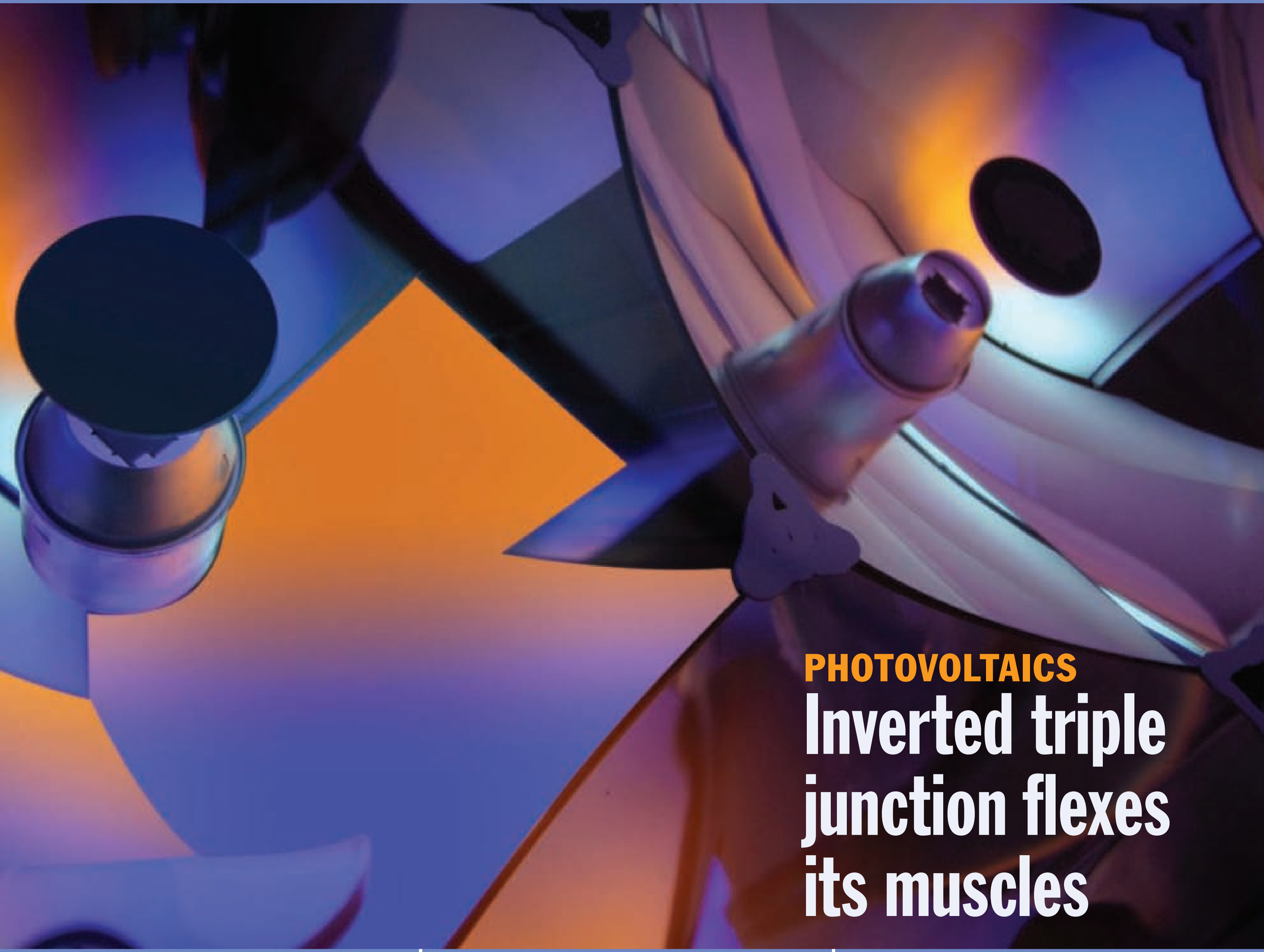
COMPOUND SEMICONDUCTOR

October 2007 Volume 13 Number 9

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY



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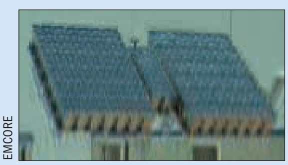

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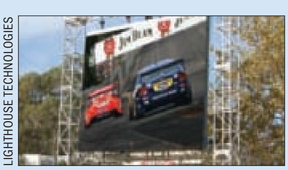

LIGHTHOUSE TECHNOLOGIES

Seeing red
Large outdoor LED-based screens offer a potential market for Quanlight's red-emitting devices. **p35**

Main cover image: *A close-up of a concentrator photovoltaic system designed and manufactured by the US company SolFocus. While concentrator systems are just entering commercial deployment for terrestrial energy production, key solar-cell innovator Emcore is already coming up with next-generation flexible cells that could lead to a much wider applications base. See p5 and 25 for more on III-V photovoltaics. Credit: SolFocus.*

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EDITORIAL

A brief history of the LED

A little over 100 years ago a British engineer unexpectedly discovered that SiC emitted light under electrical stimulation.

In that moment, Henry Joseph Round kicked off a remarkable century for the light-emitting diode. Principally a radio technologist, Round went on to become chief engineer at Marconi and help invent sonar technology for submarines.

Despite notable achievements in the world of radio, however, the ubiquity of the LED means that his oft-overlooked observation of February 1907 will turn out to be Round's most significant contribution.

That's because the LED is only just beginning to fulfil its promise as a low-energy lighting technology. But the signs are good. In January, Citizen Electronics in Japan is set to begin mass producing a white LED with a light output equivalent to a 40 W incandescent bulb for residential lighting, while Matsushita Electric Industrial is hot on Citizen's heels.

This suggests that LED technology is nearing the end of its development phase. Not a bit of it. Cree's researchers are breaking output and efficacy records weekly and breakthroughs in basic nitride materials technology are coming fast.

"The proponents of LED lighting must ensure that the technology lives up to its promise."

But here's a note of caution. The proponents of LED lighting must ensure that the technology lives up to its promise. Consumers tend to have long memories when innovations fail to meet expectations and so the results of the US Department of Energy's tests on LED lighting fixtures are worrying. Only two out of 12 fixtures the DOE recently looked at came close to their stated performance.

If he were around today, Henry Joseph Round would surely be amazed at the LED's widespread application. But if we are not careful to ensure that lighting systems match the quality of the LED chips inside them, 100 years from now we may all be equally amazed at its lack of success in general lighting applications.

Michael Hatcher *Editor*

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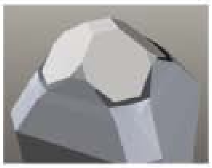
Tecdia's Scribing Tool Selection

TD-3YGP

For LED sapphire wafer use

TD-3P

For mostly InP wafer use



TD-4PB

For mostly silicon wafer use, toe-cut type

TD-420

Primarily for GaAs, glass wafer use, heel-cut type

TD-2P

Custom made, for all semiconductor wafer use

TD-8P

Custom made, for R&D use (both toe and heel cut type)

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SOLAR CELLS

Italy embraces concentrator culture

By Michael Hatcher in Milan, Italy

The next 12 months look like turning out to be critical for the nascent concentrator photovoltaics (CPV) industry, potentially sparking a substantial new market for compound semiconductor devices.

CPV systems based around tiny III-V chips figured heavily in the technical sessions at the 22nd European Photovoltaic Solar Energy Conference, held in Milan in early September. Although exponents of CPV were dwarfed by the existing silicon photovoltaics industry in the accompanying exhibition, that could change next year, as some key installations come online.

Key system suppliers Isofoton, SolFocus and Concentrix Solar expect a major ramp over the next 12 months. All three are involved in the Spanish government's Castilla La Mancha project, a 3 MW CPV installation scheduled to come online in 2008.

SOLFOCUS

The only way is up: concentrator photovoltaic systems, such as this SolFocus installation, face a make-or-break year that will be key to determining the future success of the emerging III-V application.

Thanks to its clear blue Mediterranean skies, Spain has long been acknowledged as a key location for CPV and now Italy looks set to follow its lead. Attending the Milan exhibition, Alfonso Pecoraro Scanio, Italy's minister for the environment, land and sea, outlined an initiative to install a photovoltaic capacity of 3 GW by 2016, including 500 MW produced by concentrating systems that may feature compound semiconductor cells.

Scanio said, "This will make Italy one of the leading countries both in solar energy production and technological innovation."

Although CPV does not necessarily require III-V cells, Emcore's David Danzilio said that he regarded Italy as an important growing market for the technology.

Emcore, itself developing a line of 25 kW CPV panels, is expanding production of cells for 500-sun CPV. The US company has also signed a major supply deal with the Australian firm Green and Gold Energy. Worth an expected $24 million to Emcore over the next year, the agreement will see 35% efficiency III-V cells deployed in a number of CPV generators in Australia and beyond.

With some skepticism remaining over the ability of III-V CPV systems to match the robustness and reliability of existing solar technologies in the field, the success of the Castilla La Mancha installation and other early deployments will be critical.

Nancy Hartsoch from SolFocus told *Compound Semiconductor*, "Reliability and lifetime tests are crucial. We've spent more money testing III-V cells than Spectrolab".

SolFocus is planning a controlled ramp of systems from its Indian manufacturing center in the first three quarters of 2008, before moving to high-volume production. "Cell companies will need to ramp up pretty quickly in 2008," Hartsoch predicted.

While she is confident that CPV will prove to be a robust, economic source of electricity, Hartsoch is urging the young industry to coordinate its efforts in a "global CPV consortium" and is also pushing the US Department of Energy to set up a demonstration project to mirror Spain's Castilla La Mancha.

CONVERGENCE

Silicon players ponder compound integration

The future use of III-V materials in logic applications traditionally addressed by silicon CMOS looks increasingly likely, thanks to positive noises from key player Intel, as well as a number of new, well-funded research projects.

In September, Intel's director of components research Mike Mayberry blogged about the likely role of compound semiconductors on the company's website, while Paolo Gargini, Intel's director of technology strategy, said at a Semiconductor Industry Association media briefing that III-Vs would be a "transistor option" in the year 2015.

Meanwhile, the US Defense Advanced Research Projects Agency (DARPA) – arguably the single biggest force behind the development of the GaAs industry in the US – has now put considerable financial backing behind three projects focused on integrating InP functionality within a CMOS processing platform. Collectively, the three projects are being coordinated by DARPA program manager Mark Rosker under the COSMOS acronym.

In addition, the National Science Foundation (NSF) has funded a collaboration between strained-silicon pioneer Amberwave Systems and the Rochester Institute of Technology that is aiming to provide a GaAs-on-silicon materials platform that gets around the lattice mismatch problem.

Tony Lochtefeld from Amberwave believes that the NSF project highlights the natural evolution of the semiconductor industry: "Improving CMOS performance through the addition of new materials is becoming more and more important," he said. "Adding III-Vs to silicon to exploit their unique functionality is a natural extension of this trend."

See "Behind the Headlines" on p15 of this issue for more details about the three projects that form DARPA's COSMOS program.

EPIWAFERS

$50 m deal marks IQE's returning profit

Independent epiwafer supplier IQE has shrugged off the weak US dollar and a slow start to the year by posting a sharp increase in sales revenue for the first six months of 2007. At £23.7 million ($47.1 million), sales were up 62% on the first half of 2006, reflecting the company's significant expansion over the past year.

Although the Cardiff, UK, headquartered company technically made a net loss in the six months to June 30, 2007, it broke even at the operational level and registered a profit of £1.3 million before interest, taxes and asset depreciation were factored in.

"This is a key milestone in our continuing progress and clearly demonstrates the strength of the business model," said CEO Drew Nelson. With fast-growing GaAs chip maker Anadigics signing up to a supply deal that will be worth at least $50 million to IQE over the next two years, the wafer supplier is now in an excellent position to register a net profit over the coming months and bolster its cash position.

Wireless components used in high-end applications, such as advanced handsets, high-speed wireless LAN connectivity and satellite communications, now account for around 70% of IQE's sales. With Anadigics increasing its GaAs capacity significantly, including building a new wafer fab in China, that proportion could grow.

However, IQE is also working to diversify its future business, with a number of research projects indicating the likely key future markets for epiwafer vendors.

As well as a UK project to develop very-high-brightness GaN LEDs, IQE is involved with silicon device manufacturers on advanced materials for future memory and logic applications, such as strontium tin oxide, and says that it is "aggressively pursuing the development of compound semiconductor terrestrial solar cell technology".

IQE has also decided to relocate and expand its Singapore facility, which was acquired in the December 2006 deal to buy MBE Technology. What's more, the government in Singapore has offered the IQE operation there a major incentive in the form of tax-free status over the next 10 years.

SOLID-STATE LIGHTING

Tests show credibility gap in LED lighting

The output and efficacy of commercial solid-state lighting fixtures is close to claimed performance in only two out of 12 cases, suggest the latest tests performed by the US Department of Energy (DOE).

The DOE's second round of product testing found that all other products overstated efficacy by 25–35% and light output by 30–95%, according to its August report.

"While a few manufacturers are publishing credible values for luminaire output and efficacy, many are still making wild and misleading claims," the report said.

Possible reasons for the discrepancies put forth by the DOE include fixture makers publishing LED performance values instead of luminaire values without saying so, performing luminaire testing using different methods, or even inflating values to exaggerate performance.

However, despite the general failure of solid-state lights to live up to their billing, some shone much more brightly than the rest, according to the report. "The DOE's testing has revealed both excellent and dismal performances," it said.

In DOE tests between March and May 2007, downlight luminaires and directional replacement lamps produced light output comparable to incandescent and CFL downlights, with much higher efficacy.

By contrast, non-directional replacement lamps in particular did not produce enough light to replace any existing products.

Off-state power consumption, known as vampire loading, also concerned the DOE. Testing was only performed on devices with on-off switches, which constituted two LED-based desk-lamps, one consuming 1 W and the other consuming 2.5 W in the off state. A comparable halogen lamp consumed only 0.16 W while switched off.

The desk lamp that consumed 2.5 W while off is claimed to use 70% less energy than a comparable incandescent unit and produce more light than a halogen bulb.

When tested against a halogen bulb, it used 65% less energy in the on state, but provided less than half the light output, making it dimmer and, because of vampire loading, less energy efficient overall.

"Poorly performing products are seen when SSL technology is introduced without sufficient attention toward treating it as an integrated system," the report said.

"Designers need to consider thermal management, drivers, optics, the LED sources and their directionality as an integrated system, and performance measurements need to assess the integrated system."

● Leading Japanese lighting company Citizen Electronics has begun sampling a new LED-based fixture, and expects to move into volume production in January 2008. The high-power (540 lm) lamps are said to provide a high-efficiency alternative to 40 W incadescent lamps. Citizen also offers a low-current option compatible with solar battery systems, which produces a luminous efficiency of 110 lm/W. The standard product operates at 700 mA and 74 lm/W.

Matsushita Electric Industrial, also in Japan, is to release LED lamps this month.

CHIP DESIGN

Anadigics integrates front end

As Apple brings Wi-Fi to the iPod, Anadigics has raised the stakes for GaAs device integration, with a series of single-chip front ends for Wi-Fi and Bluetooth that it says is unmatched by other power amplifier (PA) and RFIC suppliers.

Developments in BiFET processing at the company's Warren, New Jersey, site have squeezed a low-noise amplifier (LNA), RF and DC switches onto the PHEMT part of the GaAs die.

"This capability allows us to do something that no-one else can do to this level of performance," said Dave Cresci, director of WLAN product marketing at Anadigics. "To put this level of functionality into such a small single die ends up blowing a lot of people away."

Anadigics is already in full production with its first series of Wi-Fi/Bluetooth BiFETs, the AWL6254, in volumes of millions of chips per month. Its second series, just beginning its production ramp, offers the same functionality, but raises the output power level from 16 to 18–21 dBm. The company expects this product range, comprising its AWL9230, 9231 and 9232 chips, to be in full production by the end of 2007.

Anadigics' InGaP BiFET process reserves the HBT portion of these front-end integrated chips to function as the PA, which it sees as the optimal technology for this purpose.

The chips operate in the 2.4–2.5 GHz frequency band, making them well-suited to the 802.11b, g and n Wi-Fi protocols, for applications including voice-over-IP. The FEICs come in 3 × 3 × 0.55 mm packages.

More than simply putting a lot of functions on one chip, Cresci claims that Anadigics has integrated a world-class LNA with a high power efficiency PA. "We think that this process is unique, certainly on this planet anyway, in the sense that we can provide the world-class functionality of each component," Cresci said. "We're really not compromising by making this level of integration."

Cresci says that Anadigics is already selling its FEICs to a number of tier one electronics customers for notebook PCs, smartphones and consumer electronics. With Apple having just announced that its ever-shrinking iPods will now also boast Wi-Fi capacity, it looks like Anadigics is on the right track.

The GaAs chip-maker is also the latest to announce acquisition activity, having strengthened its research and development capability with the $2.3 million purchase of Fairchild Semiconductor's Tyngsboro, Massachusetts-based RF design team.

WIDE-BANDGAP DEVICES

BAE Systems scores $8 m GaN contract

Aerospace giant BAE Systems has won an $8 million contract from the US military to develop a GaN-based high-power amplifier.

Working alongside materials specialist Rohm and Haas, as well as the University of Colorado, the BAE Systems development team is scheduled to demonstrate a 160 W amplifier suitable for deployment in 2010.

The solid-state amplifier will replace cumbersome, expensive vacuum tubes that are typically used for radar, communications and in electronic warfare, for example jamming enemy communications. John Evans, the manager of DARPA's disruptive manufacturing technology program, said: "DARPA has identified BAE Systems' GaN technology as an important material for future military applications."

The target for the initial phase of the program is to produce a proof-of-concept 20 W GaN module by 2008, before scaling up the amplifier's power.

BAE Systems is a major DARPA partner and has been working with the agency as part of the wide-bandgap semiconductors program, which kicked off in early 2005, under a track led by TriQuint Semiconductor.

However, the latest development program will not be focused on GaN-based monolithic microwave integrated circuits (MMICs), with DARPA saying that an alternative substrate technology will result in much earlier deployment of GaN in military systems and significant cost savings.

Instead of MMICs, the BAE Systems program will work on so-called HyMICs – hybrid microwave integrated circuits that will feature discrete GaN-based transistors directly integrated with passive components and impedance-matching circuits.

HyMICs are based on a low-cost technology called Polystrata, which has been developed by BAE Systems under DARPA's 3D microelectronic RF systems program – also headed by John Evans.

Polystrata is the equivalent of a printed circuit board for microwave systems.

MERGERS & ACQUISITIONS

TriQuint swoops for Peak Devices

Oregon's TriQuint Semiconductor has acquired the fabless RF transistor supplier Peak Devices for $15 million in cash. Based in Boulder, Colorado, Peak currently has just 16 employees, 10 of whom are experienced RF engineers, and registered sales of $2.6 million in the first half of 2007.

Peak designs and sells a variety of silicon-based RF semiconductors for applications in broadcasting, wireless networks and defense. Its product lines include transistors previously supplied by Agere Systems, Infineon and Avnet.

While those sales will add immediately to TriQuint's revenue and also help to top up profits, TriQuint CEO Ralph Quinsey placed more emphasis on a proprietary semiconductor technology that Peak's engineers have developed more recently.

Called WiMOS, this wide-bandwidth design is said to allow a single-power amplifier device to operate over five octaves, including the 700 MHz – 2.8 GHz range in which most wireless networks operate.

Peak claims that the approach has been developed with a silicon material platform in mind, but Quinsey says that it can also be incorporated into the GaAs and GaN designs that TriQuint has pioneered.

"To replace multiple amplifiers, optimized for various frequency bands and modulation schemes, with a single device has long been a goal of our industry," said Quinsey. "This is a technology that can enable the software-designed radio."

Peak is not yet selling WiMOS commercially, although the technology is said to have been demonstrated for potential customers. Under TriQuint, the company will complete the commercialization of WiMOS, with Quinsey expecting the technology to generate meaningful revenues in 2008. Initial applications are likely to be in military and wireless infrastructure, although WiMOS has the potential to be used in future handset designs, added the CEO.

Bill McCalpin, currently the CEO of Peak, will remain in charge of the division.

Founded in 2000, Peak has until recently concentrated on providing customers with RF transistors that were made obsolete by their original suppliers, or by providing an alternative to discontinued lines.

In 2004, it acquired part of Infineon Technologies' RF module division, as well as intellectual property and inventory belonging to Avnet.

The following year, it repeated the trick with Agere Systems' high-power RF LDMOS transistor technology.

START-UP

Vietnam veterans start up GraSen

Two veterans of both the Vietnam War and the semiconductor industry have set up a new company to provide GaAs-based components for RF applications. Based in San Jose, California, GraSen Technology is using three different foundries to manufacture InGaP/GaAs HBTs, GaAs-based HFETs and monolithic microwave ICs.

Grasen's founders – CEO Brad Senge and CTO Stan Gray – have more than 63 years of semiconductor product design and manufacturing expertise between them. Said Senge: "Our current offerings of HBT and HFET products meet the growing demand of design, production and delivery requirements of the wireless communications and defense electronics markets."

GraSen told *Compound Semiconductor* that it would offer broadband gain blocks designed for military and instrumentation applications. These products could also be used in wireless infrastructure.

The start-up already has manufacturing agreements with two Taiwanese GaAs foundries and a third in southern California to manufacture the semiconductor wafers, while packaging takes place at a facility in the Philippines.

Initial wafer runs are underway and the company says that it will offer devices for sale in bare die form, as well as packaged. "With three foundries available, GraSen can handle large production orders," said a spokesman for the company. "Very large production orders will require ramping up a second packaging house."

"That second house will ensure delivery with no production loss caused by a point failure in the primary assembly house," said a company spokesman.

Gray added: "GraSen also offers customers contract design and transfer services – including CMOS, RF power amplifiers or high-speed logic circuits."

POWER LEDs

Cree raises the bar again

Researchers at Cree have posted another breakthrough in high-brightness LED performance – marking the best efficacy yet seen from white chips operating at 350 mA.

The GaN semiconductor structures have been tested by the US National Institute of Standards and Technology (NIST), showing an efficacy of 129 lm/W for a cool-white emitter (5813 K). Meanwhile, the warm-white version (2950 K) delivered 99 lm/W. The total light output for each LED was 135.7 lm for the cool-white device and 104.2 lm for the warm-white equivalent.

While the latest milestone must be treated as a laboratory phenomenon for the time being, Cree has a track record of turning its research results into production-worthy technology suitable for volume manufacture within two years.

As Cree's John Edmond notes, the key aspect of this latest result is that it has been achieved with very bright chips that operate at 350 mA – the kind of chips that will be required for general lighting applications.

Cree also announced that its laboratory team had made a single-chip LED capable of emitting 1050 lm, which it says is equivalent to the output from an incandescent bulb. The cool-white laboratory demonstration was driven at 4 A and attained an efficacy of 72 lm/W. A warm-white analog produced 760 lm with efficacy of 52 lm/W.

INTELLECTUAL PROPERTY

Seoul signs on with Osram Opto

LED makers Seoul Semiconductor and Osram have agreed a cross-licensing deal over patents relating to white and visible emitters. While specific details of the agreement have not been divulged, Seoul says that the deal will see the two companies collaborate and work as strategic partners.

Precisely what that means remains to be seen, but with the two parties saying that they will cooperate to defend intellectual property rights, the move may help in future battles with Japanese rival Nichia.

Seoul is also claiming a US court victory against Nichia. The Korean firm's legal representatives at Bingham McCutchen announced on August 24 that a district court judge in Northern California had dismissed Nichia's claim of patent infringement against Seoul.

"[The judge] rejected Nichia's allegations that Seoul had induced the infringement of four Nichia patents and entered judgment in favour of Seoul," stated the legal firm.

SEOUL SEMICONDUCTOR

All white: Seoul's latest AC-compatible Acriche LEDs deliver 200 lm from an input power of only 3.3 W.

Beth Parker from the legal team added: "This is a vindication of Seoul Semiconductor's business practices. The ruling reduces Nichia's initial claims for millions of dollars to [only] thousands of dollars."

PATENT DISPUTE

ITC raps Epistar again

A further round of the LED patent battle between Epistar and Philips Lumileds has gone the way of the US manufacturer. The US International Trade Commission turned down an appeal from the Taiwanese firm.

Epistar wanted the ITC to put a stay on its original exclusion order, which prevented the import of its omnidirectional mirror adhesion, glue-bond and metal-bond chips. However, the request was ruled out, as the ITC deemed it not likely to be a success.

The ITC judge handling the case also criticized Epistar for relying "on quotes that are presented out of order and without context in an attempt to convey a meaning that is in contrast with that actually expressed".

Amid all of this legal action, Epistar has been fighting on the technological front by ramping up production of a new range of Phoenix and Aquarius LEDs, to maintain its AlInGaP chip offering in the US.

EPITAXY

HVPE suits InGaN devices

TDI has used hydride VPE to grow device-quality InGaN for the first time and has enforced its claim by using it to produce green and blue LEDs.

The Silver Spring, Maryland, nitride semiconductor specialist presented its results at the 4th China International Forum and Exhibition on Solid State Lighting in Shanghai, which ran from August 22–24.

The demonstrated LEDs emit blue light between 450 and 490 nm and green light between 490 and 510 nm, although as proof-of-principle structures they only emit microwatt-level power.

Despite the momentum behind the existing approaches to LED production, TDI asserts that its improvements in material quality combine with the potential economy of HVPE to make an attractive offering.

"If working on long runs and large scale, HVPE has proved that it is a much cheaper method," said Alexander Syrkin, senior growth specialist at TDI. "If you need to grow a thick foundation layer by other methods [like MOCVD], it isn't practical," Syrkin added. "You need 10–20 h to grow 10–20 µm and by HVPE you make it in 10 min."

TDI is now working to turn its recent progress into commercial products, although which form these might take has not been decided. Syrkin sees potential for commercialization of the growth technology, or development of templates specifically for LED manufacture and said that TDI were "looking at" actual production of LEDs.

It seems, at least, that TDI will continue the material development underlying its LED technology, according to research director, Alexander Usikov. "We are working to increase InGaN content in the LED structures toward fabrication of yellow and potentially red LEDs," he said.

APPLICATIONS

EU green light for Audi headlamps

Audi is to bring full LED headlamp units, featuring Lumileds' Luxeon LEDs, to the road in its brand icon R8. Audi's sporty new R8 model includes the first ever all-LED headlamp option, thanks primarily to a special permit from the EU.

The German car-maker has permission to use LED front lights before official regulations covering the technology come into force in Europe, allowing it to move into series production ahead of schedule.

Legislation regulating LED headlamps is coming into force in Europe in 2008 or later and in the intervening period Audi had to apply to the EU Commission for the Adaptation of Technical Progress for official clearance to use its new lamps. Audi said that the LED headlamps would be three times as expensive as their xenon equivalent.

The headlamps' maker, Automotive Lighting, says that it uses 24 Osram Advanced Power Top LEDs for the daytime running lights that run along the bottom edge of the complete unit.

The dipped-beam is provided by a pair of four-chip arrays containing Philips Lumileds' Luxeon chips, coupled with a free-form reflector. A similar but separate arrangement also provides the main beam. A further three two-chip arrays, coupled with a high performance lens system, provide additional light around the main spot of the dipped beam.

WAFER FABRICATION

EpiValley and Forepi step up chip volume

Korea-based epiwafer manufacturer EpiValley has ordered three high-volume MOCVD reactors from Aixtron, as it steps up GaN LED production for new applications. Aixtron will deliver the CRIUS tools, made by its Thomas Swan subsidiary, to EpiValley's headquarters in Kwangju City. Each tool is designed for 30 × 2 inch wafer fabrication.

EpiValley wants to ramp up GaN epiwafer production quickly to meet the demand for side-view LEDs that are set to be used in display backlight units.

Meanwhile, the Taiwanese GaN epiwafer producer Formosa Epitaxy (Forepi) has also invested in new MOCVD kit, although it has decided to buy from Aixtron's rival, Veeco Instruments. Forepi will install two TurboDisc K300 systems for high-volume wafer production, as it looks to scale up LED fabrication for outdoor display, lighting and keypad backlight applications.

UV LEDs

Banknotes boost cash flow

Japanese UV LED manufacturer Nitride Semiconductors is making the most of the advantages that its products offer over conventional UV bulbs, ejecting the latter from lucrative applications, such as counterfeit banknote detection.

LED sales have been growing steadily since Nitride entered full-scale production at its site in Naruto City, Japan, in 2003, and have now grown to the point where the company is capable of making 10 million LEDs per month.

The company reportedly developed its technology with a maker of money-handling machines who sought to benefit from the improved efficiency and smaller size offered by LEDs.

Such counterfeit detection applications range from rapid integrated counter/validator machines aimed at banks and casinos, to cheap and simple key ring and pen lights. LED production at Nitride is performed using a novel MOCVD approach developed in association with Shiro Sakai of Tokushima University, who subsequently became a director of the company.

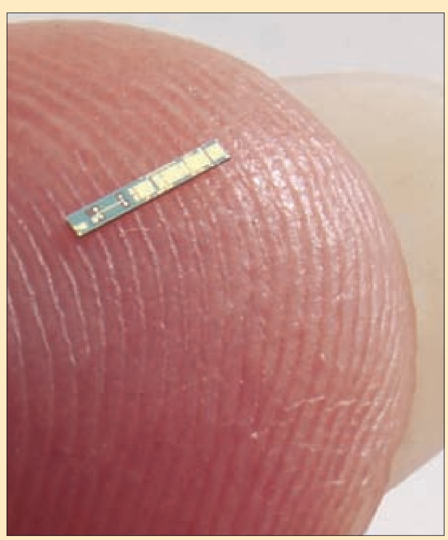
Rather than the InGaN-emitting layer used in blue LEDs, Nitride's MOCVD technique grows an AlInGaN-emitting layer to achieve wavelengths below 380 nm.

Nitride claims to be the only supplier of bare UV LED die, for packaging by other companies and also currently supplies LEDs already packaged as lamps and modules, as well as selling GaN epiwafers.

Two firms that might counter that claim are the US outfits Sensor Electronic Technology, which has been supplying Seoul Optodevice with UV LED epiwafers since the two signed up to a strategic partnership just over a year ago, and Technologies and Devices International.

Nitride is now looking to produce UV LEDs for use in developing photocatalysts, for example in curing resins and coatings, applications that demand a significant hike in power output.

● Japanese researchers have produced deep-UV LEDs using low-pressure MOCVD, with a device design that has delivered big increases in output power and external quantum efficiency. A collaboration led by Hideki Hirayama at the Riken research institute in Wako, Japan, reported UV LEDs with emission wavelengths between 231 and 261 nm.



JDSU is shrinking optical network modules by combining a tunable laser and Mach Zehnder modulator on a single tiny chip.

The laser maker says that including these InP-based photonic integrated circuits (PICs) in its products will help lower costs and increase performance.

From 2008 JDSU, which is based in Milpitas, California, will put the PICs into tunable transponders and transceivers for deployment in what it calls agile optical networks.

These PICs will provide JDSU with products able to support transmission speeds over 11.3 Gb/s, which could also be combined to support 40 Gb/s networks.

Bookham claims to lead the industry with its Mach Zehnder modulator technology, which it touts as the smallest available – something that it looks like JDSU will now be challenging.

JDSU makes its PICs by epitaxially growing the laser and modulator elements at the same time and told *compoundsemiconductor.net* that this expertise stems from its experience of researching PICs since 1996.

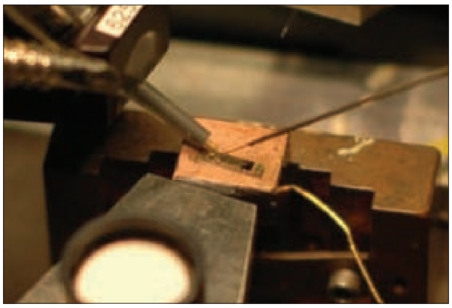
"We have always evaluated monolithic versus hybrid solutions for functional and device integration," the company said.

"Our drivers are improved economics for our customers and broad market acceptance of new integration concepts rather than increased complexity of a PIC."

In the meantime, Infinera has emerged and become the most widely acknowledged exponent of PIC engineering.

RESEARCH

Hybrid laser shows commercial promise



UCSB

Testing times: UCSB's mode-locked hybrid InP/silicon laser shows its potential for optical communications and computer interconnects.

The hybrid silicon laser revealed last year by a team from Intel and the University of California, Santa Barbara (UCSB), is showing great promise for applications in high-speed optical communications.

Led by UCSB's John Bowers, the collaboration has now fabricated mode-locked devices – lasers that produce ultrashort pulses at a very high repetition rate.

The advance means that lasers based on a silicon manufacturing platform, similar to that used in volume CMOS processing, are one step closer to becoming a commercial reality – and that the Intel/UCSB hybrid approach is the most promising.

The basic laser structure is the same as that demonstrated last year, in that an InP wafer containing the laser's active element is bonded to a silicon wafer, using an oxide plasma-assisted bonding step.

When driven electrically, the InP portion emits light at around 1600 nm and the silicon portion acts like a waveguide, amplifying the light and creating laser action. In the latest design, the team has improved the laser's efficiency via a hydrogen implantation step that confines the flow of electric current between the laser's electrical contacts to a smaller region above the waveguide.

Brian Koch, a UCSB researcher, explained: "What's nice about our technique is that when we put the InP on the silicon waveguide, we don't need to align it accurately, which makes the process relatively easy."

"To make a mode-locked laser, we altered the design slightly by adding a new section to the laser cavity. This section is called a saturable absorber and its function is to absorb some of the light generated."

The change in design means that instead of emitting a continuous stream of IR light, the hybrid laser is forced to pulse very quickly.

The design works so well that it produces light pulses just 4 ps long, at a repetition rate of up to 40 GHz, with a regular time interval in between those pulses.

For applications in optical communications, these characteristics are hugely important, as this is how information is encoded before it is sent down an optical fiber.

In the future, adds Koch, the hybrid laser will be adapted to emit at the much more useful wavelength of 1550 nm.

CONVERGENCE

Silicon and compounds get intimate

With an Intel executive blogging about integrated III-V and CMOS functionality, and DARPA setting up a three-pronged attack on the same topic, it's time for compounds and silicon to get up close and personal. **Michael Hatcher** reports.

IBM

Integration game: Under its new COSMOS program, DARPA has funded three projects, each with a different approach to integrating InP functionality with silicon CMOS processing for applications in digital–analog converters. Intel, Amberwave Systems and IBM are working on similar projects.

"Compound semiconductors have always had a huge big brother over their shoulder, and it's very hard to compete with such a behemoth." That's Mark Rosker from the US Defense Advanced Research Projects Agency (DARPA), telling us what we already know about silicon semiconductors. But the good news for compounds is that there are now some major efforts going on to address this problem and to make silicon and III-V materials happy bedfellows.

It's not a new idea, of course. What is new is DARPA's generous backing of three independent approaches to combining the benefits of the two technologies within the same device platform, each of which could receive around $18 million.

Rosker again: "If you have this technology in hand, you have the capability of building products, devices and circuits that will be absolutely revolutionary. There are an enormous number of circuits that would benefit from compound semiconductors, where today it's just cost-prohibitive to imagine doing that."

DARPA's three teams – led respectively by the familiar corporate faces of HRL, Raytheon and Northrop Grumman Space Technology – are by no means alone in imagining the possibilities that this convergence could bring. IBM is actively working on it, while Intel's executives have even taken to blogging on their company website about it. Mike Mayberry, director of component research at Intel, talked up the company's recent development of InGaAs-on-silicon transistors with epiwafer specialists at IQE.

Okay, but would Intel really consider using GaAs processes? Even while espousing the technological benefits offered by convergence in his blog, Mayberry trotted out the old "technology of the future – and always will be" joke that III-V companies have had to put up with for decades.

So maybe it makes more sense to look at what DARPA is intending to make happen in its new program, which the agency has denoted COSMOS, as in "Compound Semiconductor Materials On Silicon".

Back to Rosker: "The goal is basically to make a circuit so that it is absolutely seamless to the designer – whether they're using a silicon transistor or whether they're using GaAs. What you would ideally like is to be able to take whatever compound semiconductor you want and have that live inside the silicon circuit."

There's more than one way to do that. One is to take a CMOS-processed wafer, plus some micron-scale chips made using a III-V process – Rosker calls them chiplets – and to figure out a way to connect the two. This focus on assembly and interconnects is the approach that NGST is taking.

The extreme opposite of that scheme, explains Rosker, is to take a purely monolithic approach and integrate compounds without significantly changing the CMOS process – this is what the team headed up by Raytheon will be tackling. "That's tough," admits the program manager.

The reason that it's technologically tough is, of course, the lattice mismatch between silicon and III-V materials – the perennial stumbling block. While Raytheon will have its work cut out trying to achieve this monolithic approach, a separate collaboration outside the DARPA effort is also looking at how to solve the materials problem.

Though nowhere near the grand scale of the COSMOS program, Amberwave Systems has backing from the National Science Foundation and will work with principal investigators from Rochester Institute of Technology's microelectronics department.

Caught in a trap

So far, Amberwave's research team has been able to trap crystal defects arising from the lattice mismatch of germanium and III-Vs grown on silicon to within the first few hundred nanometers of the layers formed by epitaxial growth.

Because these defects are also confined laterally, to

"It's going to be a gold mine."
Mark Rosker
DARPA

the sidewalls of narrow openings in a dielectric mask on a silicon wafer, it is possible to fabricate device structures on the defect-free stripes that remain, with Amberwave targeting resonant tunneling diodes for static RAM applications initially.

In the DARPA program, the agency has funded what you might call, in political speak, a third way. This team, led by HRL, will fully process a wafer using CMOS and partially process the compound semiconductor separately. The two wafers can then be bonded to each other.

Interestingly, although the agency did not specify any particular compound material in its COSMOS solicitation, all three teams have decided to focus on the same compound – InP.

So, what exactly are the COSMOS program members expected to deliver in terms of device technologies? Rosker reveals that the key application will be mixed-signal electronics – in particular, differential amplifiers, analog-to-digital converters (ADCs) and their digital-to-analog equivalents (DACs). "Building a high-performance ADC is really a classic problem in electronics," Rosker said.

The first phase of COSMOS will focus on differential amplifiers, circuits requiring only five transistors, two of which will be fabricated in InP. A key building block for the rest of the program, these amplifiers will then be used to develop more complex DACs. "In phase three, then we really do the impossible – we try to make an ADC," is how Rosker put it. Except that it won't be just any old ADC: "We'll make the world's best ADCs."

The technological specifications for those high-end ADCs are tough, to say the least. Ultimately, Rosker is asking for a 16-bit converter working at a bandwidth of 500 MHz and a power dissipation of less than 4 W.

Outside DARPA's demanding requirements for military deployments, Rosker believes that the initial applications will soon spill over into wide-scale commercialization, such as digital radio. This looks likely to be the first key application in the commercial world, although Rosker sees others. "Mixed signal is very important, but its applicability to other problems is going to be huge," he said. "In optoelectronics, what if I had the ability to embed lasers inside my silicon circuit? In optoelectronics, digital electronics, an entire gamut [of applications] are going to benefit from the technologies that we're going to develop."

Then, rather than competing with the silicon behemoth, compounds could sit happily with silicon CMOS and drive it to new heights. "Instead of competing, you could make a niche – to live inside, almost literally, the silicon world...I think that it's an opportunity for companies involved in compound semiconductors," concluded Rosker. "It's going to be a gold mine for them."

Additional reporting by Andy Extance.

GaN OPTOELECTRONICS

Mixing it in academia and industry

A novel method for making native GaN has paved the way for **Wang Nang Wang's** high-power emitters and launch of a spin-off company. **Richard Stevenson** visits the University of Bath researcher.

R STEVENSON

Wang Nang Wang: mixing academia and industry

1973: BA from CCIST, Taiwan.
1974–1993: senior research scientist at CSIST, Taiwan.
1979: MS from Iowa State University, US.
1987: PhD from Cambridge University, UK, on high-temperature superconductivity.
1988–1993: consultant for Taiwan's Industrial Technology Research Institute.
1988–1992: associate professor at Tsing Hua University, Taiwan.
1993–2000: chairman and president, Quantum Optech Inc, Taiwan.
1995–1998: visiting professor at the University of Bristol, UK.
2000: co-founder of Arima Optoelectronics.
1999–2007: professor at the University of Bath.

Professor Wang Nang Wang is not your typical academic. He has not devoted his entire career to university research, but has instead worked for several years in executive roles at optoelectronic chip manufacturers. Although he didn't really enjoy running companies, his time spent leading Quantum Optotech and founding Arima Optoelectronics has given him experiences that have clearly shaped his outlook and today all of his research is focused on improving the performance of real-world devices.

The importance he places on the potential commercial impact of his work is reflected in his interest in patent literature. If many generic patents are held in a particular area he steers clear of this topic as any breakthrough will not lead to successful commercialization. In fact it just helps the existing manufacturers, says Wang, who are simply shown how to improve their own product's performance.

This desire to avoid technologies covered by a string of patents has led Wang to pursue a new technique for making GaN substrates, which have subsequently formed a high-quality basis for optoelectronic device growth. With a focus on improving commercial GaN LED and laser performance in particular, Wang's first move was to design a novel reactor. This first vertical HVPE reactor was built in 2001 and has led to the filing of seven patents.

A vertical showerhead configuration has been employed for the first two generations of this tool and will also be used for a third reactor that is under construction. According to Wang, the advantage of this design is its high degree of symmetry, which allows easy scaling up from the 2-inch GaN that has been grown so far to 3, 4 and ultimately 6-inch material.

Wang's first reactor suffered from a very narrow process window for making high-quality material and a tendency for producing polycrystalline films at high growth rates. "We also didn't have a compatible process for growing materials that are flat and free from cracks."

The second reactor addressed some of these faults, along with the introduction of a new fabrication process that Wang refers to as nano-pendeo epitaxy. This technique involves taking a silicon or sapphire substrate, patterning it with sub-micron-sized pores and then depositing GaN onto this structure. GaN nanocolumns are formed as a result, which can disrupt many of the dislocations created during conventional heteroepitaxy. "There are no threading dislocations [in our material]," said Wang, "and the dislocation density falls to $8 \times 10^6/cm^2$ when we go over 300 µm."

When it is finished this fall, the third-generation reactor will be easier to use than the previous tools and will produce faster growth rates, thanks to the combination of modifications to the showerhead, the source design and control software. "This allows us to run efficiently for a few days of operation," explained Wang. The growth efficiency, the proportion of process gases converted into GaN material, is expected to be 55% for the latest reactor, compared to 30–35 and 45% for the earlier two versions, respectively.

Wang's team is also equipped with an MOCVD reactor, a modified AIX 200 horizontal tool. This single-wafer reactor is used to grow optoelectronic structures for various collaborative programs and six patents are in the pipeline relating to device growth and non-polar materials.

The team's LED development, which will aid the UK project NoveLELS – aiming to develop very bright devices for airplane wings and cockpits – has produced polar emitters that are almost free from so-called "droop". This effect, a reduction in lumen per watt as drive current increases, plagues all of today's LED products and is a barrier to manufacturing very bright, efficient devices. Commercial LEDs that Wang has looked at produce 130 lm/W at 20 mA, but this falls to 80 lm/W at 350 mA. In comparison, his devices – which have not been packaged and are measured at the wafer level – are slightly worse at low current drive, but typically produce 100 lm/W at 350 mA.

To solve the droop problem, Wang incorporated a resonant tunnel junction into the LEDs. This cools electrons before they enter the quantum wells and leads to higher recombination efficiencies. This gain is seen in LEDs grown on both sapphire and free-standing GaN, but the latter platform produces higher efficiencies and reliabilities.

Earlier this year, Philips Lumileds claimed that it had also solved the efficiency droop problem, but it did not disclose the details behind this breakthrough.

"Lumileds have a lot of tricks up their sleeves to improve the epitaxial structure and they might have a different way," said Wang. Although he doesn't know exactly how Lumileds improved the high-current performance, he believes that excellent thermal management, which is a hallmark of it's LEDs, will have contributed to the success.

Wang's LEDs also benefit from very good thermal management. This advantage comes from forming free-standing devices with thin GaN layers, which are made by using wet etching or mechanical rotation to remove the foreign substrate. The thinner chip reduces heat confined within the device, which can also be attached to another carrier that can act as a heat sink.

This free-standing chip approach has also been employed in Blurayds, a UK government-funded project directed at developing high-power 405 nm laser diodes that is led by Wang and includes the University of Oxford, Advanced Optical Coatings of Plymouth and Arima Optoelectronics (UK) Ltd. With this approach, the laser can benefit from an air interface that improves optical confinement thanks to an increase in the refractive index contrast at this boundary. "You can also put the laser on another carrier, such as silicon," said Wang, "and align the cleaving facet of GaN with the natural facet of silicon, which means that you have a better cleaving facet." This can aid laser manufacture, as it can improve the yield of the cleaving process that defines the cavity's dimensions.

Lasers made with Wang's epiwafers, which also contain a resonant tunnel junction to cool electrons, have threshold currents below 50 mA and maximum output powers of 50–60 mW. These diodes also feature an undisclosed facet coating to improve performance that is not titanium dioxide or silicon dioxide. "With titanium dioxide, the performance of 405 nm lasers can trail off, because titanium dioxide has a cut-off wavelength around 380 nm. If this material is not of sufficient crystalline quality it can absorb at the laser's wavelength," explained Wang. This will reduce the laser's output power, an issue that he is trying to avoid with his novel coatings that also improve the threshold current density.

Wang's partnerships with device developers – he co-founded Arima in 2000 – have been very useful because they have provided feedback about material quality and helped to drive improvements in substrate and epitaxial growth.

Currently, his team is only producing a few wafers each month, but Wang is once again sensing a real commercial opportunity and shipments should increase through the launch of a spin-off company, NanoGaN, which will produce both substrates and epiwafers. This venture already has £250,000 ($499,000) from Bath University's "Sulis" commercialization fund, showing that even when Wang works in academia, his commercial nous leads him to playing a role within the manufacturing side of our community.

Light-emitting diodes hit t

Fred Schubert and **Jong Kyu Kim** guide us through 100 years of the LED, before predicting where our most promising light source will take us over the next decade.

British radio engineer Henry Joseph Round discovered the LED completely by accident. While investigating the electrical properties of a metal-semiconductor SiC rectifier, a device that offered a promising alternative to more-expensive vacuum diodes, he witnessed the first light emission from a solid-state material driven by an electrical current.

Round reported this "curious phenomenon" of electroluminescence in 1907 in a remarkably short publication of two paragraphs (figure 1), which detailed the yellow emission from a two-pole structure with an "unsymmetrical passage of current". Today this device would be called a diode, which makes Round's article the first ever report of an LED.

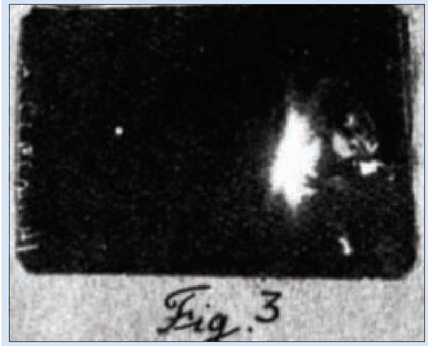
With hindsight we can see the scientific and commercial significance of such a discovery, but the phenomenon of electroluminescence was forgotten for several years. However, in 1923 it was rediscovered by a talented 20-year-old Russian scientist Oleg Vladimirovich Lossev, who produced the first photograph of electroluminescent light (see box, "The evolution of the LED"; Lossev, 1923). SiC was the material, in the form of a metal-semiconductor diode.

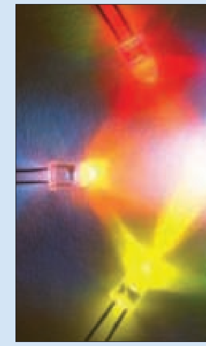
Lossev carried out detailed measurements of the diode's current-voltage characteristics and realized that forward and reverse biasing both produce emission (figure 2, p22). Today this can easily be explained because we know that impact ionization and minority carrier injection both generate light. Lossev, however, lacked this understanding and was puzzled about the origin of the luminescence. He wondered whether light was generated by heat glow (incandescence), and to test that theory he measured the evaporation rate of a droplet of liquid benzene placed on the luminous sample's surface. However, the benzene evaporated very slowly, which led him to deduce that luminescence was not caused by incandescence.

Armed with this knowledge, Lossev then postulated that the light came from a process that is "very similar to cold electronic discharge". He also showed that the emission could be switched on and off very rapidly, which would allow the device to be used in a light relay – a component that we would now call an optical communication source.

Lossev's was the first detailed study of semiconductor electroluminescence. In recognition of his accomplishments he was awarded the degree of Candidate by the Ioffe Institute in 1938, the equivalent of a doctorate.

The evolution of the LED





The LED has evolved from an object of curiosity to a product with annual sales of several billion dollars. The first photograph of electroluminescence from an LED was taken by Oleg Vladimirovich Lossev in 1924 (*Wireless World and Radio Review* 1924 **271** 93). It would be several more decades before colored LEDs were first used as in mixing these colors white light. Today ge seen as the next big and companies such producing products

The first modern, correct interpretation of light emission from a p-n junction was provided by Kurt Lehovec and colleagues at the Signal Corps Engineering Laboratories in New Jersey in 1951. They claimed that the luminescence came from minority carrier injection across the boundary of a p-n junction under forward bias (figure 3, p22).

Companies flock to LED development

Since then, LED developments have flourished, with remarkable improvements in device characteristics continuing to this day. These advances were kick-started by replacing SiC with more efficient materials based on III-V compounds. Key milestones include the demonstration of single-crystal GaAs (Welker, 1952), which provides the ideal substrate for many devices. This platform was used for the initial development of GaAs LEDs and injection lasers, which was led by General Electric in Schenectady, IBM in Yorktown Heights and Lincoln Laboratories in Lexington. It was not long before these three, all located in the northeast of the US, were competing with the then-famous Bell Telephone Laboratories in Murray Hill and the RCA Laboratories in Princeton, in an LED development race.

The first visible LEDs based on III-V materials were built in 1955 by Wolff and colleagues at the Signal Corps Engineering Laboratories. This orange-emitting GaP device generated light through the impact ionization of carriers at the metal-semiconductor junction. However, the lack

White and blue LEDs are used to illuminate the keypads and backlights of billions of handsets, as well as to provide a flashlight for the accompanying cameras. According to Strategies Unlimited, sales into this market peaked at just over $2 billion in 2004 and were worth $1.8 billion last year.

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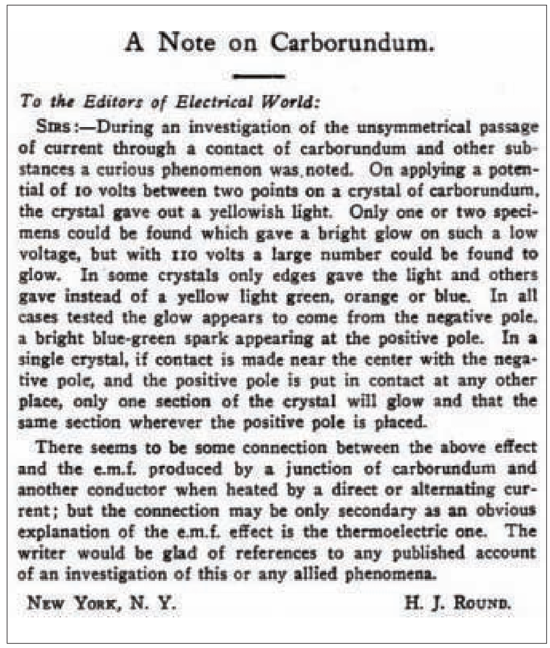

A Note on Carborundum.

To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

NEW YORK, N. Y. H. J. ROUND.

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MARCONI CALLING WEBSITE IMAGE 2A

Fig. 1. (above and left) Henry Joseph Round, a prolific inventor who filed more than 100 patents, published the first ever report of electro-luminescence in 1907 in the journal *Electrical World* (1907 **19** 309).

of a p-n junction meant that it was too inefficient and unsuitable for commercialization.

LED progress followed through the development of new red-, yellow-, orange- and green-emitting materials in the 1960s and 70s, which were made from III-V compounds, such as GaPAs, nitrogen-doped GaP, nitrogen-doped GaPAs, and zinc and oxygen-doped GaP. These LEDs were far more efficient than Wolff's metal-semiconductor structure but they still fall well short of the performance of today's equivalents employed in high-power applications, which are based on AlGaAs and AlGaInP.

Developing and improving these devices required a great deal of effort but they were still an easier nut to crack than the blue LED. Work on this type of emitter began in the late 1960s at RCA, and in 1969 Paul Maruska made the first breakthrough: a single-crystalline GaN film. However, these films were unintentionally n-doped and the addition of p-type dopant only produced insulating material. The lack of p-doped material led the team to build metal-insulator-semiconductor diodes, but such devices are inevitably inefficient and this project was abandoned in the early 1970s.

The following decade was a lean time for GaN LED research. However, in 1989 Isamu Akasaki and co-workers from Nagoya in Japan produced the first p-type doping and conductivity in GaN using magnesium doping activated by electron-beam irradiation. An LED with 1% efficiency followed three years later, but this was soon surpassed by Shuji Nakamura from Nichia, who managed to fabricate blue and green GaInN double-heterostructure LEDs that were 10 times as efficient. Further improvements have continued to this day, with the latest devices producing hundreds of milliwatts.

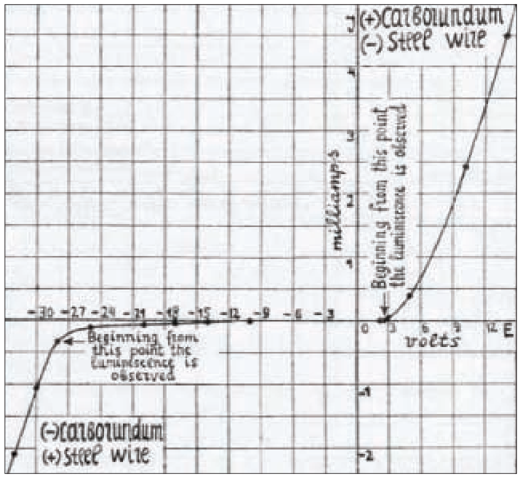
Improvements in all forms of LED have also been spurred on by MOCVD, which superceded approaches like liquid-phase epitaxy, which cannot produce uniform epilayers just several nanometers thick. The greater control led to double-heterostructure designs in the 1970s and quantum-well structures in the following decade, which provide greater confinement and boost device brightness. Commercial MOCVD tool development has also cut LED manufacturing costs, thanks to an increase in the number of wafers that can be loaded into a growth run.

The tremendous hikes in efficiencies and output powers of all of these colored LEDs have dramatically increased the number and variety of applications that they can serve.

However, current interest in single-color LEDs is overshadowed by their white cousins, which are starting to unlock the door to more lucrative markets, such as general illumination. One approach to producing white light involves the mixing of emissions from several different-colored LEDs (see box "The evolution of the LED"). However, the dominant commercial method that was pioneered by Nichia, which is simpler and produces a high color-rendering index, involves a yellow phosphor and a blue LED chip (figure 4a, p22). The blue-emitting

About the authors

E Fred Schubert is a wellfleet senior constellation professor at Rensselaer Polytechnic Institute and **Jong Kyu Kim** is a research assistant professor at the same institute.



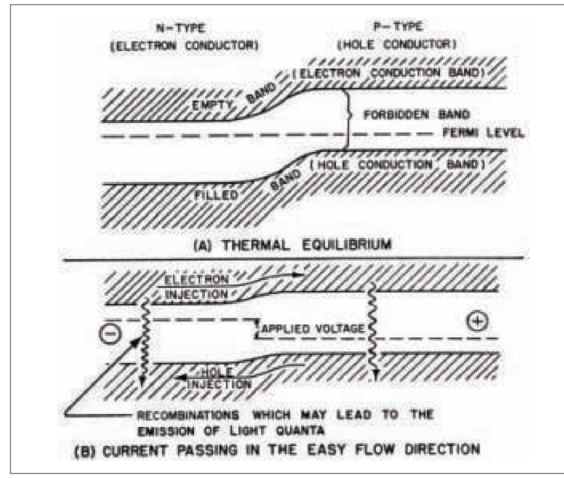


Fig. 2. (left) Lossev was keen to understand how the LED works and spent time recording the current–voltage characteristic of a SiC device. His labels reveal that electroluminescence occurs under forward and reverse bias (1928 *Philosophical Magazine* **6** 1024). **Fig. 3.** (right) Lehovec and co-workers were the first to explain the principles of LED operation. They revealed the band structure under thermal equilibrium and forward bias, which they referred to as the easy-flow direction (1951 *Physical Review* **83** 603).

chip excites the yellow-emitting phosphor and white light is created from mixing these two sources.

The white LED is the major battleground for today's chip makers, which have driven significant improvements in white LED output. Values of 100–150 lm/W have been reported during 2006 and 2007. This compares favorably with incandescent and compact fluorescent lamps, which have luminous efficacy figures of 15 and 70 lm/W, respectively.

The advantages that would come from a switch from incandescent and fluorescent lamps to highly efficient solid-state sources have been well documented, and these include energy and financial savings and a reduction in the use of mercury. The energy savings could be substantial and even lead to 280 major electrical power plants being switched off. LEDs are also beginning to provide the backlighting source for liquid-crystal displays (LCDs) used in televisions and computers. Here, the new source not only cuts power consumption but also produces a greater color gamut than a fluorescent lamp and a reduction of motion artifacts.

So far we have ignored one other aspect that fundamentally distinguishes solid-state sources from their conventional cousins – greater controllability. Scientists and engineers that strive to control and tune all of the properties of an LED have the unprecedented challenge of constructing light sources that can be controlled in terms of spectrum, polarization, color temperature, temporal modulation and spatial emission pattern. Some of these properties are relatively easy to control, such as the optical spectrum, but innovative ideas are needed to improve the control of properties such as polarization.

With LEDs on the road to becoming the dominant and most versatile light source available, controlling the emission properties will become increasingly important, particularly because this will help the technology to differentiate itself from existing competition. In turn, new classes of benefits based on the enhanced functionality will start to emerge.

Examples of such benefits include LCDs lit by linearly polarized sources. This would remove polarizers from displays that discard a significant proportion of light and create a more efficient product. Meanwhile, a switch to LEDs for general illumination would allow indoor lighting with controlled brightness and color temperature. This could accurately mimic the natural changes in outdoor light that occur during the day. Since the human daily cycle and the wake-sleep rhythm are driven by changes in sunlight, using LED-based light that can replicate this source could improve the well being of everyone.

LEDs could also feature in various transportation applications to provide additional information to visual signals. A red LED traffic light could, for example, transmit an encoded signal that tells an intelligent car to stop. This would cut the number of accidents caused by inattentive and impaired drivers running a red light.

A century has now passed since Round stumbled across the SiC rectifier crystal, which unexpectedly emitted light. The intervening years have seen breathtaking progress and created a billion dollar market for the LED, but we are still a long way from utilizing the full capability of this device. The journey is not over – in fact, it's hardly begun.

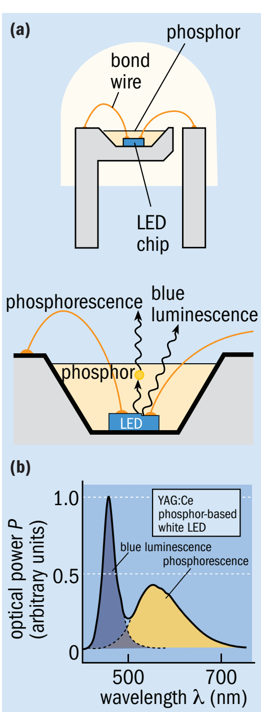


Fig. 4. White-light LEDs produce their emission by using a blue GaInN chip to pump a wavelength-converting phosphor.

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Inverting the triple junction improves efficiency and flexibility

Inverted metamorphic designs can boost the efficiency of conventional triple-junction solar cells, cut their weight and offer compatibility with flexible substrates, say **Paul Sharps** and **Arthur Cornfeld** from cell producer Emcore and **Mark Wanlass** from the National Renewable Energy Laboratory.

The most mature high-efficiency solar cells are triple-junction devices made from compound semiconductors. Such cells are widely accepted in space applications and have been deployed in more than 100 satellites. They have also produced record-breaking efficiencies in a concentrator configuration that is optimal for terrestrial power-generation.

These triple-junction cells are monolithic two-terminal devices featuring GaInP, GaAs and germanium junctions electrically connected in series through tunnel diodes. With such an arrangement, each material absorbs a different portion of the solar spectrum. When operating without a concentrator lens – the design that is used in space applications – these cells deliver an efficiency close to their practical limit of 30% under illumination from the spectrum that they would receive in orbit, which is known as the AM0 spectrum. With the addition of an optical concentrator, such as a lens, light intensity increases and boosts efficiency. This scheme, which is used in terrestrial solar cells, can concentrate the light by 500 times, leading to efficiencies of up to 40% from a standard solar spectrum at sea level (AOD). Further modest improvements can result from an increase in the indium concentration of the top and middle junctions, although this also produces lattice-mismatched material (figure 1, p26).

Despite the commercial success of space applications and the promising emerging market for terrestrial devices, it is imperative to develop alternative structures. This is because the established combination of material bandgaps (1.88/1.42/0.67 eV) is not optimal for realizing the highest efficiencies. Any improvements in efficiency will have commercial benefits, because they should spur sales through reduced costs. For space applications, increased efficiencies will reduce launch and in-orbit costs. More-efficient satellites also offer a lighter alternative for meeting any satellite's power-generating requirements. This benefit – a key consideration for any mission – will even contribute to the launch of larger, more-powerful satellites. Meanwhile, on the ground an alternative set of cell materials could reduce power-generation costs in terrestrial applications, which is the prime metric in this sector.


EMCORE

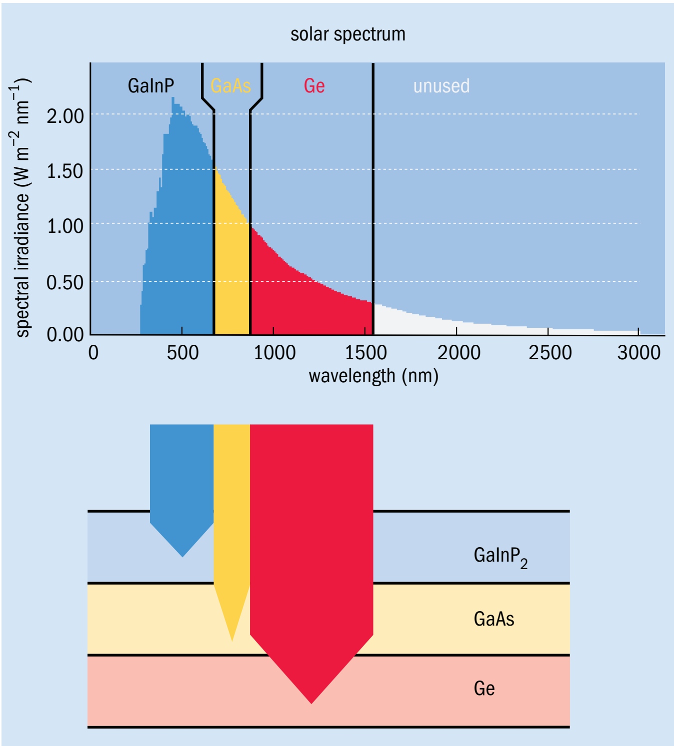
Emcore has won a series of contracts to supply terrestrial solar cells that could collectively be worth more than $300 million over the next few years. The cost of generators that use the cells is estimated at between $4 and $5 per watt, but the development of inverted structures could reduce this key figure-of-merit thanks to improvements in power conversion efficiencies.

Higher-efficiency approaches

Several approaches have been investigated for surpassing the efficiency of the GaInP/GaAs/Ge-based architecture. Those tried, which are suitable for both terrestrial and space applications, can be grouped into three categories: novel materials; mechanically stacked junctions; and lattice-mismatched layers. All of these focus on using a superior set of bandgaps to boost efficiency.

A decade ago, the most promising path to realizing 35–40% efficient solar cells for space applications involved adding the dilute nitride InGaAsN to the GaInP/GaAs/Ge structure. This material, which has a bandgap of 1.05 eV when lattice-matched to GaAs, leads to four-junction cells (1.88/1.42/1.05/0.67 eV) with bandgaps that are close to ideal for maximizing device conversion with this number of junctions. But material-quality issues, such as a short minority carrier diffusion length, have plagued InGaAsN and hampered overall progress. In fact, the work on InGaAsN for photovoltaic applications has virtually come to a halt.

Research related to novel materials is also being



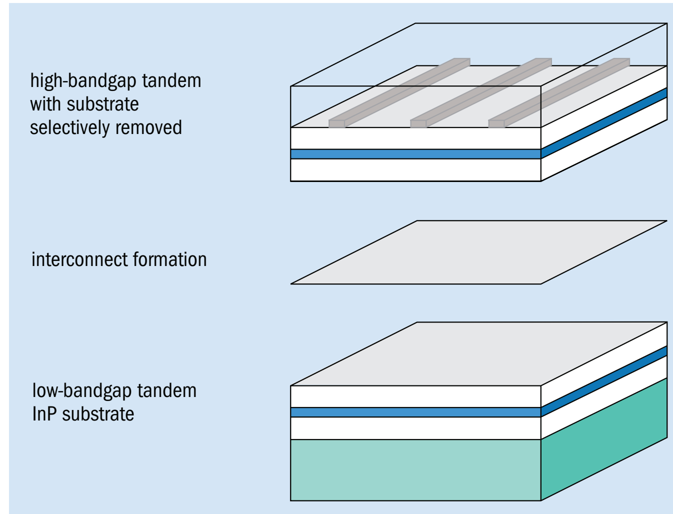
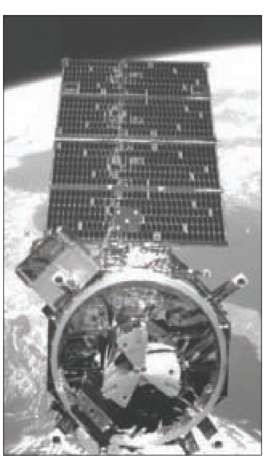


Fig. 1. (left) The solar spectrum AM0 peaks at 500 nm but extends to beyond 3 μm. The unconcentrated triple-junction solar cell GaInP/GaAs/Ge, which has bandgaps of 1.88, 1.42 and 0.67 eV, respectively, can absorb a high proportion of this radiation and deliver an efficiency of almost 30%. **Fig. 2.** (above) Four-junction solar cells built by combining two tandem cells offer a promising route to improving solar cell efficiency. These devices are fabricated by mechanically stacking a high-bandgap tandem cell that has had its GaAs or germanium substrate selectively removed onto a lower-bandgap tandem cell grown on InP.



Emcore's solar cells have powered more than 70 satellites and have been the primary market to date for the company's photovoltaic division.

carried out for two other types of solar cell, which are built from just the nitride InGaN, or are based on quantum dots. In both of these cases, development is currently focusing on fundamental materials and device issues.

For III-V quantum dot solar cells – an example of the intermediate-band approach to higher efficiencies – the challenge relates to quantum efficiency. The quantum dots must be confined to the depletion region at the p-n junction to enable photo-generated carriers to be collected before recombining. This requirement makes it a challenge to grow good-quality material that contains sufficiently thick quantum dot layers for absorbing incoming light. These quantum dots also generate threading dislocations that reduce minority carrier diffusion lengths and ultimately decrease cell efficiency.

The all-nitride solar cell built from InN and InGaN is a very attractive candidate for high-efficiency cells because it has the potential to provide continuous coverage from 0.7 to 2.4 eV. However, issues associated with growth rates, the control of p-type doping, the choice of substrate and the need for an appropriate tunnel diode are all restricting progress.

Mechanical stacking methods

Recent advances in wafer bonding have renewed interest in photovoltaic devices built by mechanically stacking multiple junctions. Typical combinations include bonding a high-bandgap GaInP/GaAs tandem cell, which is grown on either germanium or GaAs, to a low-bandgap GaInAsP/GaInAs (1.05/0.75 eV) tandem cell grown on InP (figure 2). However, cost and weight issues affect this type of design. Growth requires two substrates, and considerable processing is needed, including the removal of the underlying substrate from the GaInP/GaAs tandem cell. It is also a challenge to produce a good wafer bond over a large area of an epitaxially grown layer.

Other approaches have also produced solar cells from mechanically stacked junctions using efficient optical and electrical interconnects. Allen Barnett from the University of Delaware, for example, is leading a consortium that has produced a combination of prototype structures delivering 42.8% efficiency. This project – the very-high-efficiency solar cell (VHESC) – involves a radically different lateral architecture, with the incoming light optically split and directed at solar cells optimized for different spectral bands.

The third approach, adding lattice-mismatched layers to the existing GaInP/GaAs/Ge triple-junction cell, is also promising. Research based on this method has focused on adding indium to the top and middle junctions to reduce their bandgaps. Four, five and six junction devices that incorporate materials such as AlGaInP, AlInGaAs and InGaAsN have also been proposed. However, all of the epitaxial layers are grown lattice-mismatched, which means that they suffer from many threading dislocations that shorten the minority carrier diffusion length and reduce device performance. So up until now, with the exception of very high concentrations, the lattice-matched GaInP/GaAs/Ge triple-junction cell has always delivered higher efficiencies than any conventional lattice-mismatched devices.

Recently, a demonstration at the National Renewable Energy Laboratory, which was subsequently

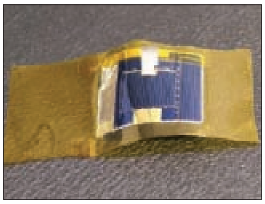


Fig. 4. The inverted metamorphic design offers compatibility with flexible substrates. The germanium substrate can be removed and mounted to kapton tape. This cell has a total area of 0.25 cm^2 and features silver tabs welded to the device to provide electrical interconnects.

confirmed at Emcore Photovoltaics, has shown that a novel lattice-mismatched, multijunction cell approach can challenge the performance of the GaInP/GaAs/Ge triple junction. This approach, which we refer to as inverted metamorphic multi-junction (IMM), involves growing GaInP and GaAs junctions that are lattice matched to a germanium or GaAs substrate in an inverted manner, where InGaP is the first subcell deposited on the germanium substrate (figure 3). Any dislocations are then confined to the lower-bandgap GaInAs junction, which is deposited on top of the GaInP/GaAs dual junctions using optically transparent compositional grades. Crucially, this design maintains the quality of the GaInP/GaAs junctions, which dominate the device's overall power-generation capability.

Calculations show that triple-junction cells built with the conventional mismatch approach will produce 37.9% efficiency at AM0 illumination and no concentration. With the IMM configuration this rises to 39.4% efficiency.

From a practical viewpoint, the IMM design enables a larger portion of the power to be generated from high-quality, lattice-matched material, which improves the chances for this type of cell to approach its maximum theoretical efficiency. Earlier this year, NREL reported an IMM device grown on GaAs with efficiencies of 33.8, 30.6 and 38.9% for standard 1 sun global (AOD), space spectrum (AM0) and concentrated direct spectrum at 81 suns, respectively (J F Geisz *et al.* 2007). For space-based solar cells, 35% efficiency should be possible by turning to four-junction devices.

The IMM cell's superior performance for space and terrestrial applications is partly thanks to the removal of the germanium junction, which has a bandgap that is not optimal for power conversion when used in combination with the GaInP and GaAs bandgaps. At best, this germanium junction generates 270 mV but it typically produces a lower output. By switching to GaInAs, as in the IMM cell, the bandgap of this junction increases to 1.03 eV. Typical voltages of 550–650 mV can be generated, which enables it to be joined to GaInP/GaAs junctions without limiting the device's current.

Flexible solar cells

For space applications the IMM design does not just boost conversion efficiency, but it also delivers a dramatic hike in the specific power (kW/kg), which cuts launch costs and offers the possibility of deploying flexible, high-efficiency solar cells. During processing, epiwafers are attached to a processing handle before the underlying substrate is removed. This handle can be a flexible material, such as a coverglass superstrate, or a tape such as kapton. A flexible cell (figure 4) opens up options for satellite power panel design, including rolled panels that can be unfurled after satellite launch.

To be economically competitive in terrestrial applications, the current IMM device needs to be optimized for high-concentration systems capable of working at higher temperatures and current densities. This requires modifications to some layers to reduce device series resistance and the insertion of tunnel diodes that are compatible with current densities of up to 14 A/cm^2. The handle can be engineered to provide optimal thermal management.

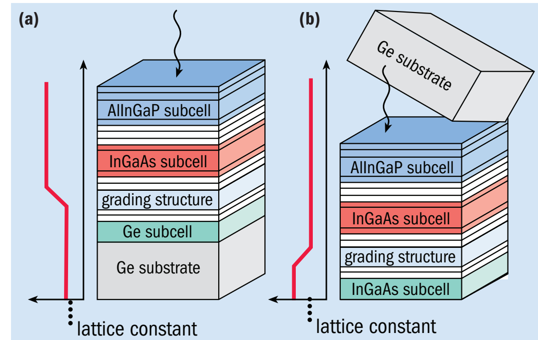


Fig. 3. Conventional GaInP/GaAs/Ge triple-junction solar cells are grown on a germanium substrate and contain grading layers to overcome lattice mismatch **(a)**. The inverted metamorphic approach **(b)** switches the growth order for the three subcells and allows a larger proportion of the device to be lattice matched to germanium. Lattice-matched AlInGaP and InGaAs layers are deposited before a grading structure is added, followed by the InGaAs subcell. The dotted line by the lattice constant chart refers to the germanium lattice constant.

The IMM approach also offers a route to extending the number of cells in the device without the drawbacks seen in other approaches. Improvements in overall efficiency could come through extensions to the high-bandgap range above GaInP and the addition of junctions with bandgaps of less than 1.03 eV. Although the low-bandgap additions will not be lattice mismatched, which will restrict their contribution to overall efficiency, at NREL and Emcore we are investigating the addition of a 0.8 eV junction beneath the 1.03 eV junction.

Despite the progress that we have made with our IMM approach, challenges still remain. These include an extension to the spectral range of the anti-reflection coating to optimize performance. We must also decide the best way to incorporate our IMM device into satellite power panels and terrestrial concentrator systems. Scaling up to high-volume manufacturing is a task in itself. Research must also continue on the other approaches to higher efficiencies, such as the use of tandem cells and novel materials. However, in the near term the IMM approach offers the most promising manufacturing route to surpassing the efficiency of today's GaInP/GaAs/Ge solar cells.

About the authors

Paul Sharps has been at Emcore Photovoltaics since 1998 and is currently director of research and development. He has been involved in photovoltaics R&D since 1985. **Arthur Cornfeld** has been at Emcore Photovoltaics since 2004 where he is a senior staff scientist. He has been involved in inverted metamorphic solar cell development since 2005. **Mark Wanlass** has been at SERI/NREL for 27 years working on the epitaxial growth and development of high-efficiency thermo-photovoltaic and solar-photovoltaic energy converters.

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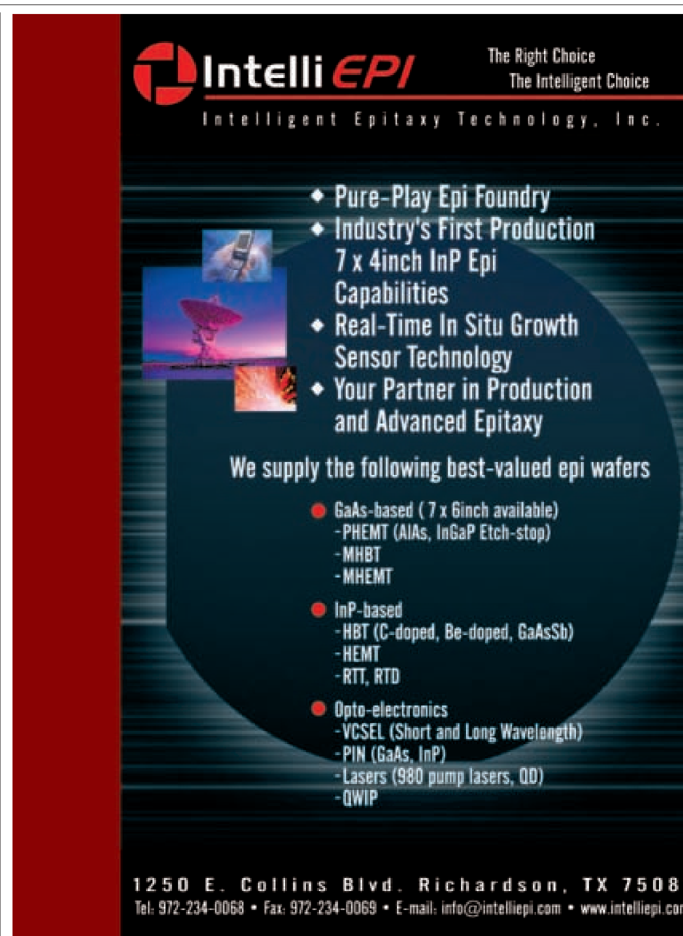

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PROCESS GATES

Spectroscopy exposes trace-water contamination in process gases

A highly sensitive optical technique known as cavity ring-down spectroscopy can reveal minute levels of water contamination in MOCVD process gases such as arsine and can demonstrate the true benefit of point-of-use purification, say **Jun Feng** and **Mark Raynor** from Matheson Tri-Gas and **Yu Chen** from Tiger Optics.

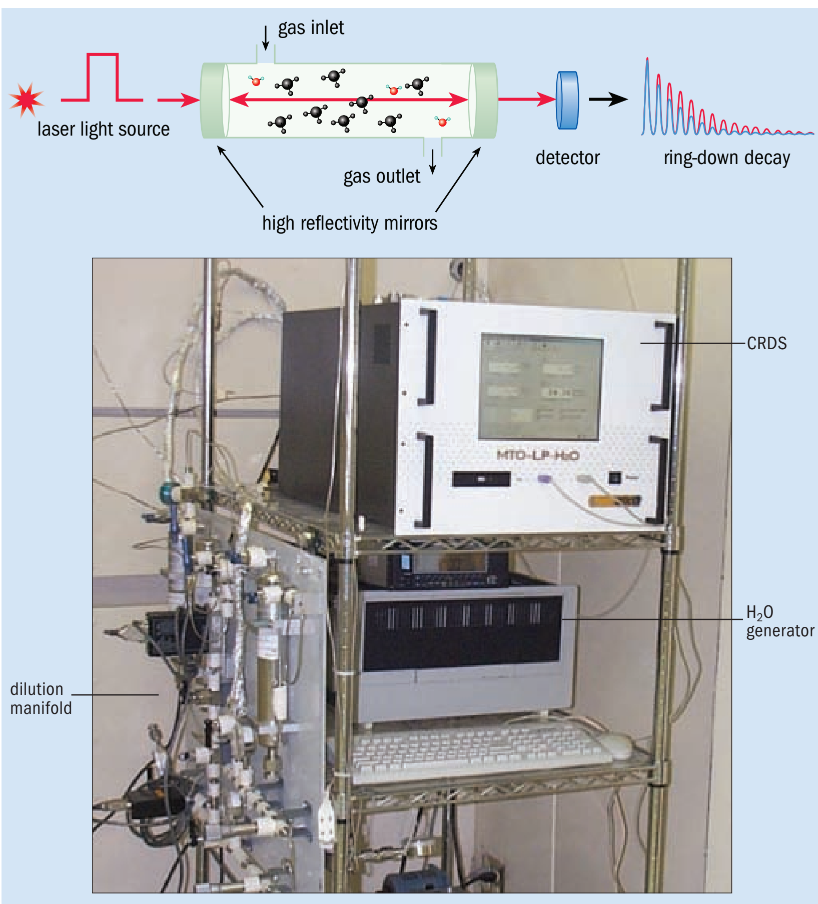

Fig. 1. Cavity ring-down spectroscopy can expose incredibly low levels of water in arsine and phosphine gases. The approach is based on injecting laser light into a cavity and measuring the decay signature of the small proportion of light that escapes when the laser is turned off.

Finding an affordable and reliable means of measuring trace contaminants in the MOCVD process gas arsine poses a considerable challenge. But earlier this year, that is just what Matheson Tri-Gas set out to do when it embarked on a collaboration with Tiger Optics, a pioneer of continuous-wave cavity ring-down spectroscopy (CRDS), which is a new laser-based technique for gas analysis.

By developing techniques to measure and control water contamination in arsine and phosphine, the partnership has found a route to manufacturing better-performing devices. This is because traces of water vapor and oxygen are the enemy of III-V devices, killing photoluminescence and degrading other properties. Oxygen is incorporated into epilayers from various sources, including incomplete purging of atmospheric contaminants from the tool, unwanted methoxide species that can be found in the organometallic precursor, and oxygenated impurities, such as water, which are present in the hydride gas. Even water levels of single-digit parts per billion (ppb) can cause marked damage to AlGaAs films. It is this molecule, rather than oxygen, that is often targeted by process engineers because water's ubiquitous nature makes it the hardest impurity to control.

To date, manufacturers seeking to confirm the purity of their MOCVD process gases, in particular arsine, have had few viable options. Based on their low cost and ease of use, capacitance sensors have commonly been employed for online water monitoring in this application. But these are far from ideal because they can drift and they are insensitive to low ppb levels. So chip manufacturers prefer to qualify their MOCVD process gases by measuring the performance characteristics of a test device, such as photoluminescence, carrier concentration and mobility. This approach may become less popular, however, if highly sensitive laser spectroscopy techniques, such as CRDS, become more widely used to monitor process lines.

Matheson turned to Tiger Optics in the hope that its CRDS gas monitor might lend itself to trace-water detection in MOCVD hydride gases. With its proven stability and wide dynamic range, the CRDS technique uses laser light to provide optical excitation of gases in a stable cavity resonator formed between two highly reflective mirrors (figure 1). The light that is injected into the cavity reflects back and forth many times and builds up in intensity. However, with each reflection a very small fraction of light leaks out to a detector. The so-called ring-down signal is measured when the light source is abruptly turned off. If the light is also absorbed by water in the cavity, it will decrease the decay time for this signal. The water concentration can then be calculated from the ring-down time measurements made on and off the water line.

The CRDS technique has strengths that include a sensitivity to water at levels of single-digit ppb or bet-

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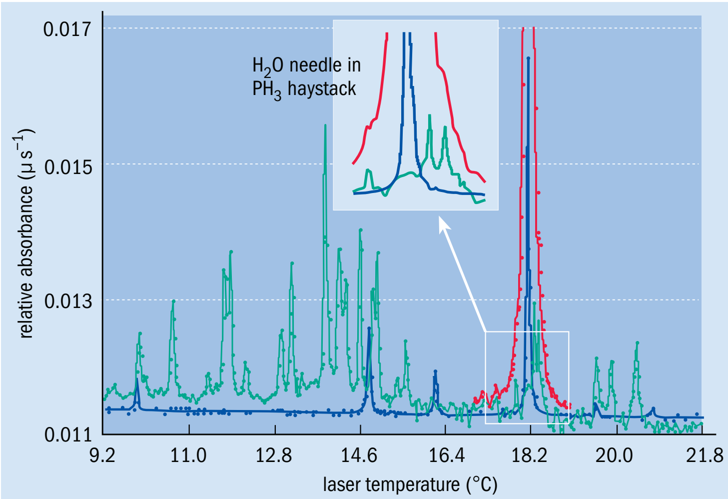
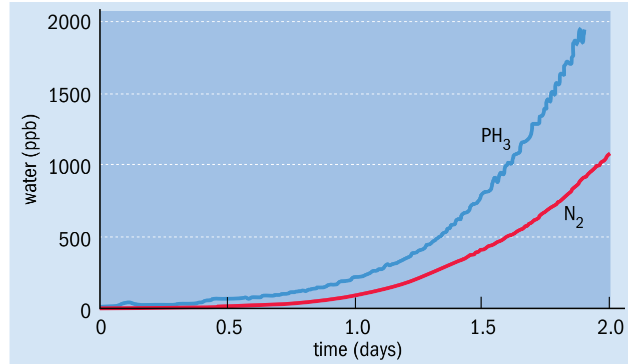




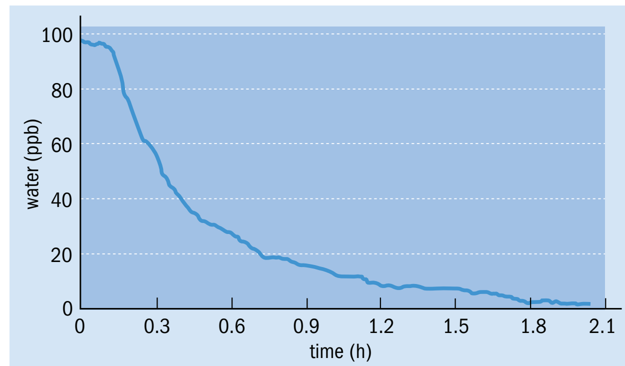


Fig. 2. (above) Water has a very strong absorption peak that is sufficiently removed from those of phosphine to allow detection in the spectral range between 1300 and 1400 nm. The prominence of this peak can be seen in the three different absorption spectra: 120 ppb water in N_2 (blue); dry PH_3 (green); and 1.5 ppm water in PH_3 (red). **Fig. 3.** (above right) Stagnant conditions can lead to a substantial build-up in the concentration of water vapor in both nitrogen and phosphine process gases over the course of a couple of days. **Fig. 4.** (right) Purifying arsine with an in-line Matheson Tri-Gas Nanochem ASX-II purifier at a flow rate of 800 cm^3/min can drive down water levels from 100 ppb to less than 5 ppb within two hours, with a pay-off in higher wafer yield.

ter, due to a measurement technique that creates an effective path-length of typically tens of kilometers. CRDS also has a high degree of selectivity, thanks to the use of a high-resolution laser and the option to conduct measurements at low pressure.

Nevertheless, one of the major challenges of trace-water vapor measurements in hydride gases is identifying a suitable wavelength where water absorbs but the matrix gas (arsine, phosphine, ammonia) doesn't. There is so much interference that the proverbial needle in a haystack comes to mind. Hydride gases have absorbances in many regions of the electromagnetic spectrum, which mask many of the absorption peaks of water at low ppb levels. Therefore, it is extremely difficult to detect the presence of trace water in a hydride gas.

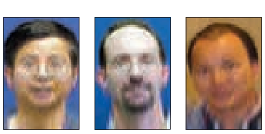
To find a suitable wavelength for water detection in each hydride gas, Tiger Optics characterized and tested 10 custom diode laser sources in the 1.3–1.4 μm spectral range. Figure 2 shows a water absorption line that corresponds to a laser operating at 18.12 ºC. This peak is sufficiently resolved from the PH_3 matrix absorbances to enable the single-digit ppb detection of water.

Matheson had thus unlocked the door to detecting low levels of water contamination and it followed this up by testing the technology's suitability for use in a commercial product. This involved tests for accuracy, linearity, sensitivity, limit of detection and response time on a Tiger Optics' MTO-LP-H_2O CRDS analyzer. Matheson Tri-Gas Ultima grade arsine and phosphine, which were passed through Nanochem ASX-II and PHX purifiers, were used as the diluent gases, and a certified water generator and dilution manifold were used to spike water vapor into the diluent gas at various concentrations (figure 1).

Matheson's tests verified that CRDS is a key technology for monitoring trace water vapor in hydride gas streams and for evaluating the dry-down of process gas lines. Measurements revealed that the concentrations of water-spiked gas measured by CRDS agreed to within 2% with the values intentionally added through the dilution manifold. The instrument can detect water down to single-digit ppb concentrations, is sensitive to changes in water concentration of less than 1 ppb and provides a linear response to the presence of water in the tested range of tens to hundreds of ppb.

The CRDS technique also reveals that even when a system has been thoroughly leak-checked and purged extensively with a dry gas stream, out-gassing of water from metal surfaces can continue for long periods and may build up if the gas flow is stopped for any reason. According to our tests, this contamination can reach levels of a 1000 or more ppb after two days under stagnant conditions (figure 3). Notably, the water levels increase more rapidly in phosphine than in nitrogen.

This high water-level implies that the high-purity process gases, which are mandatory for oxygen-sensitive MOCVD processes, must be used in conjunction with a line purge when hydride gas is not flowing. To minimize any water variations further, point-of-use purification should be employed in the line close to the tool. In tests using a Nanochem ASX-II purifier to remove water from an arsine line, this approach reduced water concentration in arsine to less than 5 ppb within two hours (figure 4). Such a reduction in water contaminants should have a pay-off in improved yields and higher device performance, and it makes an investment in process gas purity highly worthwhile.



About the authors

Jun Feng is a senior scientist at Matheson Tri-Gas, Advanced Technology Center in Longmont, CO, working on trace gas analysis techniques. **Mark Raynor** is R&D director of gas development and analytical technology at Matheson Tri-Gas. **Yu Chen** is a senior scientist working on the development of cavity ring-down spectroscopy at Tiger Optics in Warrington, PA.

Dilute nitrides fire up red LEDs

Red, orange and yellow LEDs based on a dilute nitride promise higher power and reduced temperature sensitivity, say **Vladimir Odnoblyudov** and **Neil Senturia** from UCSD spin-off Quanlight.

The race to enter the general illumination market has fuelled a dramatic increase in blue and white LED performance. In sharp contrast, red, amber and yellow emitters used in applications such as large color screens, traffic lights and architectural lighting have shown slow improvement.

However, at Quanlight, a start-up based in San Diego, California, we have developed a radically different approach to chip manufacture that can overcome these obstacles and deliver a dramatic hike in LED performance. By switching from the conventional material, AlGaInP, to the novel dilute nitride, InGaPN, it is possible to produce higher-brightness LEDs that are also less sensitive to temperature changes. This will aid applications such as large color displays, which require stable red emission to produce high-quality images.

The roots of our key technology are found in the research carried out at the University of California, San Diego (UCSD). The UCSD team, headed by Charles Tu, had already made some progress with InGaPN before it spawned Quanlight. This material, which contains about 1% nitrogen, is seen as a promising candidate for red emitters because it combines with GaP to produce a heterostructure with a larger band-offset than AlInGaP-based LEDs. Calculations had shown that it can produce brighter LEDs, thanks to greater current-handling capabilities. What's more, InGaPN produced some encouraging initial results, even though the material's system was relatively immature, poorly understood and challenging to grow.

The researchers at UCSD managed to build a working prototype LED that delivered several predicted improvements in device performance, including a reduced shift in emission wavelength with temperature. However, although these facilities were sufficient for the initial study, contaminants in the material produced by the MBE tool limited LED brightness, so further development required a switch to a commercial facility employing an MOCVD platform.

Commercializing academic research

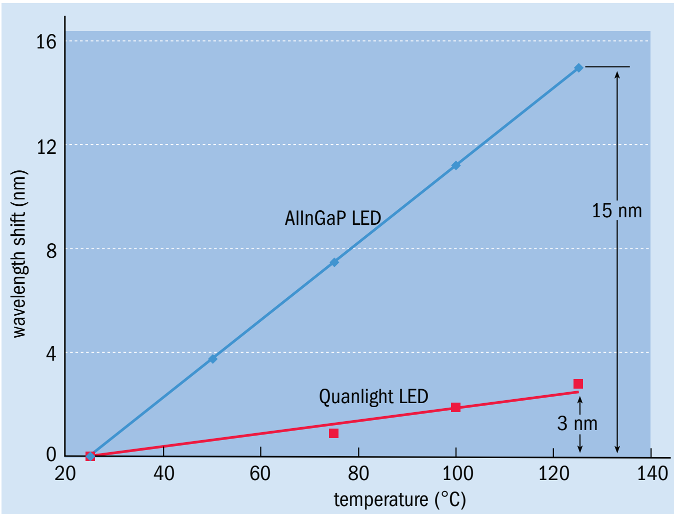
To make this transition we founded Quanlight. After assembling a development team and raising $4 million through two funding rounds from private investors, our company started to develop epiwafers in August 2006 through the foundry service Bandwidth Semiconductor. Excellent progress has been made to date and we are on track to manufacture and sell red LED epiwafers to chipmakers by the end of this year. We then plan to extend our range of epiwafer LEDs to cover orange and yellow wavelengths between 585 and 660 nm. We are also open to licensing our process, or forming a partnership with another company.

LIGHTHOUSE TECHNOLOGIES

Large outdoor LED-based screens offer a potential market for Quanlight's red-emitting devices.

The three key advantages that InGaPN LEDs have over their AlGaInP cousins are lower manufacturing costs, greater color temperature stability and brighter emission at high current densities.

The lower production costs result from a simpler manufacturing process, which is carried out with essentially the same manufacturing tools that are used to make conventional red LEDs.



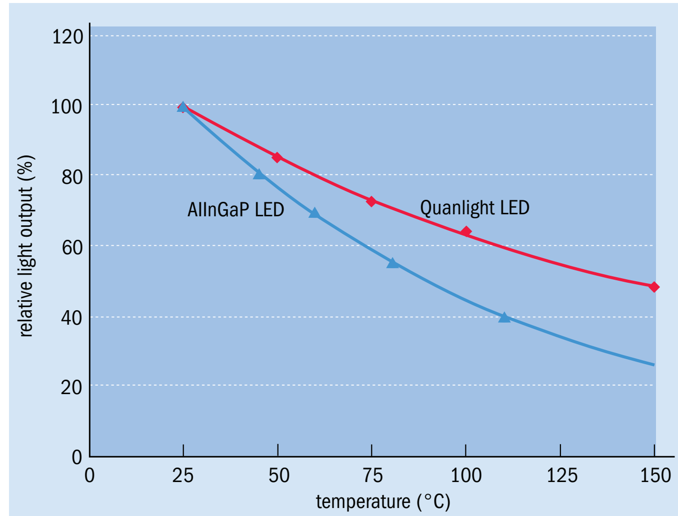


Fig. 1. (left) Quanlight's 635 nm LEDs are much more stable over temperature than conventional designs. **Fig. 2.** (right) Increased carrier confinement cuts the reduction in the output power of these 635 nm emitters at higher temperatures. The data for the AlGaInP LED comes from a leading LED manufacturer.

Traditional AlInGaP-based emitters are grown on GaAs substrates. To boost output the epilayer is often transferred to a transparent GaP platform or a mirrored carrier. Our process eliminates this epilayer removal and bonding process, and it involves dilute nitride growth directly onto GaP. This cuts the number of process steps that are needed and also reduces the bill of materials.

There is a small lattice mismatch between the GaP substrate and the InGaPN material in our device. It means that the epilayers are pseudomorphically strained, but this allows for enough quantum wells to be incorporated within the LED for high-power output. This produces a structure with a quality akin to AlInGaP grown on GaAs, but with the caveat that there are no commercially available substrates grown by the vertical-gradient freeze (VGF) method – an approach that produces boules with very low defect densities.

Improving GaP quality

We are currently using 3 inch substrates grown by the liquid-encapsulated Czochralski technique, which should yield LEDs that are commercially competitive in terms of brightness and reliability. However, we are also working with PVA TePla to develop GaP boules grown by the VGF method. We expect this venture to be successful, because the VGF approach is well understood and it is already used to produce other forms of substrate. Although we cannot predict the precise benefits of a transfer to VGF material, we expect that it will improve the lifetime and output of our InGaPN LEDs. We have already started to conduct initial tests of LEDs grown on this platform and we expect to have preliminary results very shortly.

InGaNP has intrinsic properties that ensure the LED's peak wavelength shift with temperature is smaller than that of AlInGaP-based devices. This makes them more attractive for incorporation into color displays, as they require stable light sources.

These improvements in the color stability of our red emitters were seen in the lab at UCSD using MBE-grown material, but they have also been replicated with LEDs produced by MOCVD. The results of this test, which are shown in figure 1, were obtained by externally heating LEDs from 25 to 125 °C and recording the peak emission wavelength at various temperatures. Our LED's peak emission wavelength varied by just 3 nm over this temperature range, which is one-fifth of the shift shown for an AlGaInP chip produced by a leading red LED manufacturer.

The third advantage of our InGaPN LEDs – brighter emission at higher temperatures – results from a superior band structure that improves carrier confinement in the active region. The InGaPN LEDs combine with GaP barriers to produce a band offset that is two to three times as great as AlGaInP quantum wells and AlGaInP barriers.

The stronger performance at elevated temperatures has been verified by a test that compared Quanlight's LED output with that of a conventional red emitter at external temperatures between 25 and 150 °C (figure 2).

"The performance advantages of our products will provide a great match for applications requiring high power or a stable color output."


BMW

Conventional red LEDs are already used in car brake lights, but a switch to GaInPN devices could boost brightness or reduce the number of devices required.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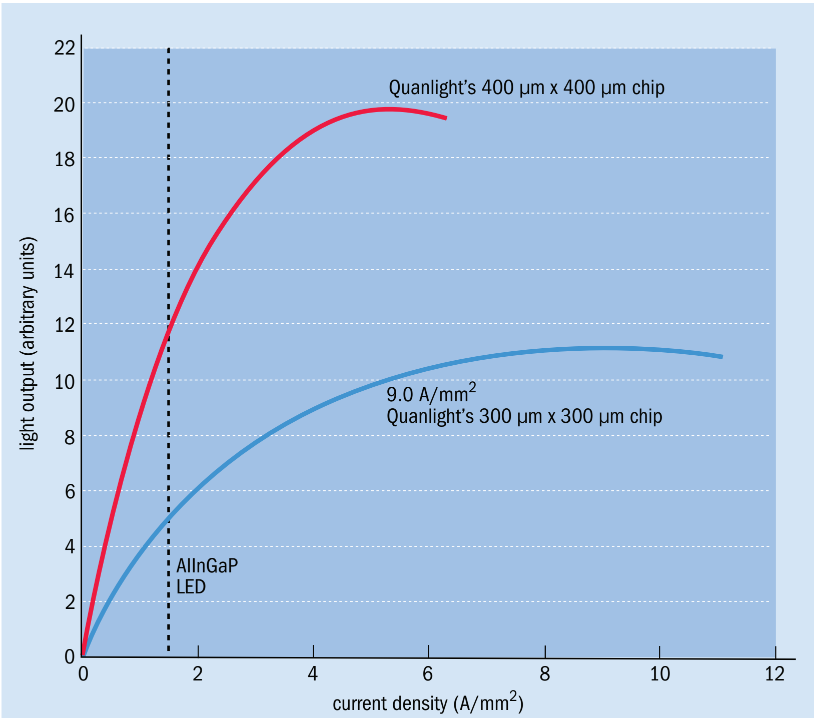


Fig. 3. Quanlight's LEDs withstood very high current densities. Unlike conventional LEDs, which deliver a peak brightness below 2 A/mm^2, these InGaNP emitters produce brightest emission at 9 A/mm^2 for 300 × 300 µm chips, and 5.5 A/mm^2 for 400 × 400 µm devices, measured on wafer.

At the top end of this range the Quanlight device emitted a power equal to 48% of its output at 25 °C, but the reference LED delivered only 25%. When our device development is completed, we expect our material to produce devices with the same brightness as AlInGaP chips at room temperature and a near two-fold increase at 150 °C. The improved performance at higher temperatures will make these InGaNP LEDs more attractive for use in red and yellow traffic lights, which have minimum flux standards in the US at 25 and 74 °C.

Improved carrier confinement in the active region also aids current handling, and values of up to 9 A/mm^2 have been produced in developmental tests (figure 3). These measurements were performed on-wafer, rather than from individually diced chips, and it is reasonable to expect that the operational limits of production versions will be lower. Nevertheless, we can expect our InGaPN LEDs to deliver saturation current densities that are two to three times as great as those of their AlInGaP equivalents.

Higher current-handling capabilities will help LED package and application engineers. Switching from conventional chips to InGaPN devices enables the use of smaller components with greater drive currents, which combine to produce an equivalent amount of light, or the deployment of fewer large LEDs in a high-power array. Both approaches cut the LED footprint and reduce overall costs. Either fewer LEDs are deployed or an equivalent number are used that are cheaper due to their smaller size.

We are now testing the reliability of our red emitters. This will begin with 5000 h tests on development devices. We are also planning to compare the performance of LEDs grown on LEC and VGF substrates.

Preparing for the launch

We have already transferred our device growth to an MOCVD platform and are optimizing the epilayer design. Improvements are being seen in the light output from our devices. This benefit is not at the expense of color or thermal stability, which are related to the intrinsic properties of our dilute nitride.

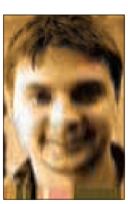
Although many people in our community may regard dilute nitride as an awkward material that has not fulfilled its promise in the telecoms sector, we have good reason to believe that our devices will be a commercial success. The high indium concentration that is required in the epilayers of dilute nitride telecom lasers increases the strain in the material and degrades lifetime and reliability. However, red, orange and yellow InGaPN LEDs will not suffer from this because they contain far less indium.

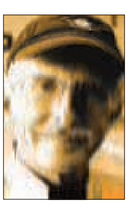
We will also benefit from our extensive experience of producing dilute nitrides, which will give us a strong competitive edge over other companies that might start developing products using this material. Although our epiwafers are grown at Bandwidth Semiconductor, process knowledge and intellectual property resides with our technical team, which is on site for all development growth sessions. This team drives the material development.

When we launch our portfolio of powerful red, amber and yellow epiwafer LEDs covering 585 to 660 nm, we will be in a position to target a $500 million market with a rapidly growing high-brightness sector. The performance advantages of our products will then provide a great match for applications requiring high power or a stable color output. Back-lighting units for LCD televisions, light engines for projectors, outdoor displays and other red-green-blue color-mixing applications will benefit from the smaller temperature-induced wavelength shifts, which will translate into simpler control mechanisms. In addition, transportation, hazard, theatrical and architectural lighting will benefit substantially from our enhanced color stability and intensity output.

Applications such as traffic lights and automotive brake lights all use AlInGaP LEDs to reduce energy use and costs. For these types of high-power application, InGaPN LEDs will enable lamp designers to make further cost cuts by using smaller chips driven at higher currents, or fewer large LEDs in an array. As the Quanlight LED operates efficiently at higher temperatures, a more compact or heat-intensive enclosure may be used.

The only area where the advantages of InGaPN LEDs are less significant is low-power applications with less rigid output specifications, such as Christmas tree lights. This is the only market that we will not be targeting aggressively, as low-power AlInGaP chips can already be supplied cheaply.





About the authors
Vladimir Odnoblyudov is Quanlight's CTO. He has a PhD from the University of California, San Diego, which focused on the development of InGaPN LEDs. He also has five years of experience developing 1.3 µm dilute nitride lasers at the Ioffe Physico-Technical Institute in St Petersburg. **Neil Senturia** is the company's CEO. He is a technology entrepreneur with 25 years of experience in founding and managing start-ups.

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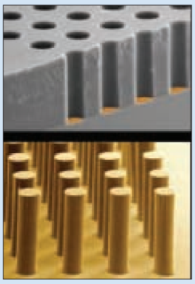

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NON-POLAR LASERS

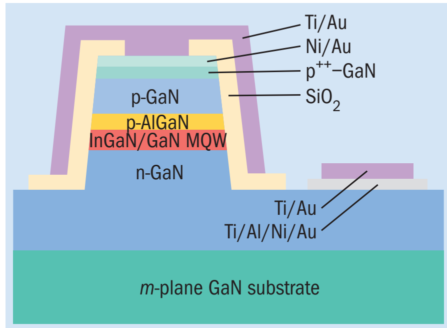
Al-free cladding eases laser production

Researchers from the University of California, Santa Barbara (UCSB), say that they have produced the first continuous-wave emission from a non-polar GaN-based laser that does not contain AlGaN cladding layers.

The switch from an AlGaN cladding to a GaN cladding and a thicker active region could improve the manufacturing process for 405 nm laser diodes employed in high-density DVD players, according to Robert Farrell, a member of the UCSB team that includes Shuji Nakamura, James Speck and Steven DenBaars.

"Aluminum-containing waveguide cladding layers in conventional InGaN/GaN laser diodes introduce problems such as cracking due to tensile strain, higher voltage operation, reduced yield and reduced reactor stability from parasitic reactions involving aluminum-containing precursors," explained Farrell.

Turning to AlGaN-cladding-free non-polar designs can alleviate many of these problems and promises greater laser efficiencies and lifetimes thanks to the switch away from polar material.



UCSB's laser diodes are built on Mitsubishi's HVPE-grown *m*-plane substrates and contain a five period undoped InGaN/GaN multiple quantum well active region with 8 nm-thick InGaN quantum wells.

Earlier this year the UCSB team reported pulsed operation from AlGaN-cladding-free non-polar lasers. "These initial devices were 15 µm wide broad-area laser diodes with high threshold currents of around 500 mA and voltages of 6.7 V," said Farrell.

"By scaling our devices to a 1.9 µm ridge geometry and improving the electrical properties, we achieved lower threshold currents and voltages of 77 mA and 5.6 V." These lower values reduce heat generation and ultimately lead to continuous operation.

On-wafer testing of UCSB's uncoated diodes produced a peak emission of 403 nm, a maximum output power of over 25 mW and a threshold current density of 6.8 kA/cm^2. When the laser was driven at 175 mA its output fell from 3.4 to 1.0 mW over 15 hours.

Farrell says that the team is starting to package its devices and is aiming to develop diodes with higher output powers, longer lifetimes and lower threshold current densities. The researchers are also aiming to extend their laser's emission to blue and green wavelengths.

Journal reference
R M Farrell *et al.* 2007 *Jap. J. Appl. Phys.* **46** L761.

TUNABLE LASERS

Bookham boosts output

Bookham's engineers claim that they have broken the output power record for full-band tunable monolithic lasers.

"Our results show that we can match the 20 dBm typical of a good high-power [fixed wavelength] DFB laser across the whole tuning range," said Andrew Ward, a senior scientist at Bookham.

According to him, the monolithic aspect of Bookham's digital supermode distributed Bragg reflector lasers – which are designed for optical networks – is important because it enables scalable, low-cost manufacture. In comparison, external-cavity tunable lasers require multiple optical elements and are not scalable from the wafer level.

The team's latest laser, which delivers a 4 dB improvement in gain over the company's previous best result when coupled into an optical fiber, produces a higher output thanks to lengthening the semiconductor optical amplifier region from 350 to 425 µm.

The width at the facet of the flared ridge waveguide was also adjusted from 3.2 to 4.5 µm, which altered the far-field pattern and led to a slight reduction in fiber coupling.

Ward says that the team's latest laser should deliver the same levels of reliability as its commercial tunable lasers thanks to the use of a common fabrication process. The company is now integrating these improvements into its tunable products.

Journal reference
L Ponnampalan *et al.* 2007 *Electron. Lett.* **43** 872.

Research in brief...

...Hybrid growth improves AlN

Asif Khan's group from the University of South Carolina, Columbia, has developed a new growth tool for producing AlN templates that are used to make ultraviolet LEDs.

The hybrid tool, which combines the benefits of HVPE and MOCVD, can produce high-quality 20 µm-thick AlN layers on sapphire in just a few hours. The templates are a better match for ultraviolet LEDs than sapphire thanks to an eight-fold improvement in thermal conductivity.

The researchers, who produced their templates using a metal-organic hydride vapor phase epitaxy reactor, started by growing a thin AlN layer by MOCVD. They inserted grooves into this layer using photolithography and etching, before adding an AlN layer by lateral overgrowth.

The AlN film had a root-mean-square roughness of 0.2 nm and has already been used as the platform for making 285 nm LEDs that have a high-quality AlGaN active region according to cathodoluminescence imaging.

Journal reference
Q Fareed *et al.* 2007 *Jap. J. Appl. Phys.* **46** L752.

...Japan ups amplifier output

Engineers from Japan's R&D Association for Future Electron Devices say that they have produced the world's most powerful solid-state amplifiers operating at 5 GHz.

The team's GaN-based FET amplifier, which could be used in mobile and satellite communication systems operating at this frequency, produced 208 W in continuous mode and 232 W under pulsed operation.

This beats the team's previous record for continuous output of 170 W, which was reported earlier this year, thanks to a new design that incorporates Wilkinson couplers to reduce power combining losses.

Journal reference
Y Okamoto *et al.* 2007 *Electron. Lett.* **43** 927.