maintaining this rapid growth in cell deployment hinges on further cost reductions, which is possible with the introduction of third generation cells. Those that are tipped to make the first major contribution are the triple-junction cells based on GaInP, GaAs and germanium. This type of device is already the cell of choice to power satellites, and when it is used on earth it can realise efficiencies in excess of 40 percent – roughly three times that of second-generation, thin-film cells made from materials such as cadmium telluride and copper indium gallium selenide.

The key to realizing low costs compared to second-generation cells is to use the triple-junction devices in concentrator systems that employ cheap plastic mirrors and lenses to focus sunlight by factors of around 500 onto the expensive III-V cells.

High concentration systems are automated to track the sun and keep the sunlight focused on the small, high efficiency cells. The first systems have been deployed in locations with large amounts of direct solar insolation Image courtesy of Daido Steel

Like any new technology, the initial cost of these concentrating photovoltaic (CPV) systems is high. This partly accounts for their initial deployment in the very sunniest climes, where it is most cost-effective. Here engineers are honing the technology that is used to track the path of the sun across the sky and ensure that the sunlight is optimally focused on the cells. As time goes on, increased sales of this technology will drive down costs at both the system and cell level. This will increase the appeal of this technology, which can generate up to three times the electricity from the same system area as one based on second-generation cells.

Quantasol's quantum wells

Quantasol, a spin-out from Imperial College London that is based in Kingston upon Thames and was founded in 2007, is well placed to supply high-efficiency cells to the growing number of CPV module and system manufacturers. One of our key strengths is our exclusive, patent-protected, quantum-well (QW) technology that boosts the efficiency of triple-junction cells by around 3 percent in absolute terms (see Figure 1). This means that we can regularly realise 40 percent median efficiency across our production wafers, making the performance of our cells comparable to those made by the market leaders.

What's more, our novel cells promise to set a new benchmark for efficiency that cannot be matched with conventional triple-junction cells, a factor that has helped us run a successful sampling campaign with customers through the US, Europe and Asia. This has swelled our order book, which stands in excess of 1MW of solar cells for delivery through the first half of 2011.

We have been pioneering the commercial development of III-V cells with QWs for several years, beginning with the incorporation of these layers into single and dual junction cells. Incorporating wells into the cell increases device efficiency, because it enables the cell to absorb light at longer wavelengths. However, it is only possible to benefit from this if the introduction of multiple quantum wells (MQWs) does not degrade the material quality of the entire cell. We meet this criterion by strain-balancing our

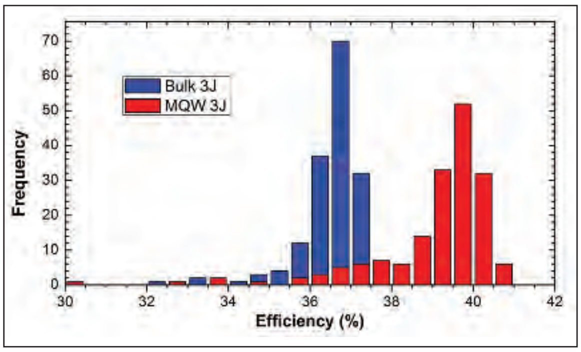

Figure 1. The blue histogram shows efficiency measurements at 200x concentration of 171 cells of standard triple junction design from one of eight wafers grown on a multi-wafer production reactor. The red histogram shows measurements of cells on a similar wafer with 50 quantum wells grown in the middle cell. The median efficiency has increased by 3 percent absolute. Measurements were made at 200x concentration on a WACOM solar simulator (1000 Wm^{-2} at 1 sun)

structure. In these QW cells of high material quality, the only loss mechanism for current carriers generated by the incoming sunlight is radiative recombination back to photons, a process that cannot be prevented from happening. But we do not waste these photons. Instead, we confine a significant proportion of them within the device – so that they can be re-absorbed and generate electricity – by incorporating a reflector into the structure that is similar to the type used in vertical-cavity lasers. This modification to the conventional device architecture justifies our claim to be the greenest of the solar cell companies – we even recycle waste photons!

Recently, we have been developing triple-junction cells with QWs in the middle junction. This structure gives us a major advantage over competitors, because our engineers can optimise the absorption edge of the middle cell during growth. Thanks to this, the absorption in the middle cell can be tuned to match the spectrum of sunlight at different times of day or year, and consequently optimise the cell for a given concentrator, at a given geographic location, for maximum electrical energy harvest over the year.

Optimising short wavelength performance

CPV systems rarely operate at their full potential at shorter wavelengths due to relatively high optical attenuation in this spectral range. Mornings and evenings, atmospheric pollution and turbidity, and the concentrator optics themselves all serve to reduce the energy available for the top two cells in triple-junction devices. However, by adding quantum wells and redesigning the top cell absorption appropriately, it is possible to increase the spectral envelope from which the top two cells harvest energy by about 5 percent, according to calculations that we presented at the 5th World Conference on Photovoltaic Energy Conversion in Valencia last September. These calculations employed a variety of atmospheric data sources, which were used to generate the solar spectra for each hour of the year in locations deemed favourable for the first CPV installations. The solar spectra were used to model the annual energy harvest of a traditional triple-junction device and another featuring MQWs. Efficiency gains stemming from the introduction of the QWs varied from 3.5 percent to more than 5 percent, with the greatest benefit coming in areas where the spectrum contains more red-light than the ASTM reference spectrum, such as Solar Village in Saudi Arabia (see Figure 2).

Even higher gains are possible by modifying the band-edge of the middle cell and the transparencies of the top two sub-cells so that they are all tuned to the incident spectra. This results in roughly another 1 percent increase in energy harvest.

Deciding on the best design for a particular location requires a full-year analysis of the ratio of short circuit currents for the top and middle cells. The photocurrents from these cells must be closely matched to achieve the highest energy harvest efficiencies (see Figure 3). Interestingly, the highest daily energy output coincides with the peak in incident energy (blue and black lines in Figure 3). So, to extract as much electrical energy as possible from our cells, we are tailoring device design to maximize the energy harvest efficiency at the same time of the day and year as the peak in irradiance. This principle is also being applied to boost revenue generation by tuning cells to perform at their best during utility peak delivery times.

Doubling up on quantum wells

Looking to the future, we have started to investigate the advantages of MQWs in the top and the middle cells of a triple-junction device. One motivation behind this effort, which has been pursued in partnership with the Imperial College London QPV group that first developed the QW cell, is to optimise the absorption profiles of the cells. In a

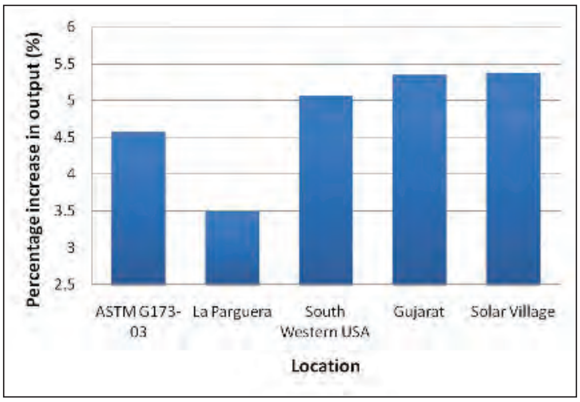

Figure 2. The simulated increase in power output of a MQW triple-junction device over a bulk triple-junction device under the ASTM G173-03 reference spectrum, and the increase in energy harvest calculated using hourly spectra specific to La Parguera in Puerto Rico, South West US, Gujarat in India and Solar Village in Saudi Arabia

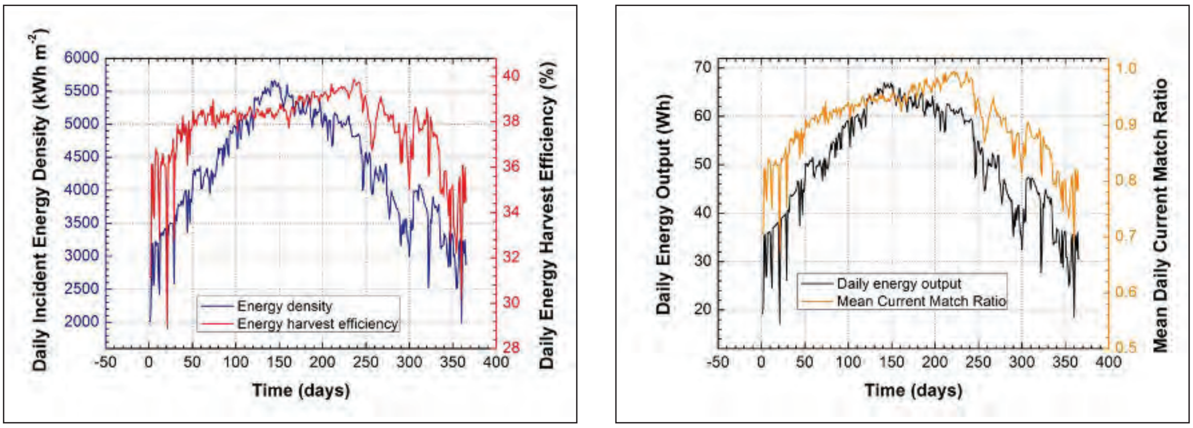

Figure 3 a) Daily incident energy density (blue), energy harvest efficiency (red), b) device energy output (black) and mean current match ratio (orange) for a simulated device under an hourly varying spectrum specific to the South West US

conventional triple-junction device, the absorption edges of both the top and middle cell are at shorter wavelengths than ideal.

Our modeling indicates that efficiencies well in excess of 40 percent are possible with MQW-based cells that shift the absorption edge to longer wavelengths (see Figure 4). These calculations – which are based on a concentration factor of 500 and have been plotted for the specific choice of the solar spectrum used in the standard test condition – show how optimising the absorption edge of our top and middle cells can yield overall efficiencies up to 45 percent. To illustrate what is feasible for a dual MQW device, a rectangular area bounded by a green dotted line is included in this plot and it can be seen that absorption edges reaching the 45 percent efficiency contour are possible.

As the solar spectrum changes by day and during the year, it shifts these contours that map out the conversion efficiency. The large rectangular area shows that the quantum wells add tremendous flexibility in the choice of absorption edges for both cells, indicating that it should be possible to optimise the design for maximum energy harvest over a very wide range of spectral conditions.

The primary rival to our dual-MQW triple-junction cell is the metamorphic triple-junction cell grown on a relaxed buffer layer, which is often referred to as a virtual substrate. With this design, the absorption edges of the top and middle cells can be extended to longer wavelengths. However, these adjustments cannot be made independently – the tuning of absorption that is possible with the metamorphic design is shown by the black arrow in Figure 4. This arrow can, in principle, be extended to higher efficiency contours. However, such a move pays the penalty of greater relaxation in the buffer, leading to more residual dislocations and ultimately an increase in efficiency loss. One assumption in these calculations is that the main loss mechanism in the top MQW cell is radiative recombination, which is known to dominate the loss in the middle cell. An intriguing possibility arises if this also happens in the top cell. In that case, the majority of the photons created by radiative recombination in the top cell will be emitted from the bottom of the quantum well, and most of these will then be re-absorbed in the middle cell, boosting its current output.

To understand how this affects the overall performance of our triple junction device, we have repeated the calculations for this scenario. Results are plotted in Figure 4, using blue contours and blue numbers. These results indicate

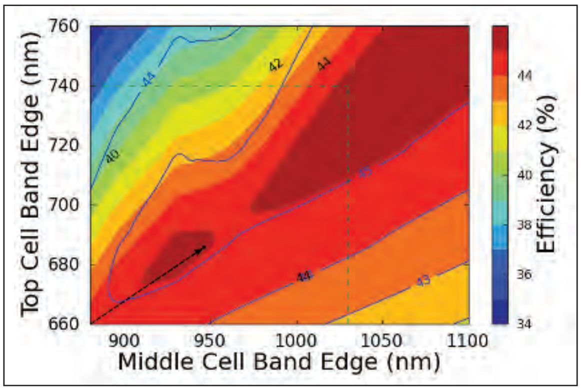

Figure 4. The colored areas separated by black numbers show how the efficiency of a dual-MQW triple junction cell at 500x concentration varies with the absorption edge of the top cell and the middle cell. The green broken-line rectangle represents the variation in absorption edge possible for the dual-MQW cell. The black broken-line arrow represents the absorption edge variation possible for the competitor metamorphic cell. In all cases the recombination loss in the top and middle cell is assumed to be radiative. The blue contour lines (blue numbers) show the efficiency when radiative recombination photons from the top cell are absorbed in the middle cell. These contours are wider than when radiative coupling is ignored

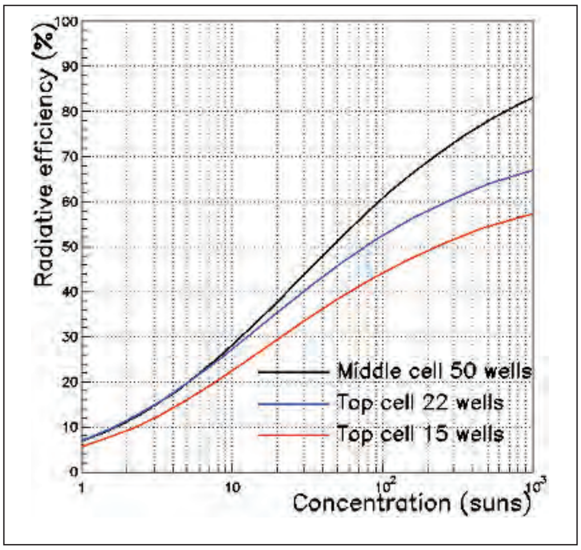

Figure 5. The radiative efficiencies of two MQW top cells grown on a research reactor compared with a typical MQW middle cell. Efficiencies have been extracted from measurements of the cell dark-current.

that radiative recombination of photons from the top cell that are subsequently absorbed by the middle cell has a major benefit - a widening of the sweet spot for very efficient operation. This means that the efficiency of a triple-junction device with QWs in two of the cells will vary less with changes in spectral conditions than one incorporating wells into just one cell.

Realising such high efficiencies in real devices requires the top cell to be radiatively efficient. Initial results, which we presented in Valencia, are promising. The radiative efficiency, which was extracted from measurements of the dark-current of MQW top cells grown on a research reactor at the EPSRC National Centre at the University of Sheffield, increases with concentration (see Figure 5). The initial values for radiative efficiency for the top cells are not as high as for the more mature middle cell, but it does increase with the number of quantum wells. If around 50 of these are incorporated into the top well, the efficiencies predicted in Figure 4 should be realised.

Focusing sunlight by a factor of 500 or so onto a cell causes it to heat up. Cooling can reduce this rise in temperature, which is beneficial for conventional triple-junction cells, because as they get hotter, the cell efficiency falls. In our novel cells this is far less of an issue, because they can be designed with deep wells in the top and middle cells, a modification that allows efficiencies of more than 40 percent to be achieved at operating temperatures of 90 °C.

This cell heating can be put to good use, allowing this device to feature in integrated, combined heat-and-power applications that further reduce electrical generation costs. High temperature operation of the cells mean that the cooling water can be used in the building, because a temperature of 90 °C is high enough to run an absorption chiller providing air conditioning.

Meanwhile, the cells can generate electricity. With three times the efficiency of a second generation cell, they can be used on buildings in less than ideal locations, such as vertical walls in northern latitudes, and still generate more electricity per square meter over a year than second-generation cells.

Our MQW cells are also ideal for use in smart, power generating windows. The blinds, which are transparent Fresnel lenses tracking the sun, focus the direct sunlight on a luminescent light bar while allowing the indirect sunlight into the room for internal illumination, thus reducing electricity demand. The QW cells are mounted in the window frame. The cooling water can be used for internal purposes including running air-conditioning, the demand for which is highest when the sun is shining.

Many other applications will open up for small-sized, high-concentration units offering more than double the electrical efficiency of first- and second-generation photovoltaics. If first-generation cells, which supplied the household's electricity, were replaced by such a system covering the same roof area, the extra electricity produced could power the family electric car for the year, even in rainy England! In addition, this system could supply the household's hot water requirements.

At Quantasol, we are well placed to capture a significant proportion of the ever-increasing orders for third-generation cells, and we are destined to become a major player in this market. The versatility of our cells enables them to maximise electrical energy harvesting in varying spectral conditions as well as to cope with the challenges provided by the ingenuity of concentrator manufacturers.

Power generating window formed from transparent blinds feature Fresnel lenses that focus direct sunlight onto luminescent light bars which further concentrate the sunlight on cells in the frame. Diffuse light illuminates the room. (Courtesy Solarstructure Ltd.)

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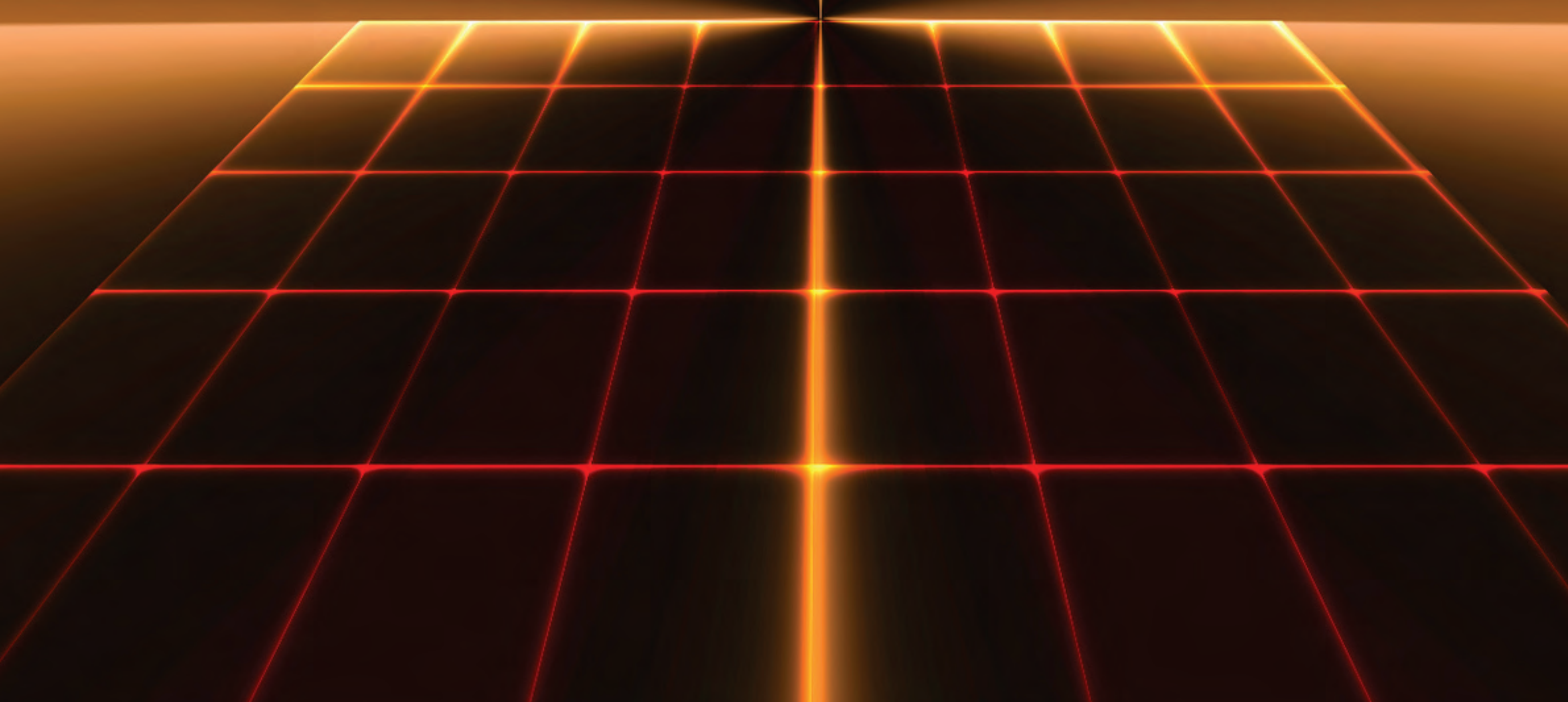
Getting to grips with nitride laser failures

Nitride lasers, which are a key component in Blu-ray players and recorders, still suffer from limited reliability. The origin of this failure is controversial, but there is strong evidence to suggest that point defects are to blame, argues **Matteo Meneghini, Nicola Trivellin, Gaudenzio Meneghesso and Enrico Zanoni from University of Padova, Italy.**



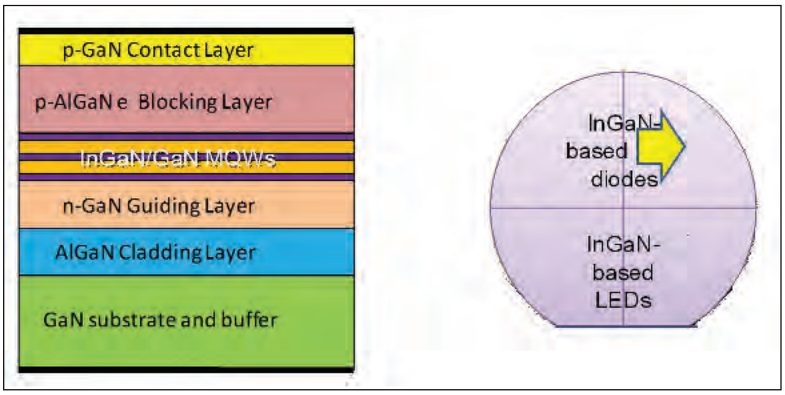


Fig. 1: The structure of the lasers analysed within this work, and of the split-wafer experiment that was carried out to study laser degradation

Shipments of nitride lasers are going up and up. These devices are already being used for optical storage systems, such as Blu-ray players, and as time goes on they will also start to be deployed in laser projection systems based on red, green and blue lasers, plus a variety of biomedical systems.

Today, Blu-ray players and recorders represent by far the biggest market for the InGaN-based laser. In this application 405 nm sources are focused to a spot size of 580 nm and used to extract data from discs storing up to 25 GB per layer. Reading the data from the discs requires just 5-10 mW, but writing demands far higher powers. 100-300 mW sources are not uncommon, and even higher powers are needed to realise really fast writing speeds, because then the laser has even less time to transfer energy to the media.

Reaching high optical power levels requires operating at current densities of up to 10 kA/cm^2 and electrical input powers in excess of 1W. The effective penetration of these devices into commercial applications is governed by their reliability; while some studies have demonstrated lifetimes of several thousand hours, device reliability during operation at high output power levels is still a critical issue. Many research groups around the world are trying to understand the cause of laser failure and putting forward conflicting views regarding its primary cause.

The first generation of laser diodes, which were made in the 1990s, had very short lifetimes. In many cases high dislocation densities were to blame, which led to catastrophic failure. To address this and other problems related to dislocation densities, improved growth techniques such as Epitaxial Lateral Over Growth (ELOG) were introduced to improve crystal quality. Dislocation densities then fell to 10^6 cm^{-2} or less.

Despite these important improvements, InGaN-based laser diodes still suffer from a gradual decrease in device performance during operation. This weakness, which is known as parametric degradation, is something of a hot topic within the nitride laser community and is being avidly discussed at conferences and in the academic literature.

Is it this, that or something else?

One view is that InGaN-based laser failure stems from degradation at the facets, which leads to increasing mirror losses, higher threshold currents and reduced slope efficiency. Others argue that over time there is an increase in point defect density in the active layer, which increases the non-radiative recombination rate and ultimately the threshold current density, while there is also a school of thought that as the laser is driven, current confinement under the ridge worsens, inducing an increase in the threshold current and a shift in emission wavelength. Meanwhile, some are saying that operating the laser for many hours leads to the formation of dislocations in the active region, and subsequently the generation of dark regions, as recently demonstrated for MBE-grown samples.

The lack of consensus over the cause of parametric degradation is partly because the physical mechanisms responsible for the degradation of InGaN-based laser diodes have not been univocally identified. This is generating important discussion in the GaN-laser community.

Our group at the University of Padova, Italy, in close co-operation with Panasonic Corporation, has been able to demonstrate that the increase in non-radiative recombination – due to the generation of point defects – plays a major role in determining the degradation of InGaN-based lasers. We have also shown that long-term degradation of lasers is not strongly related to the degradation of the facets, nor to the worsening of the confinement or injection efficiency. Our results strongly support the hypothesis that a necessary step towards the development of highly reliable laser diodes is the optimisation of the active layer, including its radiative efficiency, over the full lifetime of the device.

We arrived at these conclusions after extensively comparing the electro-optical degradation of laser diodes and LED-like samples – devices with the same epitaxial

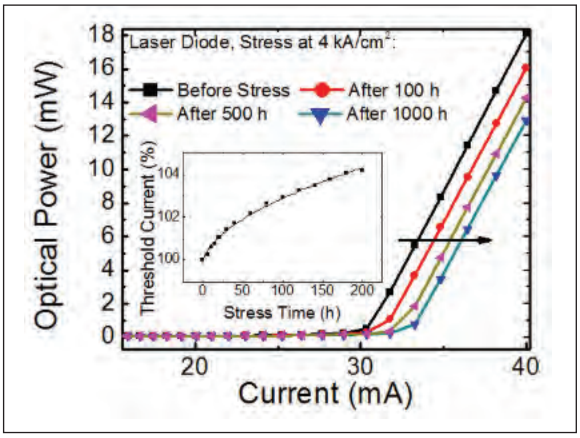


Fig. 2: Degradation of the optical characteristics of one of the analysed lasers. Inset: threshold current increase measured during stress time on one of the analysed samples. Threshold current increases according to the square-root of stress time, indicating that a diffusion process is involved in degradation

structure as the lasers, but devoid of ridges and facets. Results indicate that the same degradation mechanism, namely the decrease in internal efficiency, is present both in laser diodes and LED-like samples. In other words, devices with strong geometrical constraints, mirrors and cavities degrade in the same way as simple structures with no ridges or facets.

Analysis was carried out on triple-quantum-well devices grown on a GaN substrate and emitting at 405 nm (Blu-Ray technology). A split-wafer experiment was designed as follows (see Figure 1): half of the wafer was processed in order to obtain laser diodes with 600 µm-long cavities; the other half was used to yield LEDs with an area of 75 x 200 μm^2. Devices were submitted to constant current stress, with current densities in the range 2-4 kA/cm^2, and a case temperature equal to 75 °C.

The most noticeable consequence of this stress is the increase in laser diode threshold current (Figure 2). No significant variation in slope efficiency was detected after stress, demonstrating that carrier injection efficiency is unaffected by ageing. Furthermore, during ageing, threshold current increases with the square-root of stress time. This result has been described by several research groups, and indicates that a diffusion process is involved in degradation.

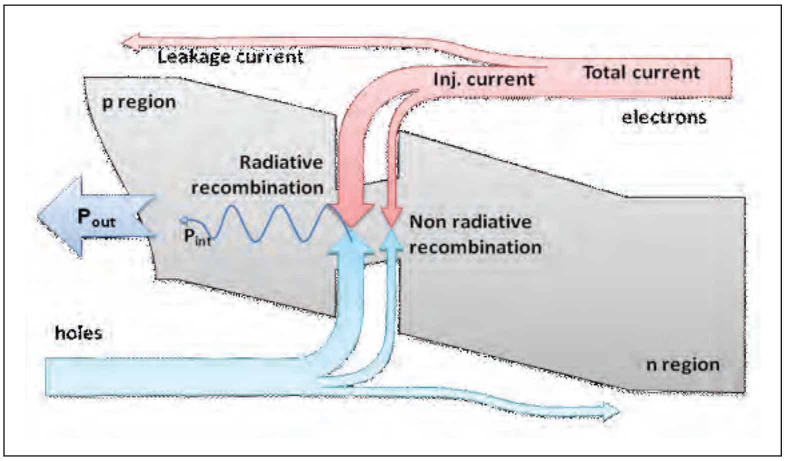


Fig. 3: Recombination dynamics in laser diodes

Many groups have tried to identify the impurity or defect involved in this diffusion process: both an experimental effort based on Secondary Ion Mass Spectroscopy (SIMS) and a theoretical approach based on the analysis of the degradation kinetics were recently adopted. SIMS investigation by Piotr Perlin and colleagues from Unipress, Poland, which was reported at the EMRS Fall meeting in 2010, indicated that degradation is not correlated to the instability of magnesium and hydrogen, two species that were previously indicated to be involved in the degradation process.

Meanwhile, the theoretical approach taken by Kenji Orita and co-workers from Panasonic demonstrated that under nominal operating conditions the diffusion coefficient of the impurity involved in the degradation process is around 1.9 x 10^{19} cm^2/s. This is very high compared to the diffusion coefficient of the most common impurities in GaN.

Getting to the point

We also found that our LED-like samples exhibited a significant degradation during constant current stress: Degradation was found to be more prominent at low measuring current levels, indicating that stress induces an increase in non-radiative recombination. Furthermore, laser diodes and LED-like samples submitted to constant current stress showed similar degradation kinetics, strongly suggesting that the two different kinds of devices degrade due to the same physical process, which is the generation of point defects.

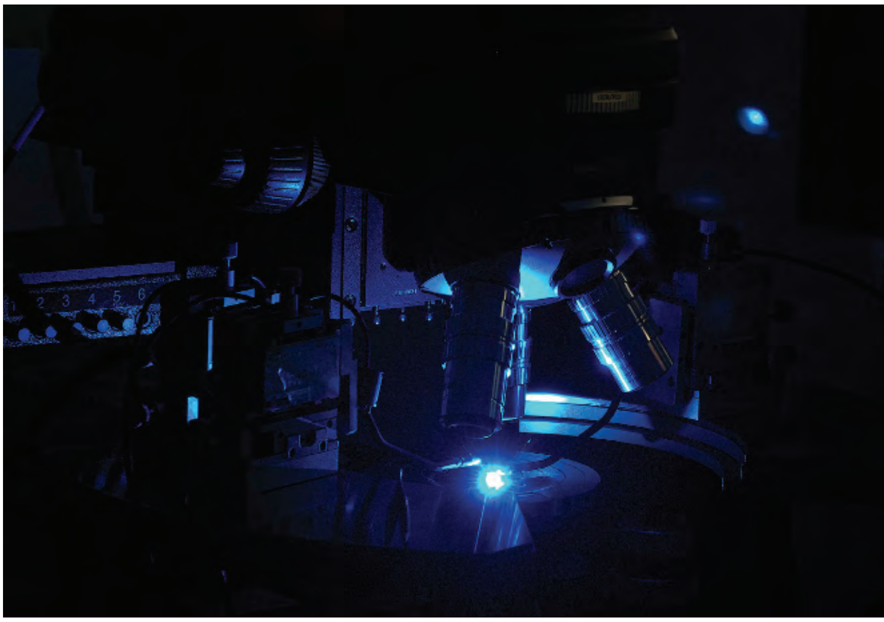
It is possible to gain further insight into the degradation process by performing extensive characterisation of the electrical characteristics of the devices during stress time. We have found that stress induces a significant increase in defect-related current components, such as generation, recombination and reverse currents. This suggests that the defectiveness of the active layer is increasing during stress time. Interestingly, defect-related current was found to increase according to the square-root of stress time, exactly as we have found for the optical power degradation.

Our set of results allows us to draw several important conclusions regarding the origin of degradation. First, it is

Another point worth noting is that the optical degradation of LED-like samples is more prominent at low measuring currents, indicating an increase in non-radiative recombination components under these conditions within the active layer. Since degradation occurs both in laser diodes and in LED-like samples, we can argue that the laser's ageing is not due to the high optical field present in the cavity

clear that the slope efficiency of the lasers is unaffected by stress, which indicates that long-term degradation of the device is not related to a decrease in injection efficiency (the proportion of electrons that are injected into the quantum wells). We can also say that a diffusion process can be responsible for the measured optical degradation, because degradation kinetics follow the square root of stress time.

Another point worth noting is that the optical degradation of LED-like samples is more prominent at low measuring currents, indicating an increase in non-radiative recombination components under these conditions within the active layer. Since degradation occurs both in laser diodes and in LED-like samples, we can argue that the laser's ageing is not due to the high optical field present in the cavity. And finally, we note that optical degradation is strongly correlated to the increase in defect-related current components: Stress, therefore, is considered to induce the generation/propagation of defects within the active layer of the samples.



Is current confinement to blame?

Recently, Jens Müller and co-workers from Osram suggested that the optical degradation of lasers could be related to the worsening of current confinement under the ridge, which could lead to an increase in threshold current.

However, our study demonstrates that degradation occurs in both laser diodes and in LED-like samples. This strongly supports the hypothesis that degradation is not correlated to the geometry of the devices, nor to a degradation of the mirrors.

Despite the important results presented recently in the literature, the challenge is still open: Several issues must be solved to identify the origin of the degradation of InGaN-based laser diodes. First of all, although we know that degradation is related to a diffusion process, the impurity or defect involved in diffusion has not been univocally identified. In addition, although we indicate that non-radiative recombination plays a major role in the degradation process, the defect or deep-level responsible for recombination is still to be exposed. How to identify this villain remains a big question. Finally, most of the studies on laser reliability have been carried out on Blu-Ray devices, which have a relatively good lattice quality. What about longer-wavelength samples? Will green lasers show similar degradation characteristics? The road to the optimisation of InGaN-laser diodes is still long.

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Burning beats scrubbing in LED fabs

Mike Czerniak, product marketing manager for exhaust gas management at Edwards makes the case for combustion based abatement as a cheaper, more environmentally friendly alternative to wet scrubbing.

The volume of compound semiconductor processing has risen rapidly over the last decade, driven primarily by increasing demand for LEDs. These high-brightness light emiters that are made by a GaN MOCVD process are now widely used for backlighting flat screen televisions and computer monitors, and they are likely to see increasing adoption as an alternative to incandescent and fluorescent lighting. The benefits LEDs offer include longer operating life, a more natural light spectrum and reduced power consumption.

As with solar manufacturing, compound semiconductor manufacturing must address two key concerns to successfully supplant more conventional, established technologies. The first is to lower the price of manufacturing to make LEDs cost-competitive with the alternatives. The second is to ensure that the LED manufacturing process has a minimal environmental impact and complies with the increasingly stringent global regulations concerning air emissions and waste water. While the extraction, safe handling and disposal of the gases used in the MOCVD process used to manufacture LEDs significantly adds to manufacturing cost of ownership, the choice of abatement technology can significantly reduce manufacturing costs in terms of energy use, water consumption and treatment. This article will compare the costs and efficiency of traditional water scrubbing abatement technology with combustion technology.

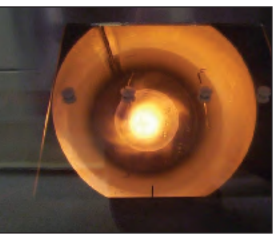


Figure 1: 160 slm NH_3 + 320 slm H_2 being combusted under low-NO_x conditions

The GaN abatement challenge

The two most common gas by-products of the GaN MOCVD manufacturing process are ammonia (NH_3) and hydrogen. Both of these gases are highly flammable, while ammonia is, in addition, toxic and has an objectionable odour. The emission of ammonia is strongly regulated globally, both to water and atmosphere. In the past, hydrogen emissions were not tightly regulated, since this gas was not seen as a pollutant. This is changing in many regions, mostly because of the increasing fire risk this poses. In addition, care must be taken in abating emissions from GaN MOCVD processes, to ensure that nitrogen oxide and nitrogen dioxide (i.e. NO_x), both regulated global warming gases, are not created.

Wet scrubbing – the traditional approach

While wet scrubbing is probably still the abatement technology most commonly used with MOCVD processing, it is becoming less popular because of the hidden costs associated with it. In wet scrubbing, emission gases are typically bubbled through a tub of water. Unfortunately, this does not remove hydrogen, the most common MOCVD gas by-product, which has typically been vented into the atmosphere. While hydrogen is not considered a global warming gas, it is highly flammable, and there is always a slight, but potential danger that static electricity could ignite the hydrogen during the abatement process, causing an explosion and fire. In Asia, a formerly popular solution was to place an electrically-heated thermal oxidizer in series with a wet scrubber to incinerate the residual hydrogen. This hot-wet scrubber approach has become less acceptable in Korea, for example, due to new water emission regulations and the increased cost and system footprint.

While water scrubbing can eliminate ammonia, the second most common gas by-product, there is a danger in those regions with hard water that ammonia will react with the salts that are present, producing solids that can build up in the abatement system, thereby requiring increased maintenance and raising system cost of ownership. Since hard water occurs anywhere that mountain run-off is a major source of water, this is an issue in most parts of the globe. It is not a problem, incidentally, that is solved by using hot-wet scrubber technology.

In addition, dissolving ammonia in water can result in the presence of nitrogen that can promote biological activity such as algae blooms, which deteriorate water supplies by reducing the oxygen content. As a result, the allowed discharge limits in many regions have been reduced. While there are a number of ways of treating this problem, each has its own drawback. By adjusting the acidity and temperature in a high flow of air, ammonia can be removed from the solution and turned back into a gas. It can then be treated in a number of different ways. It can be diluted with non-polluting gases and discharged into the atmosphere. While this is cheap, it typically fails to meet new regional emission standards and pollutes the environment. One can use a catalytic converter, which breaks the ammonia down into nitrogen and hydrogen. While this approach works, it does result in a safety issue due to the pyrophoric nature of the hydrogen, and it is expensive in volume production environments. Finally, one can expose the waste water to an acid like ammonium sulfate, which does have the benefit of producing a by-product that has value as a fertilizer, but this approach typically fails to meet the new nitrogen-in-water emissions regulations. Each of these approaches, however, increases the cost of abatement, and, in addition, may not meet emission requirements in all regions.

Efficient cost

Combustion-based abatement technology addresses the abatement challenges involved in GaN MOCVD manufacturing by burning the ammonia and hydrogen in a controlled way. This approach eliminates the hydrogen safety issue and the maintenance problems caused by ammonium solids at a significantly lower operating cost than that of wet scrub technology. Both ammonia and hydrogen are flammable, so a combustion-based abatement system, such as Edwards' Spectra G, uses the gases to be abated to fuel the reaction. Figure 1 shows these gases being burned in a combustion-based abatement system. The only outside energy source employed by a combustion-based abatement system operates a small pilot light similar to the one used in home heating systems, with the exhaust gases themselves providing the bulk of the fuel for combustion. As a result, combustion-based systems use considerably less energy than wet scrub systems, which helps lower operating costs and results in a smaller carbon footprint. In addition, heat generated during gas combustion can be recovered and used for facility water heating, which can save up to $20,000 a year in facility utility costs.

Spectra G combustion systems are cooled using the air flow generated by the house extraction system. This design feature ensures that combustion by-products are efficiently transported from the system to the factory central scrubber or dust filter. This air-cooled design eliminates many of the fixed and operating costs associated with wet scrub technology, including the cost of water, the capital and operating costs associated with the pumps required to pump the water, the energy required to run the pumps and the costs of water treatment. As a result, combustion-based abatement technology is extremely well-suited for regions with tight water-use regulations.

Figure 2: A combustion-based abatement system, such as Edwards' Spectra G, uses the gases to be abated to fuel the reaction

Compared to wet scrub systems, with their pumps and water treatment subsystems, combustion-based abatement systems are much simpler in design and have far fewer moving parts. As a result, maintenance requirements – as well as maintenance times and spares inventory – are significantly reduced.This produces a much lower operating cost per process tool per year. While the capital costs of wet scrub and combustion-based abatement systems are roughly equivalent, the operating cost per tool per year for a combustion-based system is approximately one-tenth that of a wet scrub system. In addition, combustion-based systems have a smaller footprint, thereby saving valuable fab real estate. A combustion-based abatement system may occupy as little as 1.8 x 1.2 x 0.75 m^3, compared to a wet scrub system that may occupy 2-3 times this space.

When burning ammonia in a combustion-based system, there is always a danger of creating NO_x emissions, which are strictly regulated in most regions. Careful management of the combustion process, to prevent oxidation of the gases being burned, can avoid the formation of these polluting emissions. If not, a NO_x removal plant is required, which adds considerably to both equipment size and annual operating costs. In a non-oxidizing combustion system, however, destruction and

Edwards' Spectra G systems are designed to provide reliable, high performance, low cost abatement of hazardous exhaust gases from MOCVD processes that use large flows of hydrogen and ammonia

removal efficiencies of greater than 99.5 percent can be achieved with resultant NO_x levels below threshold limit volumes.

Edwards' Spectra G systems (see Figure 2) are designed to provide reliable, high performance, low-cost abatement of hazardous exhaust gases from MOCVD processes that use large flows of hydrogen and ammonia. They offer up to six process inlets and a very large gas handling capacity. Typical gas loading for a system is 300 liters of hydrogen and 200 liters of ammonia per minute, which equates roughly to the exhaust output of two to three process tools.

In addition to the benefits of combustion-based exhaust systems in terms of safety, lower CoO and reduced environmental concerns, combustion-based abatement technology has a well-established track record for reliability. Hundreds of these systems are deployed at a variety of companies in the flat panel and solar cell industries. The efficiency of its gas treatment process has been field-tested and meets the most stringent air emission regulations in Europe, the US and Asia. It is currently experiencing a high rate of adoption by leading LED manufacturers world wide. Edwards offers an additional technology for treating the significant ammonia flows present in the exhausts of nitride-based MOCVD processes by decomposing this gas into its constituent elements, nitrogen and hydrogen, using a heated dry cartridge technology. This technology, which comes in a modular system known as GaNcat, eliminates the possibility of contamination of the cartridge by the metalorganic gases that are also present, such as TMG, TMI and TMA. This is achieved without the need for external traps by including a special pre-cleaning stage in the first portion of the cartridge that results in the formation of stable inorganic solids. Each module treats up to 20 slm of ammonia and multiple modules can be combines together, making it suitable for R&D applications. This kind of low-cost abatement approach eliminates concern about NO_x generation and uses neither water nor fuel, making it an ideal approach for regions with water usage restrictions. Nitrogen can be safely vented to the atmosphere, while hydrogen must be treated in another fashion in regions restricting its release to the environment. It is clear that LED technology must overcome two major challenges to successfully supplant conventional established mass lighting technologies – lower the cost per lumen, and ensure that the GaN MOCVD processes used to produce them are not seen as major pollution sources. These manufacturing processes use large flows of hydrogen and ammonia which must be abated for both environmental and safety reasons, since they are both flammable and ammonia is toxic. In addition, it is critical that the formation of NO_x be avoided during the abatement process.

Table 1. A comparison of the benefits of different abatement technologies

Feature	Wet scrubbers	Hot-wet	Catalyst	Burn-dry
Capital cost/ MOCVD exhaust	Low	More expensive than wet	High	Good
Running cost	High	High	Extremely Low	Very low
Issues	Cost of water, treatment, maintenance & safety issues (H_2)	As wet scrubbers	Doesn't treat H_2	
Features	Well known technology	Treats H_2	No water, fuel or NOx, used at Aixtron	No water, low NOx, heat recovery, high capacity

While wet scrubbing has traditionally been the abatement technology of choice for MOCVD processes, it is more costly than combustion-based abatement technology in terms of energy consumption, water usage, and it does not treat hydrogen. In regions where hydrogen is regulated and cannot simply be vented to the atmosphere, an electrically heated thermal oxidizer must be used in series with a wet scrubber to address this issue, further increasing the cost of this technology. In addition, there is the danger of the build-up of ammonium solids in the abatement system, which requires increased maintenance, further increasing abatement costs. A further concern involves free nitrogen in the waste water, which can lead to algae blooms, thereby lowering water quality.

Combustion-based abatement systems offer a lower cost and more efficient solution. Since they use no water and use the emission gases themselves as a fuel source, operating costs are much lower than wet scrub systems in terms of operating costs. Combustion-based systems are also simpler in design, requiring less maintenance and occupying less fab real estate, which further contributes to a low cost of ownership. In addition, non-oxidizing combustion-based technology, such as that employed in Edwards' Spectra G system, eliminates the danger of the formation of NO_x, which is tightly regulated in most regions of the world.

Nitride cells start delivering high efficiencies

Reduced internal electric fields, rougher surfaces and the introduction of superlattices are helping to drive up the efficiencies of nitride solar cells

COMPARED to lasers, transistors and LEDs, solar cells based on nitrides tend to deliver poor performances. But these materials can yield efficient photovoltaics, according to research by both a pair of Japanese Universities and by a team led by the University of California, Santa Barbara (UCSB).

Engineers at Meijo University and Nagoya University have shown that InGaN/GaN superlattice structures can realize an external quantum efficiency (EQE) of more than 40 percent over the 380-425 nm range. And researchers at UCSB and the Ecole Polytechnique, France, have reported a peak EQE of 72 percent at 380 nm. Both cells have the potential to be incorporated into a traditional multi-junction device to harvest the high-energy region of the solar spectrum.

"However, the ultimate approach is that of a single nitride-based cell, due to the coverage of the entire solar spectrum by the direct bandgap of InGaN," says UCSB's Elison Matioli.

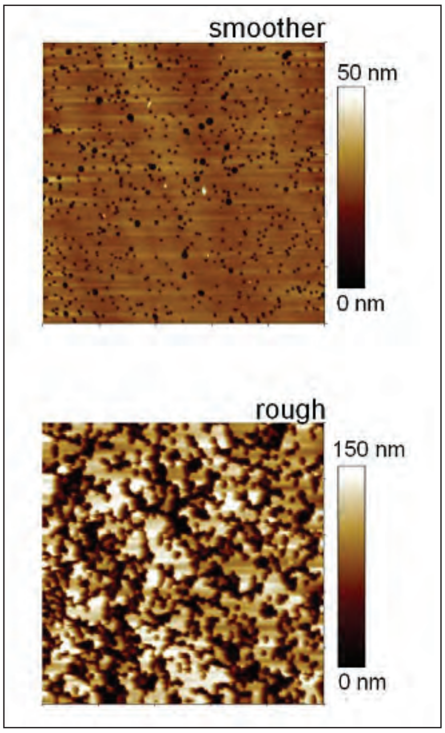


Figure 1: Lowering the temperature of the p-type GaN capping layer from 955 °C to 880 °C increases its roughness, leading to a higher proportion of radiation being trapped by the cell. Credit: UCSB

He explains that the main challenge to realizing such devices is the growth of high-quality InGaN layers with high indium content. "Should this problem be solved, a single nitride solar cell makes perfect sense."

Matioli and his co-workers have built devices with highly doped n-type and p-type GaN regions that help to screen polarization-related charges at hetero-interfaces that limit conversion efficiency. Another novel feature of their cells are a roughened surface that couples more radiation into the device. Photovoltaics were produced by depositing GaN/InGaN p-i-n structures on sapphire by MOCVD. These devices featured a 60 nm-thick active layer made of InGaN and a p-type GaN cap with a surface roughness that could be adjusted by altering the growth temperature of this layer (see Figure 1).

The researchers measured the absorption and EQE of the cells at 350-450 nm (see Figure 2 for an example). This pair of measurements revealed that radiation below 365 nm, which is absorbed by GaN, does not contribute to current generation – instead, the carriers recombine in p-type GaN.

Between 370 nm and 410 nm the absorption curve closely follows the plot of EQE, indicating that nearly all the absorbed photons in this spectral range are converted into electrons and holes. These carriers are efficiently separated and contribute to power generation. Above 410 nm, absorption by InGaN is very weak. Matioli and his colleagues have tried to optimise the roughness of their cells so that they absorb more light. However, even with their best efforts, at least one-fifth of the incoming light is either reflected off the top surface or passes directly through the cell. Two options for addressing these shortcomings are to introduce anti-reflecting and highly reflecting coatings in the top and bottom surfaces, or to trap the incoming radiation with photonic crystal structures.

"I have been working with photonic crystals for the past years," says Matioli, "and I am investigating the use of photonic crystals to nitride solar cells."

Meanwhile, Japanese researchers have been fabricating devices with higher indium

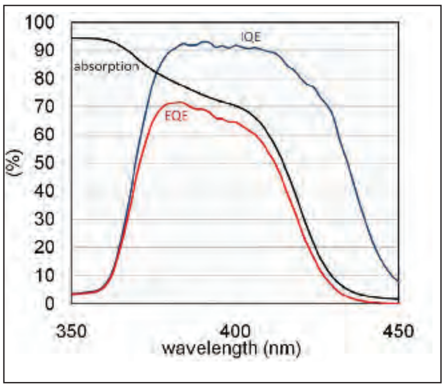


Figure 2: Absorption and EQE data highlights the device's high internal efficiency in the 380-420 nm range . Credit: UCSB

content layers by turning to superlattice architectures. Initially, the engineers fabricated two type of device: a 50 pair superlattice with alternating 3 nm-thick layers of $Ga_{0.83}In_{0.17}N$ and GaN, sandwiched between a 2.5 μm-thick n-doped buffer layer on a GaN substrate and a 100 nm p-type cap; and a 50 pair superlattice with alternating layers of 3 nm-thick $Ga_{0.83}In_{0.17}N$ and 0.6 nm-thick GaN, deposited on the same substrate and buffer as the first design and featuring an identical cap.

The second structure, which has thinner GaN layers in the superlattice, produced a peak EQE in excess of 46 percent, 15 times that of the other structure. However, in the more efficient structure the density of pits is far higher, which could account for the halving of the open-circuit voltage.

To realize high-quality material with high efficiency, the researchers turned to a third structure that combined 50 pairs of 3 nm-thick layers of $Ga_{0.83}In_{0.17}N$ and GaN with 10 pairs of 3 nm thick $Ga_{0.83}In_{0.17}N$ and 0.6 nm-thick GaN. Pit density plummeted to below 10^6 cm^{-2} and peak EQE hit 59 percent.

The team is aiming to now build structures with higher indium content. "We will also fabricate solar cells on other crystal planes and on a silicon substrate," says Kuwahara.

Y. Kuwahara et. al. (2011) App. Phys. Express ***4*** *021001*
E. Matioli et. al. (2011) Appl. Phys . Lett. ***98*** *021102*

Standard model fails to fully account for LED droop

Plotting LED efficiency against carrier density exposes fundamental limitations in the widely used 'ABC' model

A TEAM led by Fred Schubert's group at Rensselaer Polytechnic Institute have uncovered a fundamental flaw in the model used to describe carrier behaviour in an LED. This model – often referred to as the ABC model – has been widely used in discussions about the origin of droop, the decline in nitride LED efficiency at high current densities.

The ABC model states that carriers undergo one of three processes: Shockley-Reed-Hall recombination, a non-radiative process that is proportional to the carrier density; radiative recombination, which is proportional to the square of the carrier density; or Auger recombination, a non-radiative recombination process that depends on the cube of the carrier density and has been claimed by several groups to be the primary cause of droop.

One of the predictions made by the ABC model is that any plot of LED efficiency as a function of carrier density (plotted on a log scale) will be symmetric.

"Real data from us and others is not symmetric," says Schubert. "For this reason, we feel that the ABC model is insufficient for describing droop."

The team, which includes researchers at Sandia National Labs and Samsung LED, have measured the efficiency of two different multi-quantum well devices: a commercial LED emitting at 463 nm and a 444 nm emitter.

Direct measurements of carrier density are not possible, so the researchers recorded the light output power instead. The square-root of this is proportional to the carrier density. Plots of LED efficiency as a function of the square root of light output power show that the ABC model could not account for the behaviour of real LEDs. If a good fit is obtained for the efficiency curve at carrier densities below that of the peak LED efficiency, then the model fails to keep pace with the decline in efficiency at higher carrier densities.

The team has also studied how predictions of the ABC model vary when it accounts for phase-space filling – the filling of the conduction and valence bands in an unequal manner, due to the different masses of electrons and holes. Catering for this effect still leads to even symmetry in plots of internal quantum efficiency as a function of carrier density. Schubert says that these experiments show that at high current densities there is a significant loss process that depends on the fourth power of the carrier density.

" The fourth order term suggests an active process that goes beyond the three conventional processes [non-radiative recombination, radiative recombination and Auger recombination] and could be carrier leakage."

Q. Dai et al. (2011) Appl. Phys. Lett. ***98*** *033506*

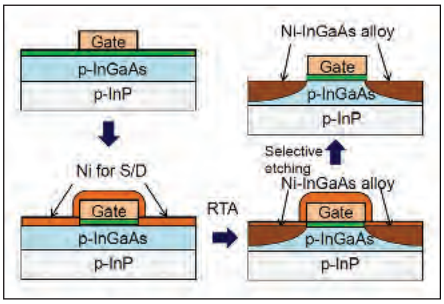
Metal-semiconductor alloy boosts MOSFET performance

Nickel-InGaAs alloy slashes source and drain resistance, paving the way to higher drive currents

JAPANESE engineers have turned to a metallic nickel-InGaAs alloy to cut the source and drain resistance of InGaAs channel MOSFETs, which are promising contenders to maintain the march of Moore's Law at the 11 nm mode.

Forming low resistance contacts with conventional methods is tough due to low dopant solubility, according to corresponding author SangHyeon Kim from the University of Tokyo. If source and drain resistances are too high, they saturate the on-resistance in deeply scaled MOSFETs with a gate length of 30 nm or less.

The team, which includes researchers from Sumitomo Chemical Company and Tsukuba's National Institute of Advanced Industrial Science and Technology, produced their transistors using a type of self-aligned salicide source/drain process, which is used to reduce contact resistance in silicon MOSFETs.



InGaAs MOSFETS are fabricated with a self-aligned metal source-drain structure

"Using salicide – an alloy between silicon and a metal like nickel-InGaAs – we can reduce the source-drain resistance due to a very low resistivity of salicide," explains Kim.

With this approach, it is possible to control the indium content of the contact during epitaxial growth and ultimately reduce the Schottky barrier height between the contacts and the channel. This promises to increase the drive current produced by the MOSFET.

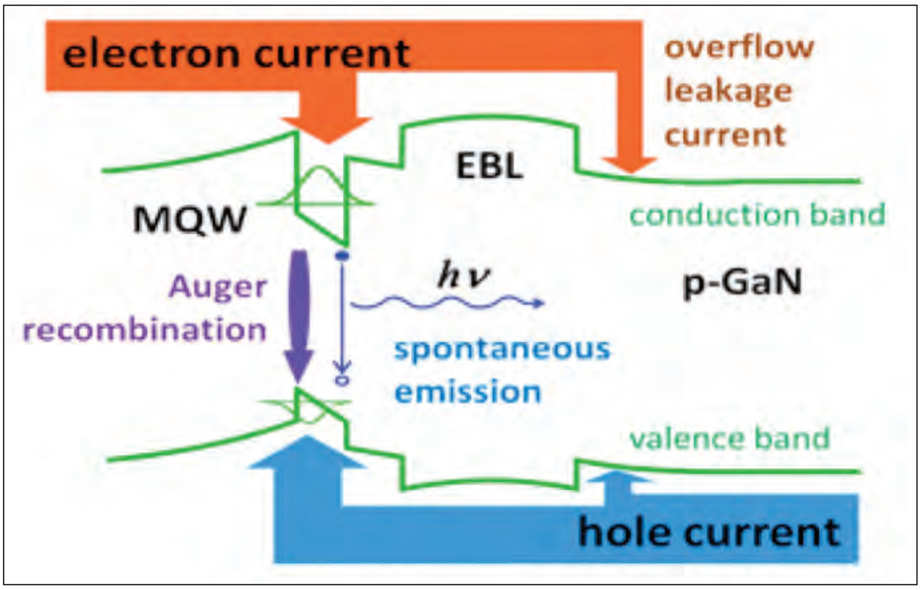
The researchers produced their novel contacts for their InP-based MOSFETs by directly reacting nickel and InGaAs during a rapid thermal annealing step at 250 °C. There is a high degree of uniformity in this alloy, according to transmission electron microscopy measurements.

Engineers have fabricated a portfolio of transistors with gate lengths of 5 μm, gate widths of 150 μm and a range of InGaAs compositions. On-off ratios are 10^4, peak mobilities hit 2000 $cm^2 V^{-1}s^{-1}$, and source and drain resistances are five times lower than that in p-n junctions.

"We are planning to optimise our devices and scale them," says Kim.

SH Kim et al. (2011) App. Phys. Express ***4*** *0242017*

Insight into GaN-based LED efficiency droop



Auger recombination and electron leakage within an LED energy band diagram

THE efficiency of most GaN-based LEDs decreases with higher injection current. Such a reduction in LED efficiency is commonly referred to as the LED efficiency droop. The droop phenomenon is universally observed across a broad wavelength spectrum of InGaN/GaN LEDs and also with ultraviolet AlGaN/AlN LEDs. This efficiency droop is currently subject of intense research worldwide, as it delays general lighting applications of nitride LEDs. Many proposals have been forwarded to explain the efficiency droop. One popular explanation is that the Auger recombination dominates the non-radiative loss at high injection current.

Auger recombination is easy to understand and model since its rate increases with the third power of the carrier density, while the light-emission rate scales with the square of the density. As the carrier density increases with higher current, the Auger process quickly overpowers the light emitting process, resulting in the efficiency droop.

Despite its simplicity and convenience, the Auger droop model is not generally accepted. GaN-based materials have wide bandgaps while the common Auger process is known to be strong only in semiconductors with a much narrower bandgap. The Auger droop model assumes an Auger coefficient four orders of magnitude larger than predicted by text-book theories of the GaN Auger process. Researchers from the NUSOD Institute LLC (Newark, DE, USA) and Crosslight Software Inc. (Burnaby, BC, Canada) recently undertook investigations that shed new light on the origin of the LED efficiency droop phenomenon [2]. Using the advanced simulation software APSYS, they studied another possible cause of the droop phenomenon: electron overflow into the p-doped layers of the LED.

Based on an earlier APSYS simulation study, electron leakage was first suggested in 2007 as possible origin of the efficiency droop[3]. The new study reveals how sensitive the electron overflow is to the properties of the AlGaN electron blocker layer (EBL) typically employed in nitride LEDs. Not only is the EBL band gap of major importance but also the EBL band offset. Assuming a reasonably small Auger coefficient, the new APSYS study shows that an EBL band offset ratio of about 50:50 would make the electron leakage current large enough to account for the efficiency droop. The often assumed AlGaN band offset ratio of 70:30 does not allow for significant overflow. As the exact offset is hard to measure or calculate, a ratio of about 50:50 seems quite reasonable.

The electron overflow is more difficult to calculate than the Auger recombination as the former is influenced by the interplay between the built-in polarization charges and the p-type doping in the neighborhood of the EBL. The polarization interface charge tends to reduce the electron barrier of the EBL while the ionized magnesium acceptors screen the interface charge, resulting in a strong influence of the EBL acceptor profile on the leakage current.

However, the EBL acceptor profile is often not well controlled during the epitaxial LED growth process, which may be the reason for some confusing droop observations reported in the literature [1]. The new APSYS simulation study also reveals a quite abnormal thermal behavior: the electron overflow decreases with higher temperature. This is a surprising prediction since most semiconductor devices ranging from transistors to laser diodes perform better at lower temperatures while higher temperature usually causes undesirable power losses. The reason behind this droop abnormality is that the hole transport improves at higher temperatures, leading to reduced electron overflow.

So, can this surprising temperature abnormality be observed experimentally? Yes indeed! In an independent experimental study, a team from Nagoya Institute of Technology (Japan) recently published electroluminescence measurements on 264 nm AlGaN LEDs [4]. The Nagoya team not only found direct evidence for the electron overflow, they also observed that the amount of leakage decreases with increasing temperature. These measurements serve as an impressive confirmation of the overflow model for the efficiency droop; however, other mechanisms may still be involved [1].

With sophisticated simulation software and increasing computational power, researchers are nowadays able to look beyond the symptoms of the droop and into the interplay of the different internal physical mechanisms, thereby moving towards the ultimate cure for the efficiency droop.

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Nanotechnology boosts thermoelectric performance

Researchers from Boston College and MIT have turned to nanotechnology to achieve a 60-90% increase in the thermoelectric figure of merit (ZT) of a p-type quinary compound semiconductor known as a half-Heusler. ZT is a term scientists use to measure a material's relative thermoelectric performance. The work by Xiao Yan and co-workers paves the way for a new generation of cleaner products as diverse as semiconductors, air conditioners, exhaust systems and solar power technology. The material improved by the team was a half-Heusler p-doped bulk semiconductor compound with the chemical formula $Zr_{0.5}Hf_{0.5}CoSb_{0.8}Sn_{0.2}$. This material isan attractive prospect to the thermoelectric community due to its thermal stability, good mechanical sturdiness, non-toxicity and inexpensiveness.

However, the application of half-Heuslers is limited due to their poor thermoelectric performance - peak ZT is around 0.5 at 700oC for bulk ingots. A good thermoelectric material should have a ZT above 1 across this temperature range. The scientists have increased the ZT value of the p-type half-Heusler to 0.8 at 700°C.

Moreover, according to Xiao Yan, their techniques are less time-consuming and cheaper than conventional methods.
The researchers formed alloyed ingots using arc melting, before creating nanopowders by ball milling the ingots. Application of hot pressing yielded dense bulk material. Transport property measurements and microstructural studies were performed on the nanostructured samples and bulk ingots. Results revealed that the ZT improves thanks mostly to the low thermal conductivity arising from enhanced phonon scattering at grain boundaries and defects in the material and partially to the high "Seebeck" coefficient. The Seebeck coefficient, or so-called thermopower, is a measure of the magnitude of an induced thermoelectric voltage with respect to the temperature difference across that material.

"In other words, the resistance to heat flow increases without a degradation or even with an enhancement in the material's electrical properties," explains Gang Chen of MIT. Contributions to this work were also made by S. J. Poon from University of Virginia and T. M. Tritt from Clemson University.

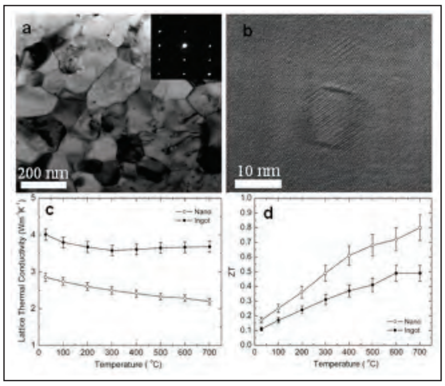


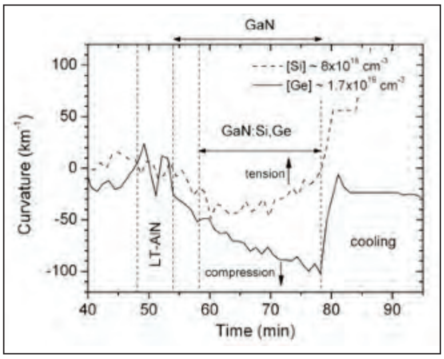
Figure 1. TEMimages of hot-pressed nanostructured samples under (a) low and (b) high magnification. The inset in (a) is the selected area electron diffraction pattern showing the single crystalline nature of the individual grains.Temperature-dependent (c) lattice part of thermal conductivity, and (d) ZT of ball-milled and hot-pressed sample in comparison with that of the ingot

This work was published in the paper "Enhanced Thermoelectric Figure of Merit of p-Type Half-Heuslers" by Xiao Yan,Giri Joshi,Weishu Liu,Yucheng Lan,Hui Wang,Sangyeop Lee,J. W. Simonson, S. J. Poon, T. M. Tritt, Gang Chen,and Z. F. Ren, in Nano Letters, DOI: 10.1021/nl104138t

Germanium takes the Strain out of GaN-on-silicon epi

If you want to grow n-doped GaN layers on silicon with minimal tensile strain, then consider using germanium, rather than silicon as the n-type dopant. That's the key finding of a study by researchers from the Otto-von-Guericke-University Magdeburg, Germany, that have compared the tensile strain of GaN layers doped with both of these group IV elements.

The researchers say that until now, good quality thick n-type doping of GaN-on-silicon has not been possible due to edge dislocation climb. This results in an increasing tensile strain during epitaxial growth. In fact, studies have shown that doping GaN-on-Si with silicon enhances edge-dislocation climb. The scientists compared samples grown by MOVPE using precursors for AlN and GaN growth processes. These were diluted silane (100ppm) and germane (10%) in H_2 for the silicon and germanium doping processes.



Germanium doping has already been tested by Nakamura in the early 1990s. However, with a lower doping efficiency and as a more costly option to silicon doping, germanium doping has not been established. The recent results obtained by the team headed by Alois Krost, on the other hand, show the absence of edge-dislocation climb in the case of germanium-doped GaN-on-silicon.

Krost points out that using germanium as a dopant opens up the possibilities of realizing a wide range of GaN-on-silicon devices, where thick highly n-conducting layers are required. The researchers also discovered that the formation of SiN at the edge dislocation core is the initiator of an enhanced dislocation climb, even for already tensely strained layers. This is in contrast to previous assumptions that the surface roughness of highly silicon-doped GaN-on-silicon leads to edge-dislocation climb.

Doping GaN-on-silicon with an alternative is and old idea that is just coming into its own. The researchers expect not only an impact for GaN-based LEDs grown on silicon substrates, but also in power electronics. For example in vertical Schottky diodes which could now be grown with a highly conducting n-type layer and a thick, undoped layer on top without any impact on strain development.