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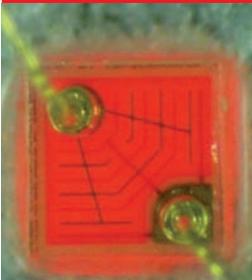
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Ring lasers, GaN VCSELs and dilute nitrides

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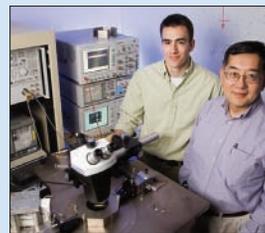
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Speeding into the future

Milton Feng's research team at the University of Illinois at Urbana Champaign has been developing high-speed InP transistors since 1995. **p19**

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Main cover image: Fabricated using both InP and GaAs substrates via a wafer-bonding step, these microring lasers each emit at a slightly different wavelength and could dramatically shrink the size of an optical transceiver. See p10. Credit: WAPITI.

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Europe joins the dots



The compound semiconductor industry is a genuinely global one, but in volume manufacturing there exists a glaringly obvious disparity. Though home to the fabrication facilities of a handful of key industry players – wafer foundry IQE, giant LED maker Osram Opto Semiconductors and 3S Photonics spring to mind – in terms of sheer production output, Europe is dwarfed by competitors in the Far East and North America.

However, as our articles on silicon-based lasers (p21) and nitride VCSELs (p24) show, at the research and development stage it is a different story. The European Commission (EC) dishes out plenty of funding for basic and applied research via its Framework Programmes, the major economic centers support their own research priorities, and in Belgium's independent Interuniversity Microelectronics Center the region has a world-leading resource for semiconductor development.

It's probably too late to catch up in some areas, but there are opportunities for Europe to leapfrog the rest of the world.

“Europe could become much stronger in the photonics field”

For example, a new roadmap compiled by the Merging Optics and Nanotechnologies (MONA) project group – the product of an EC project – is urging the commission to use forward thinking when it comes to funding photonics-related projects under its 7th Framework Programme.

The authors of the MONA roadmap are convinced that, with adequate EC funding, Europe could become much stronger in the photonics field. They are calling for various technology areas – from organic LEDs to carbon nanotubes – to be backed, with quantum-dot structures in particular receiving a lot of attention.

Because of their atom-like properties, these structures have huge potential to improve compound semiconductor devices, for both photonics and other applications. The problem is that controlling their growth reliably enough for volume production and commercial application is a real headache at the moment.

If that problem can be cracked, the spin-off benefits would be enormous – more efficient solar cells; low-cost, low-energy lighting; and improved imaging systems are all highlighted in the roadmap. The influential Photonics 21 consortium is now set to take the MONA findings and begin setting the research agenda. The projects funded will hopefully sow the seeds of Europe's future compound semiconductor makers.

Michael Hatcher *Editor*

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PROCESS EQUIPMENT

Veeco hikes epitaxy research budget

Equipment supplier Veeco Instruments is to invest heavily in its epitaxy division as part of a wider plan to boost future sales.

Noting rapid growth in bookings for MBE and MOCVD equipment in 2007, CEO John Peeler says that the strong market pull for high-brightness LEDs and high-efficiency solar cells is providing "an exceptional multi-year growth opportunity".

To support it, Peeler says that Veeco would hike its research and development spending in the epitaxy field by 40% in 2008.

Although Veeco still lags behind Germany's Aixtron as the dominant global supplier of MOCVD equipment, Peeler believes that his company has made inroads into Aixtron's market share recently. Based on orders placed, Peeler says that Veeco increased its share of the MOCVD process equipment market from 20% to 35% during the year. "We have penetrated several top-tier accounts where [Aixtron] holds the installed base," observed the CEO.

Although Veeco has been struggling overall – hit by difficulties in the data storage sector, the wider company posted a net loss of \$9.4 million on revenue of \$106.8 million in the final quarter of 2007 – its epitaxy tools have been selling well and profitably.



New applications of LEDs, such as in the daytime running lamps of the new range of GM-Opel Insignia cars shown above, and in concentrator photovoltaics, are behind a boom in MOCVD reactor sales. Veeco Instruments is now looking to increase its investment in epitaxy research and development significantly.

In 2007, combined sales of MOCVD and MBE equipment were \$116 million, up 23% on the 2006 figure of \$94 million. This year promises to be even stronger, since Veeco registered a 37% increase in orders for MOCVD and MBE tools, with \$164 million worth of bookings.

This growth means that epitaxy equipment for LED, III-V solar cell and RFIC manufacturing is now the biggest of Veeco's three business segments, accounting for 36% of total company bookings in 2007.

Demand from solar cell makers is now fueling a significant proportion of that growth. Veeco received \$20 million worth of bookings in 2007 for its MOCVD tool used to make multijunction cells and has already shipped half of those orders.

According to Peeler, Veeco has a technological advantage over its competitors in the III-V solar sector, because its E475 As/P TurboDisc tool provides more than 50% more wafer throughput than its competitors' systems.

CONVERGENCE

Compounds appear on the silicon roadmap

The International Technology Roadmap for Semiconductors (ITRS) could soon feature III-V materials, with one of its subcommittees now listing III-V channel transistors under official consideration.

The Emerging Materials Committee (EMC) chaired by Mayank Bulsara of Atlas Technology has listed incorporation of III-Vs as one of the ways to make faster transistors, by enhancing the mobility of charge carriers in such devices. Other approaches include development of carbon nanotubes, strained silicon and germanium channels.

According to the EMC, modern transistor technology has "essentially reached the limit of the fundamental electronic capabilities of silicon", with the inclusion of higher-mobility materials now considered to be of paramount importance for CMOS applications.

The EMC is part of the ITRS Starting Materials Committee, the job of which it is

to come up with real targets for wafer sizes, defect densities and strain for future CMOS processing. It cautioned that, while these materials show significant promise, there are also some major challenges associated with their implementation. "Any new material destined to replace or enhance CMOS integrated circuits must ultimately integrate well with silicon," it said.

According to the committee notes, the most promising materials have lattice constants significantly different from silicon's, meaning that the engineering of epitaxial films combining the two material systems is a major technical hurdle. Another challenge is that the density of states for many high-mobility materials is low, which limits the amount of current that they can support.

"Improving the ability to dope the source-drain regions of such materials will be key to reducing parasitic resistances external to the channel," added the EMC. High-k gate dielectrics, which already feature in the latest generation of transistors from Intel, will also be needed to minimize gate leakage and further gate length scaling for III-V

compound channel materials.

While the ITRS waits for these problems to be solved, researchers in Europe are embarking on a multinational project to attempt just that. Under the new €9.1 million (\$13.4 million) Duallogic program, a team that includes collaborators from as far afield as Greece and Scotland will attempt to produce the first dual-channel CMOS technology featuring III-V compounds in the n-channel and germanium in the p-channel.

\$8.5 million of the funding comes direct from the European Commission, with the remainder provided by the project partners. Asen Asenov, the Duallogic project manager at the University of Glasgow, says that the European effort will have an advantage over a similar project taking place at the Semiconductor Research Corporation in the US because it will be able to exploit IMEC's 200 mm pilot line in Belgium at the proof-of-concept stage.

MOCVD tool specialist Aixtron, Philips spin-off NXP Semiconductors and IBM's Zurich operation are Duallogic partners.

FOUNDRIES

Optical step halves MMIC costs

Borrowing a technique used widely in silicon CMOS fabs, TriQuint is now offering a volume GaAs process that halves the cost of millimeter-wave PHEMT production for commercial applications such as automotive radar and satellite communications.

The TQP13-N process, which has been offered in a limited form for the past few months but has now progressed to a full-volume roll-out, produces GaAs PHEMTs with a 130 nm gate on a 6 inch wafer line.

Crucially, TriQuint uses standard optical lithography to define the 130 nm PHEMT gate region – a process step that until now has always demanded the use of electron-beam lithography.

Mike Peters, director of marketing for TriQuint's commercial foundry business in Hillsboro, Oregon, says that because standard I-line lithography equipment and photoresists are used, there is a direct cost saving of between 40 and 50% compared with the previous electron-beam process.

The key to fabricating the tiny gate features that are able to produce frequencies of up to 95 GHz is a concept known as "sidewall spacers", something that has been widely applied in CMOS processing to shrink gate sizes. In TriQuint's process the gate lengths initially defined using I-line equipment are actually quite large.

However, after a dielectric is deposited onto the wafer and then removed selectively using a plasma etch system, dielectric spacers are left along the sidewall of the original gate opening, effectively yielding a much smaller feature size.

Once the 130 nm gate opening has been defined, a gate-reinforcement metallization step forms the upper portion of the gate, producing a T-shaped gate contact that is very short and has a very low resistance.

Having developed these steps to a point

where the overall process is completely stable and mature enough for high-volume use, TriQuint is already seeing a strong pull from lead customers who are keen to exploit the step-change in manufacturing costs.

Peters told *Compound Semiconductor* that the process was ideally suited to low-noise, medium-power applications in the millimeter-wave spectrum, for example automotive radar and receiver components used in satellite communications.

With customers and TriQuint's own business groups now able to manufacture these kinds of component at a much lower cost, Peters is expecting to see lots of commercial products containing the PHEMT die appear in the second half of 2008.

However, for high-power millimeter-wave applications – required by the military – the more expensive electron-beam process remains the best option, Peters explains.

"The optical process will not meet all of the needs for millimeter-wave functions," he said. "It is optimized for low-noise, lower-power, higher-volume applications."

The marketing director adds that customer interest is already very strong and that this market pull was a key factor in TriQuint's full release of the process.

Adaptive cruise control (ACC) for cars looks likely to be one of the biggest volume drivers for TriQuint. Figures from the market research firm Gartner suggest that this technology has only a 1% penetration at the moment. By 2015, however, it expects that more than half of the approximately 50 million new cars manufactured each year will use ACC or some other form of auto radar.

Receiver components for satellite television systems fitted to larger, luxury vehicles could also be a major driver for the PHEMT process, says market analyst Sandeep Kar from Frost & Sullivan.

FINANCIAL ROUND-UP

Anadigics invests as fab hits capacity limits

Anadigics is rapidly adding more equipment at its wafer fabrication facility in New Jersey after demand for its RF products began to outstrip capacity in the closing quarter of 2007.

The RFIC manufacturer is also qualifying external foundries to meet that demand, while its construction of a new fab in China continues and is expected to be completed by around the end of 2008.

Anadigics' focus on the various broadband wireless protocols now looks to have paid off, with the company registering its first annual net profit since 2000. In fiscal 2007 it posted a net profit of \$6 million, building on the fast-growing 3G and WiMAX protocols as sales rose 40% over 2006 to reach \$230.6 million.

In contrast, RF Micro Devices had a disappointing end to 2007, recording sales of \$268 million in the fourth quarter and a net loss of \$15 million – its first quarterly loss in more than a year. A slow ramp-up of a new low-cost product and sluggish sales to Chinese customers were behind the dip, which will continue for the first quarter of 2008.

With RFMD's stock price sinking, management took the opportunity to initiate a share-buyback program valued at \$150 million. The availability of extra wafer capacity at the former Filtronic site in the UK should help RFMD to cut the cost of GaAs PHEMT switch manufacturing from now on.

Skyworks Solutions posted a quarterly sales revenue of \$210.5 million, equivalent to an 11% sequential increase, and a net profit of \$19.1 million as it closed out 2007. CEO David Aldrich says that the Woburn, Massachusetts, firm is now looking towards a set of novel applications for its RFICs, including femtocells, where it is working with the Korean electronics giant Samsung.

There is also a possibility of Skyworks products featuring in futuristic "energy-management" applications, where they could transmit readings of customer utility meters to their respective service providers. Aldrich says that service providers want to deploy economic RF technology that allows them to read meters remotely and in real time. He added that Skyworks has developed such a technology and has won a deal to supply a custom solution to "one of the largest energy providers in the US".

Meanwhile, fabless supplier Hittite Microwave, based in Massachusetts, registered \$156.4 million in sales revenue for 2007, up 20% after a strong finish to the year.



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...Infineon RF CMOS switch

Germany's Infineon Technologies says that it is now shipping RF switches manufactured using a CMOS process that offer equivalent performance to GaAs-based switches.

...Nitronex develops amp

GaN-on-silicon RFIC maker Nitronex has

partnered with Prescient Wireless to develop a broadband 20W Doherty power amplifier for WiMAX applications.

...Epiworks certified

Epiwafer vendor Epiworks has received ISO 9001:2000 certification from Quality System Registrars.

WIDE-BANDGAP ELECTRONICS

Fujitsu fires up GaN base stations

Fujitsu looks set to confirm its RF GaN pioneer status by selling WiMAX base stations based on wide-bandgap transistors, beginning in the second quarter of this year.

The BroadOne WX300 outdoor macrocell base station uses the Japanese corporation's GaN HEMTs to provide wide-area transmission over a range of several kilometers.

The base station offers world-class efficiency and performance, Fujitsu says, and is the first of a wider series of BroadOne WiMAX transmitters due to be marketed.

"By combining energy efficiency with the world's smallest base-station enclosure, Fujitsu has significantly reduced the costs associated with installing and operating base stations," the company claims. The compact unit weighs only 20kg and occupies a volume of 20l, making it tiny by comparison with conventional base stations.

The WX300 will operate in the 2.3 and 2.5GHz frequency bands used by the emerging WiMAX standard, using two high-power output transceivers, each containing three GaN HEMTs.

After the WX300, the next release in the series will be a microcell base station, with a several-hundred meter range designed for areas with poor coverage. Then, an ultra-compact picocell for indoor networks will complete the product family's current lineup, although Fujitsu also has plans for the technology that reach beyond WiMAX.

A spokesman for Fujitsu told *Compound Semiconductor* that the company intends to sell 30,000 units of mobile WiMAX products over five years, beginning in 2008. The company also confirmed that GaN HEMT-based transceivers will be used in base-station products other than the WX300.

"The BroadOne brand name covers an integrated series of base stations and other products for the Long Term Evolution (LTE)



Fujitsu inside: The networking giant will use transceivers based on GaN HEMTs in WiMAX and Long Term Evolution cellular base stations.

project under which next-generation mobile phone systems will be developed for the rapidly emerging wireless broadband market," Fujitsu said.

This vision is being supported by roll-out plans that include Fujitsu partnering with Airspan Networks for the sale of the WX300, which Airspan will call MicroMAXe.

That deal comes on top of the existing strong industry reputation that is seeing Fujitsu partner with Japanese telecoms firms in developing LTE base stations. It reportedly demonstrated prototype base stations with NTT DoCoMo last year, following initial development with KDDI.

Early demand for WiMAX products is coming from Korea, the US and Japan, Fujitsu says, with Europe and other Asia-Pacific countries soon to follow.

Although Japan is the only country to have begun field trials for LTE, Fujitsu expects that tier-one network operators in the US will soon follow suit.

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...II-VI sees SiC wafers ramp

Materials company II-VI Incorporated has celebrated record shipments of semi-insulating SiC substrates for RF applications.

...Bad year for Ribier

MBE equipment and components vendor Ribier posted a loss of more than €9 million as sales declined 15% annually to only

€17 million in 2007. The French company has launched an extensive cost-cutting program.

...IQE on track

Epiwafer foundry IQE expects to post total sales of \$100 million for 2007, an increase of some 65% on 2006. Growing revenue from sales of wafers for wireless applications is the main reason behind the boom.

SOLID-STATE LIGHTING

Use of LED streetlights needs incentives

Streetlights that are based on existing high-brightness LEDs will require government or utility incentives if they are to become adopted on a much wider scale to cut energy consumption in the US.

A study for the US Department of Energy (DOE) by energy company Pacific Gas and Electric (PG&E) found that, while the quality of light produced by solid-state luminaires was at least as good as that from regular high-pressure sodium lamps, their much higher upfront cost means that the energy savings offered could take decades to translate into genuine financial savings.

The assessment took place on public roads in Oakland, California, where 15 LED luminaires rated at 78 W replaced standard 121 W high-pressure sodium lamps.

In her report, project manager Mary Bryan from PG&E found that although the LEDs delivered a lower average brightness to the street, this did not compromise the quality of illumination. In fact, the LED luminaires improved overall uniformity compared with the sodium lamps, which tend to create over-illuminated "hot spots".

"The LED luminaires used in this study reduced energy [consumption] by over one-third compared with the previous luminaires," wrote Bryan, adding that in PG&E's service territory some 860 GWh of electricity is used annually for road lighting. If adopted in half of the road-lighting luminaires in PG&E's area, LEDs would slash an estimated 150 GWh from this figure.

Interestingly, the sodium lamps used in the study actually had a higher efficacy than the LED-based luminaires (60 lm/W com-



LED streetlights are up to the job and do cut energy bills significantly, but their high upfront cost means that at current prices any economic payback may take decades. Improving luminous efficacy and subsidizing their use are two ways to combat this.

pared with 57.5 lm/W). However, because of the better uniformity of the LED illumination, sufficient performance could be achieved with these luminaires running at a reduced power and total lumen output.

The downside, economically speaking, is that the 36% reduction in electricity consumption offered by the switch to LED lamps remains massively outweighed by their cost. "Despite the electrical savings, the present upfront cost of LED street lighting luminaires may be a barrier to their current adoption," Bryan said.

In various lamp-replacement scenarios described in the report, the payback period for LED lamps – at their current cost – varied from nearly 12 years to more than 25.

But that could soon change. As acknowledged in the DOE report, the rapid improvement in LED efficacy (estimated at 35% each year) and the decreasing cost of

the technology (estimated to drop an average of 20% annually) should dramatically shrink those payback periods before long.

For brand-new streetlights, where there are additional construction costs to take into account, each LED luminaire would need to cost only \$250 to meet an ideal payback period of two years.

But for the more likely retrofit replacement scenario, the aims are tougher. "It would be difficult for the LED luminaire to meet a two-year simple payback period and the price would have to be below \$100 to meet a five-year simple payback," the report said.

The conclusion is clear. Currently, LED lamps for road lighting are too expensive to make economic sense in the US. As the report puts it, "LED luminaires show economics that are still at the outskirts of acceptability for the majority of commercial customers."

There are two ways to change that scenario. The first is technological, through improving LED efficacy and by cutting chip costs through increased manufacturing volumes. The second is through subsidies from utilities or governments.

"These utility incentive programs should require minimum performance standards for qualifying products in order to ensure long-term energy savings," concluded the DOE report.

● Austin, Texas, has become the latest North American city to sign up to the "LED City" program initiated by Cree. Utility company Austin Energy has expanded its electricity rebate program to cover lighting and it aims to cover 30% of the upfront cost of LED lamp installation.



Apple's high-profile launch of ultra-thin MacBook computers could herald a key year of transition for LED backlighting in liquid-crystal display (LCD) screens.

The latest MacBook Air notebook, revealed by Apple CEO Steve Jobs at January's Macworld exhibition in San Francisco, has delighted technophiles – largely because of its incredibly thin display, which measures just 0.16 inch at its thinnest point.

Incorporating high-brightness LEDs into the LCD backlight is crucial for producing such a sleek, lightweight design. The iconic electronics company could set a trend for much greater LED backlight production in 2008, for both notebook computers and TVs.

MANUFACTURING

Lumileds restarts flip-chip line

The Philips Lumileds LED packaging line that was shut down due to problems with epoxy underfill was restarted in late January, the Californian company confirmed.

Production of Luxeon K2 and Rebel lamps, using thin-film flip-chip (TFFC) technology, is now being revalidated at the company's Malaysian plant.

"We expect to deliver the first products at the beginning of March," commented Steve Landau, Lumileds' director of marketing communications. "I would think that by April we'll hit full volume, getting the line back to normal."

Landau emphasized that production of the TFFC die remained unaffected, which will help the company to ramp up manufacturing of packaged products more rapidly than normal. "Typical production process is about a 12-week lead time, so we're probably cutting that in half because we're not starting from scratch," he said.

The problem epoxy had suffered uniden-

tified contamination, which put the LED die under excess stress and caused cracking as the epoxy warmed and cooled. This material has now been replaced.

The company is confident that there will be no further problems: "As you might imagine we're paying very, very close attention to all of this, including additional tests to give everybody the comfort level that we think is appropriate," Landau said.

"The engineering teams have done their job in close co-operation with the epoxy vendor, worked to [find] the root cause and put the checks in place so this situation is not going to occur again," he added.

The packaging problem had forced the company to shut down production and issue a product recall that could have affected up to three months of TFFC LED fabrication.

Production of the LEDs in question had only just started in the second half of 2007 and so was still being ramped when the problem was discovered.



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...Cree buys LLF

Chip maker Cree is to acquire LED Lighting Fixtures (LLF), its North Carolina neighbor that specializes in solid-state lighting. LLF, which already has Cree founder Neal Hunter as its CEO, agreed to a cash and stock deal valued at \$77 million, plus up to another \$26.4 million, dependent on product milestones and key employee retention.

...Epistar expands again

Taiwanese LED giant Epistar has ordered another set of high-volume MOCVD tools from Aixtron to increase GaN production.

...Auto market movement?

Japan's Nichia looks set to increase its share of the market for LEDs in automotive applications, say analysts at IMS Research. Osram OS is the current market leader with a 23% market share, but Nichia could increase its 16% share as car manufacturers increasingly use white LEDs in forward lighting.

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WAFER BONDING

Euro project creates microring lasers

By Andy Exance

High-speed networking could benefit from more compact InP components, thanks to a new chip-fabrication technique.

Europe's WAPITI collaboration claims that its customized wafer-bonding approach has produced compact wavelength-division-multiplexing (WDM) transmitters and multiplexers for optical communications.

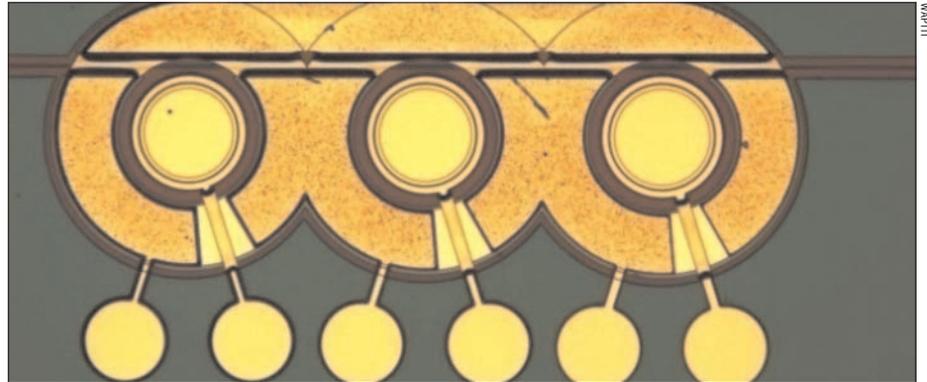
The €2.1 million (\$3.2 million) project specifically exploits microring laser technology. WAPITI's approach has also allowed the first demonstration of a monolithic transceiver based on the novel devices.

The WAPITI (Wafer Bonding and Active Passive Integration Technology and Implementation) collaboration has constructed 900×400µm chips, on which sit three microrings, with radii increasing from 50 to 60µm. In comparison, InP array wave grating multiplexers are on the millimeter scale, and those based on silicon measure 10 times as large again.

Although the output power from the WAPITI components is currently below 0.1 mW, Heidrich says this should be enough for short-range transmission at 10 Gb/s data rates, and could even allow 100 Gb/s.

"We see two fields of applications for these microrings: low output-power WDM sources for short-reach data links and exploitation of nonlinear phenomena," project leader Helmut Heidrich told *Compound Semiconductor*.

The fabrication method involves epitaxial



Three rings: changing the radius of the microring lasers creates a shift in emission wavelength and allows wavelength multiplexing for high data-rate transmission. The result should be smaller optical transceivers.

growth of the waveguide, spacer and laser layer stacks on an InP substrate, before attachment to a GaAs transfer wafer using benzocyclobutadiene. The original InP substrate is then chemically etched down to the waveguide layer before further processing.

The advantage is that it allows multiple microrings to be integrated onto a single transparent optical waveguide, enabling optical multiplexing. Microrings with different radii produce different laser wavelengths, which can each carry individual data streams within a multiplexing protocol.

Heidrich, who has worked for 25 years as a project manager at the Berlin-based Heinrich-Hertz Institute, is hoping to secure funding to follow up the 40-month WAPITI

project. Among the collaborators was industrial partner EV Group, which lent its expertise in the crucial wafer-bonding stage.

● The trend to data rates beyond 10 Gb/s will demand increased chip complexity and earn active optical component makers more than \$1 billion annually by 2016, according to an industry analyst.

"The capabilities of InP have never been doubted theoretically, but now it seems to fit with a genuine industry-wide commercialization effort," Lawrence Gasman, from Communications Industry Research commented. "The hope is that with InP-based integration, 100 Gb/s components won't be that much more expensive than 40 Gb/s components."

PHOTOVOLTAICS

Emcore readies plan for solar spin-off firm

Emcore, the chip maker that currently serves both the solar energy and fiber-optic telecommunication markets, is likely to split into two separate companies.

The move comes after the Albuquerque-based firm revealed plans to convert loan notes into common stock, a switch that will make it easier to divide the company.

At an investor call to discuss Emcore's latest financial results, CEO Reuben Richards said that the spin-off will lead to an initial public offering of stock that would help to finance the rapid growth that its photovoltaics business is beginning to experience.

Emcore's photovoltaics unit has announced a number of potentially very

large contracts in the past couple of months, as the momentum behind concentrator photovoltaics (CPV) continues to grow.

As well as servicing an expanding, global customer base, Emcore's own second-generation CPV system is up and running at its chip-manufacturing base. Richards says that the "very impressive" system is already operating and generating 8% more electricity than had been expected.

Surprisingly, Emcore's photovoltaics division registered a dip in revenue in the closing quarter of 2007, although this was solely due to the delayed installation of a key piece of manufacturing equipment at its own fab rather than any drop in demand.

The problem was an automated, high-volume die-attach machine, which should have been delivered in November but only ended up arriving in January. That delay meant that \$3 million worth of solar prod-

ucts were not delivered on time, although Emcore expects to make up the shortfall within the next few months.

Even without the inclusion of Emcore's latest deal with renewable energy specialist SunPeak Solar – which should result in Emcore deploying up to 700 MW of CPV systems in the US – the soon-to-be-separated photovoltaics business looks likely to begin its independent existence with a very healthy order book.

For 2008 as a whole, Richards is expecting the photovoltaics unit to bring in some \$150 million, as shipments to customers in Europe, Canada and Korea gather steam.

In 2009 that figure should increase to something approaching \$230 million – not including the SunPeak deal, which is dependent on the US Congress granting an extension of investment tax breaks relating to renewable energy sources.

RESEARCH ROADMAP

Fund quantum-dots, urges report

Europe's leading photonics companies and institutions have produced a new roadmap for photonics and nanotechnology research.

The 161-page European Roadmap for Photonics and Nanotechnologies, which is the culmination of a two-year effort by the MONA (Merging Optics and Nanotechnologies) project, features III-V and II-VI compound semiconductor technologies.

MONA's is not the only input that the EC will use to determine its allocation of research funding for photonics – other influential channels include the “Photonics 21” industry consortium – but its findings are expected to have a strong impact on research topics that will be funded around the 2009–2010 time-frame.

CEA-Leti's Laurent Fulbert, one of the senior figures involved in MONA, said that while Europe did lag behind other parts of the world in terms of photonic component manufacturing, it was often at the forefront of research. “We are convinced that nanophotonics could strengthen the European position if adequate funding is provided for research and development, and for industrial players,” he commented.

Quantum-dot structures feature strongly in MONA's recommendations. They are seen as key “nanomaterials” likely to have a significant impact in a wide range of applications highlighted in the roadmap as being of major economic importance in Europe.

For example, the roadmap recommends that III-V quantum dots are developed for photovoltaic applications, where they could provide a significant improvement to the

efficiency of high-end solar cells.

However, more research is needed to better control the size uniformity of the dots, which will be crucial for reliable, repeatable cell manufacturing.

Pushing the current limits of the conventional Stranski-Krastanow quantum-dot growth technique is touted as one of the major avenues for research, along with the development of novel growth methods.

Imaging, lighting and data storage are three more applications where quantum dots could have an impact, says the roadmap.

Quantum-well infrared photodiodes based on III-Vs have already had a major impact in the imaging industry, and in Sofradir and CEDIP, Europe is home to two of the leading companies in the field. According to the MONA roadmap, these companies want to use quantum dots in future detector designs, but, again, there are problems with size control and symmetry.

In lighting, where Osram and Philips are Europe's global players, nanostructured II-VI compounds, such as ZnO, hold promise. But, again, there is a question mark over accurate size distribution, a key requisite for volume production.

Fulbert believes that the emerging field of photonic-electronic convergence, such as silicon photonics, could be one where Europe may get a head start: “[This] is a field where Europe is strong in research and development,” he said. “It could be an opportunity for the European microelectronics and compound semiconductor industries to combine their efforts.”

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...BluGlass CEO switch

David Jordan, CEO of Australian GaN-on-glass company BluGlass, has resigned from his post citing personal reasons. He will however continue as a non-executive director and take up an advisory role. Giles Bourne is now acting as CEO.

...Nichia goes long

Japanese company Nichia is set to begin shipping a 488 nm semiconductor laser this month. The 5 mW device, which represents the longest-wavelength GaN-based laser yet to be developed commercially, is designed to

replace larger argon-ion lasers.

...Infinera posts record

Photonic integration specialist Infinera has posted its best-ever financial quarter, with record invoiced shipments of \$93.4 million and an unofficial profit of \$15.9 million.

...JDSU hits straps

Sales of JDSU's reconfigurable optical add-drop multiplexers grew by 39% in the Californian chip maker's most recent financial quarter. The boom helped the wider company swing to a profit.

Edward D. Gagnon
General Manager,
Spire Semiconductor




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RF MICRO DEVICES

Switching on to new technologies

Vic Steel is looking to keep RFMD ahead of the rest of the GaAs field with MEMS for RF switch integration in handsets and an unexpected foray into photovoltaics. The company's vice-president of corporate R&D shares his game plan with **Andy Extance**.



Which is the single most important technology currently in development at RFMD?

Of course, I would say they're all important, so that's a hard question. I think our MEMS technology has the best potential to revolutionize several aspects of our next-generation systems, not just the RF switch.

There are several ways that MEMS could change the way front-ends work. It could reduce all of the cellular power amplifiers (PAs) that might be in a multi-mode phone down to one PA with a load switch. The MEMS switches could allow one PA to be frequency-switched between bands, then switch between a linear mode and a saturated mode, allow for load changes and retain the optimum performance from the PA.

They can also allow other types of function. We've talked about the potential for adding resonators or sensors, such as accelerometers and gyroscopes, in the same technology that we're developing for RF switching. These functions can be implemented in a very low cost, incremental fashion.

When will we see the MEMS switches on the market and in what format?

The first implementation is going to be on CMOS because our initial concept is to put it directly on the driver circuitry for the switch. It will be a low-cost driver that supports the MEMS switch, which can then be applied in a module with our PAs or with other circuitry. Longer term this process can be integrated directly on GaAs as well, so it's really fairly flexible. It's still in development but we expect to release the MEMS technology for production next year.

So, will MEMS be replacing PHEMT switches?

We believe it would be possible, yes. Initially we are focused on mode switching [between bands], which is currently done with PHEMT and is a slower process with fewer switching cycles than transmit-receive (TR) switching. We believe the MEMS technology

that we're developing will have the lifetime to support TR switching as well, so in the longer term we could replace the PHEMT switch for both.

What does this mean for the long-term future of GaAs at the company?

We see opportunities in the mobile phone area and other areas that we're addressing for compound semiconductors and silicon CMOS-based circuits for a long time. We don't see a transition from one to the other. We're beginning to pick up more CMOS, doing development and applying more of our efforts in silicon for various applications. That's not transitioning from our core competency in GaAs. You can see that obviously we're committed to our GaAs because of the capacity that's coming with the Filtronic deal.

Why has RFMD been slower than other companies to use BiFET technologies?

We're working on BiFETs at the moment and we're well aware that our competitors have these on the market. We are really, really focused on what our customers' needs are. We felt that the technologies we had with HBT and PHEMT as separate die met the needs of our customers very well. We can see some applications as we move forward that will need BiFET technology, so we're developing it, but we didn't feel that it was something we had to have years ago, when they first appeared.

There are some applications that can benefit from on-board control logic and bypass switching, so these types of applications are interesting. But full integration of a PA and a TR switch with decoding logic onto a single HBT or BiFET die? We're still not convinced about that direction for the transmit modules. We're going to have BiFET technology in some products, but as far as I'm aware we don't have a definitive plan to offer products that are fully integrated in that way, at least in the very near term.

Is RFMD really moving into photovoltaics?

We're actually quite excited about our opportunity in concentrator photovoltaics. From my perspective, this technology will have the biggest benefit to the use of photovoltaics in the end. We're actively pursuing that business area and I believe we have a good opportunity to have a significant impact on the availability of these high-efficiency concentrator photovoltaic cells. The way that we can address that market is by providing very large volumes at the lowest cost.

Would RFMD's focus on MBE be a problem?

We agree that MBE is not widely used. We're evaluating it to make photovoltaic cells, but we're not depending on that. Whether MBE is the technology we use, or MOCVD, it's not going to affect our entry into the business.

Vic Steel: GaAs man

1987: MSEE from University of Illinois.

1987–1991: Employed by Teledyne Monolithic Microwave in Mountain View, CA, as a design engineer, developing a variety of MMICs for electronic warfare systems.

1991–1993: Employed by ITT GaAs Technology Center in Roanoke, VA, as a senior design engineer, developing commercial power amplifier products as well as managing the test lab for the wafer fab.

1993: Joined RFMD as engineering manager for power amplifier product development.

2000: Formed RFMD's R&D group.



NEW IPOs

Mixed fortunes for latest floaters

Rubicon, Infinera and IPG Photonics are all new to the stock market in the past year. So how did they all perform?



Fig. 1. (left) Optoelectronic chip manufacturer IPG Photonics launched itself on the Nasdaq in late 2006 and was followed by Infinera last summer. Despite early gains, both stocks have been dragged down amid wider concern about the global economy. **Fig. 2.** (right) Sapphire substrate maker Rubicon floated in late 2007 and its stock value has so far tracked that of LED maker Cree, perhaps reflecting a growing appreciation of the energy-saving potential of LED lighting.

After going a good few years with barely any compound semiconductor companies going public, the last 15 months or so have witnessed a bit of a change. Photonic integrated circuit innovator Infinera, sapphire substrate specialist Rubicon and fiber laser manufacturer IPG Photonics all listed on the Nasdaq exchange in the US, while 2008 should see at least one more addition when Emcore hives off its photovoltaics unit as a separate entity.

So, how did these new stocks do? Given the great volatility of global markets in the past year, that is not an easy question to answer. But with the Dow Jones, London's FTSE and the Nasdaq index all either flat or down over the past year, any increase in stock value could be viewed as a success.

When it listed back in June 2007, Infinera initially took the market by storm, rising from its IPO price of \$16 per share to more than \$25 in no time, and outperforming all of the indices for the next couple of months. Since the turmoil of the late summer, however, that price has largely headed south and, as pessimism took a wider hold, Infinera dropped below the \$10 mark – 50% below its IPO list price.

Is that a fair reflection on Infinera's performance since going public? Certainly not, would be my view – it may have burned through a large pile of cash during its formative years, but Infinera really does seem to be finding its place in the optical communications industry now. With its client base expanding quickly and its reliance on a handful of major customers shifting to a much more balanced portfolio, it is beginning to look like a force to be reckoned with.

IPG Photonics floated at the very end of 2006 with a launch price of \$25. Like most stocks it enjoyed an early boom, but since then it will have disappointed investors. Again, when looking outside general market strife, it is difficult to see why that is. After all, IPG has pretty much cornered the market for high-power fiber lasers and, as a vertically integrated company (it manufactures high-power GaAs laser diodes using MBE at its headquarters in Oxford, Massachusetts),

it is also in control of its key supply line.

At the Photonics West exhibition in San Jose in January, IPG indicated a strategic change when it revealed plans to enter the merchant high-power laser diode market, rather than using all of the diodes that it produces internally. Whether the decision reflects lower than expected internal demand following significant expansion remains an open question.

Either way, like Infinera, its stock has underperformed the major indices since that launch, possibly reflecting the negative sentiment around some of the end markets that IPG serves. One application area in which IPG is thought to be increasingly finding its feet is automobile manufacturing. Perhaps the worries of the impact of a slowing US economy on the car industry are weighing down the stock.

Sapphire substrate vendor Rubicon is the most recent addition to the compound semiconductor portfolio, having listed in November last year. Its early days, but, of the three recent additions, Rubicon will have pleased its investors the most, and by early February it had registered a 73% gain on its \$14 launch.

That increase could be a direct result of its exposure to the market for high-brightness LEDs. Certainly a comparison with Cree's recent stock performance appears to confirm this – the two stocks have tracked up pretty much identically for the past three months (figure 2) at a time when many others had been crashing through the floor.

While it might make sense for investors to peg Rubicon shares with those of the leading LED maker Cree – despite the latter's use of SiC, not the sapphire material sold by the Illinois-based firm – Rubicon has tough competition in the sapphire substrates field.

Strangely then, the two companies who are market leaders in their own niche have slumped in value, while the one with a smaller market share and the toughest competition is flying high. My guess is that IPG and Infinera may well end up being the better long-term investments, so remember folks: the price of stocks can go up, as well as down.



Michael Hatcher does not own or intend to purchase any of the stocks in this article.

Novel layers enhance red-

Better extraction efficiencies for red LEDs are now possible, thanks to specially designed transmitting and reflecting layers that feature in two of Epistar's latest product lines, say the company's **Tzer-Perng Chen** and **Min-Hsun Hsieh**.

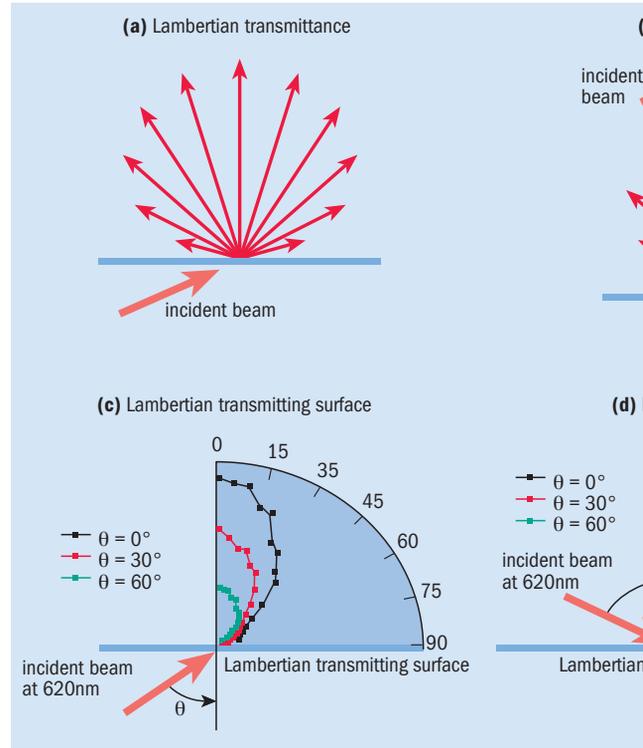
Many of today's AlGaInP-based LEDs are used to provide red sources for traffic signals and automobile brake lights. However, this type of device could enjoy even greater commercial success if its cost-per-lumen was lower, as this would spur deployment in projectors, LCD TV backlights and color-temperature tunable lighting fixtures.

One approach to cutting the cost-per-lumen involves the introduction of new technologies that boost LED efficiency. Improvements in epitaxial growth and device processing have pushed this device's internal quantum efficiency close to its theoretical limit, so any further gains must come from increases in the emitter's extraction efficiency.

Several methods have already been developed for this purpose, but none is ideal. Adding a distributed Bragg reflector (DBR) to an LED reduces light absorption in the GaAs substrate, but reflectivity at oblique angles of incidence is relatively low and this results in significant optical loss. Replacing the substrate with a transparent one, such as sapphire or GaP, also has downsides, because this approach can't deliver the significant improvements in thermal conductivity that are needed to boost maximum drive current and lumen output. Surface texturing, meanwhile, can increase light output, but it is difficult to control the shape and feature sizes with this conventional chemical-etching process.

The thermal conductivity issue has recently been addressed by transferring epitaxial layers to electrically and thermally conductive substrates. However, even with this advance, optical efficacies of many of the best commercial 620 nm LEDs are only about 50 lm/W. This means that the high-brightness LEDs produced by bonding techniques can't fulfill customer expectations in terms of efficiency.

However, at Epistar Corporation, Taiwan, we have just unveiled a new series of AlGaInP LEDs that can deliver far higher efficacies. These products – which are named the P- and A-series (although they were initially launched as Phoenix and Aquarius LEDs, respectively) – feature improvements in light extraction efficiency of at least 50%, thanks to the addition of multilayer structures with an undulating surface and a graded refractive index. Fabrication takes place on existing equipment and the production capacity is hardly impacted at all.

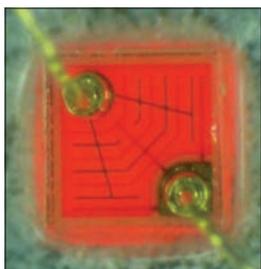
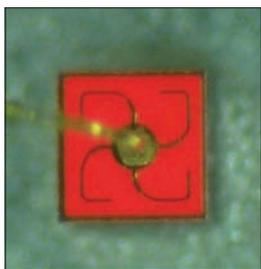


We call these proprietary multilayer structures “Lambertian transmittance and reflectance surfaces” because they obey Johann Heinrich Lambert’s cosine emission law. Such structures reflect or emit with their greatest intensity in the direction normal to the surface, and with least intensity at the most oblique angles (see figure 1 for a definition).

Our P- and A-series LEDs feature Lambertian transmitters and reflectors on the top and bottom of the device, respectively. The transmitter boosts extraction by directing the majority of the light in forward directions and reflecting very little back into the device, where it could be absorbed by the quantum well. The reflector, meanwhile, directs most of the light heading towards the substrate back into the device at angles that prevent multiple internal reflections within the chip.

We manufacture our P-series chips by creating a Lambertian reflector on the GaP surface, which is the top layer of the AlGaInP-on-GaAs epiwafers (figure 2a). This wafer is then bonded to silicon, before the GaAs substrate is removed. Next we etch the n-type cladding layer to form the Lambertian reflector and define a gold p-type contact on the back of the silicon substrate. Wafer probing follows, before the bonded device wafer is diced into individual chips.

A-series LEDs have a slightly different design



P-series (top) and A-series (bottom) LEDs, which were initially named Phoenix and Aquarius, respectively, produce homogeneous illumination at a low drive current. This indicates very uniform current spreading across the whole chip.

LED extraction efficiency

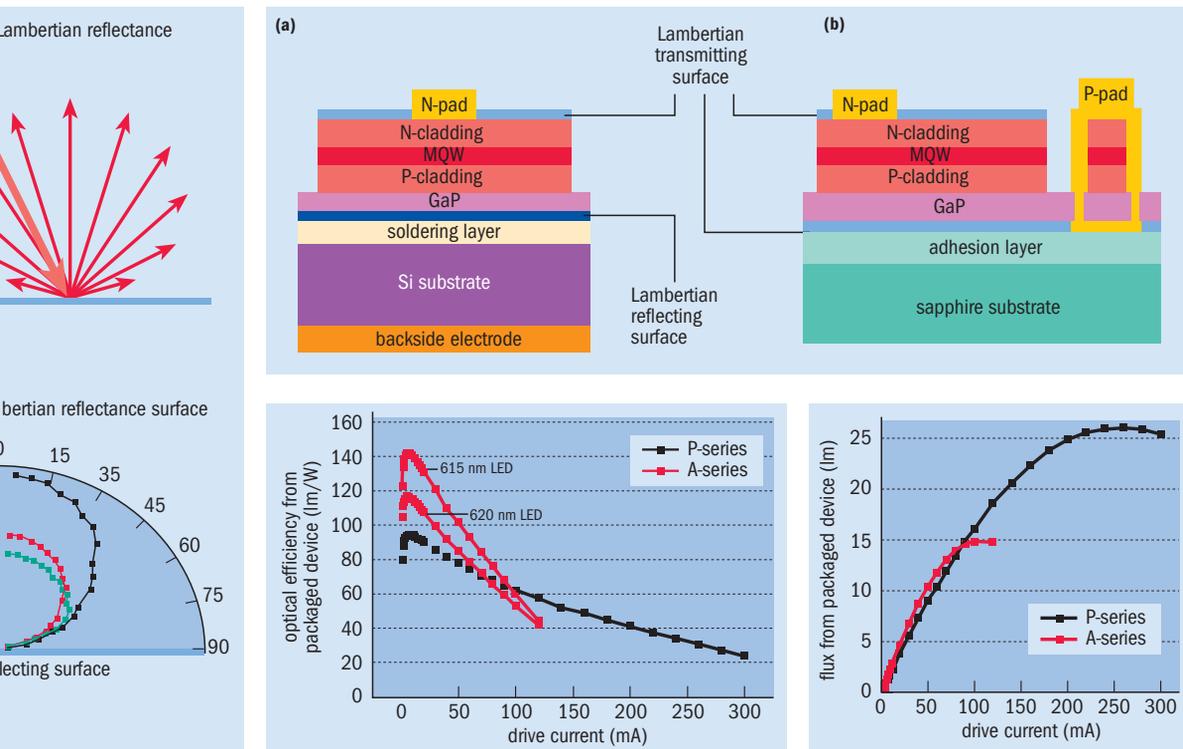


Fig. 1. (far left) (a) Lambertian transmittance surfaces produce their greatest throughput normal to the plane of the surface (the output intensity is proportional to $\cos(\theta)$, where θ is the angle subtended from the normal). The length of the arrow in this figure represents light intensity. (b) The Lambertian reflectance surface produces the same intensity profile. Epistar has confirmed the Lambertian properties of its transmitters (c) and reflectors (d) with incident beam angles (θ) of 0° , 30° and 60° and observation angles from 5° to 80° . **Fig. 2.** (top) The P-series (a) and A-series (b) LEDs feature Lambertian transmittance and reflectance surfaces. **Fig. 3.** (bottom left) The A-series design produces the highest efficacy at low currents but is overtaken by the P-series chip at higher currents. **Fig. 4.** (bottom right) P-series LEDs saturate at higher drive currents than A-series chips due to the superior thermal conductivity of their platform.

Table 1. AlGaInP LEDs

UHB product	Chip size (μm)	Dominant wavelength (nm)	Forward voltage (V)	Flux (lm)	Optical efficiency (lm/W)	Saturation current (mA)
P-series	350×350	620	2.04	3.70	90.7	280
A-series	350×350	620	2.11	4.53	107.5	120
A-series	350×350	615	2.13	5.57	130.4	120

Optical properties measured at 20mA drive current. The data have been confirmed by Electronics and Optoelectronics Research Laboratories, Industrial Technology Research Institute, ROC.

(figure 2b), with the wafer bonded to sapphire and a transparent adhesive film used as the bonding agent. Aside from that, the fabrication process is similar to that for the P-series.

Our A-series chips emit at 615–620 nm and have a forward voltage of just over 2 V (see table 1 for details). The 620 nm version delivers 107 lm/W at 20 mA and the 615 nm equivalent produces 130 lm/W at the same drive current (see figure 3 for efficacies at other drive currents). This product's maximum forward current rating is 40 mA, and the device is intended for backlighting and architectural, entertainment and decorative lighting.

The P-series chips are the same size as their A-series cousins but operate at higher currents, thanks to the silicon substrate's superior thermal conductivity. At a current of 250 mA they can

deliver 25 lm (figure 4), but we recommend that the drive current is kept below 70 mA. This LED is suitable for the same applications as our A-series chips, but we are also targeting deployment in traffic lights, signage and channel letters.

Both of our products are highly reliable. 1000 hour tests revealed very stable light outputs for P-series chips driven at 80 mA under conditions of 85°C and 85% humidity, and A-series chips at 40 mA under the same conditions.

We believe that our red LEDs deliver record-breaking efficacies at 20 mA and our customers say that they offer an improvement of 30–50% over other products in the market. We will be manufacturing these devices on our production line this year and we are confident that they will help to drive greater deployment of the red LED.



About the authors

Tzer-Peng Chen (left) and **Min-Hsun Hsieh** (right) are senior vice-president and vice-president of Epistar's R&D centre, respectively. They thank Chih-Chiang Lu, Ta-Cheng Hsu, Ching-San Tao, Jui-Hung Yeh, Jong Fu Dai, Chiu-Lin Yao, Meng-Lun Tsai and Chun-Yi Wu for assistance.



NITRIDES

Pyramids produce crack-free UV lasers

Epiwafer cracking hampers UV-laser diode production, but this problem can be avoided by inserting triangular-shaped GaN pyramids on top of the sapphire substrate, says **Harumasa Yoshida** from Hamamatsu Photonics.

UV lasers are used for various industrial and scientific tasks, including fluorescence spectroscopy, laser-ionization mass spectrometry, photolithography and material processing. These applications have driven the sales of nitrogen gas, HeCd, XeF excimer and triple harmonic generation Nd:YAG lasers, but these are bulky, inefficient, expensive to run and only cover a discrete range of wavelengths. In addition, HeCd and XeF lasers contain toxic substances.

Switching to UV-laser diodes could address all of these issues. However, it is not easy to extend the emission from 405 nm, the semiconductor laser wavelength of choice for Blu-ray and HD DVD players, into the UV. Far more aluminum is required in the cladding layers, along with aluminum rather than indium in the active region, and these changes lead to more defects in the epilayers, alongside greater strain, which can ultimately cause cracking.

This is not the only problem, as device development is also held back by substrate availability. AlN and AlGaIn are the ideal choices, as they would allow crack-free growth of high-aluminum-content AlGaIn layers, but these substrates are poor quality. The next best option is native GaN, but this is very expensive, so many devices are built on sapphire, SiC and silicon. However, these foreign platforms cause cracking and dislocations in the epilayers, due to significant differences in lattice constant and thermal expansion coefficients between the nitrides and the substrate.

These difficulties have hampered UV-laser diode progress and forced researchers to develop novel fabrication processes. These include the introduction of compliance layers for epitaxial lateral overgrowth (ELO) and methods described as a combination of low-temperature AlN interlayer technology and hetero-ELO. However, these techniques do not appear to produce epiwafers with crack-free regions, which is essential for high-yield laser diode manufacture.

It is possible to produce crack-free laser diode epiwafers on sapphire using a process called hetero-facet controlled (FAC) ELO, according to the work of a partnership between our team at the Central Research Laboratories of Hamamatsu Photonics KK and researchers at Meijo University, Japan (figure 1). This MOCVD-based technique involves the growth of a 2.5 μm thick GaN layer on sapphire. SiO₂ stripes 3 μm wide, separated by 3 μm , are defined on this surface, so that subsequent GaN growth creates 6 μm high triangular-shaped “seeds” (figure 2). AlGaIn is then grown laterally from the inclined facets of these seeds. Although dislocations are formed, they generally propagate in the horizontal direction and the dislocation density falls as more material is deposited.

The hetero-FACELO technique was initially applied to LEDs by researchers at Meijo University. However, we have extended this process to laser diodes by overcoming challenges associated with the

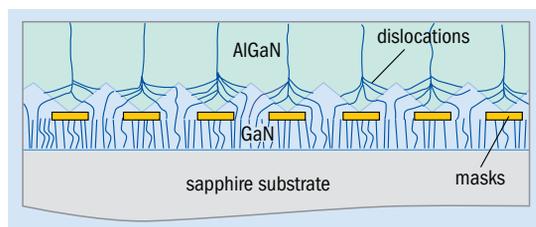
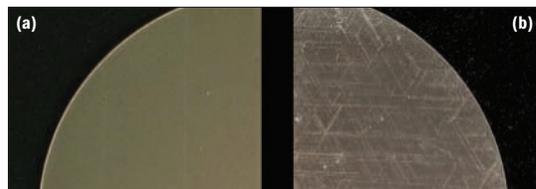


Fig. 1. (top) Hetero-facet controlled epitaxial lateral overgrowth (FACELO) can produce crack-free material on 2 inch sapphire, which appears opaque due to light-scattering within the structure **(a)**. Without this process, which involves the creation of GaN seed crystals, numerous cracks are formed on the wafer **(b)**. **Fig. 2.** (bottom) The hetero-FACELO technique involves the fabrication of GaN pyramids, which are formed by deposition of a SiO₂ mask on GaN. Subsequent AlGaIn growth produces dislocations that are predominantly in the plane of the substrate. Additional growth leads to better-quality material.

growth of thicker and more complex structures that can provide optical and electrical confinement. This has led to the production of crack-free 2 inch material on sapphire with a total film thickness of 18 μm .

Laser stripes 5 μm wide were fabricated from these epiwafers, which span the wavelengths 355–362 nm. Threshold current densities for these emitters ranged from 7.3 to 19 kA/cm². Room-temperature output under pulsed conditions peaked at 15 mW at a current density of 34 kA/cm², and the typical polarization ratio (transverse-electric/transverse-magnetic) was 150.

The threshold current densities of these lasers are too high for commercialization. However, we have recently produced diodes with far lower threshold current densities that can deliver outputs of several tens of milliwatts under pulsed operation. These improvements resulted from optimization of the growth conditions for AlGaIn, which increased the conductivity of the p-type AlGaIn layers and decreased the number of defects acting as non-radiative centers.

We are continuing to improve our UV-laser diode characteristics and trying to produce novel devices operating at shorter wavelengths. In particular, we are aiming to produce a 337 nm emitter that offers an alternative source to the nitrogen gas laser.

Further reading

S Kamiyama *et al.* 2002 *Phys. Status Solidi A* **192** 296.

H Yoshida *et al.* 2007 *Jpn. J. Appl. Phys.* **46** 5782.

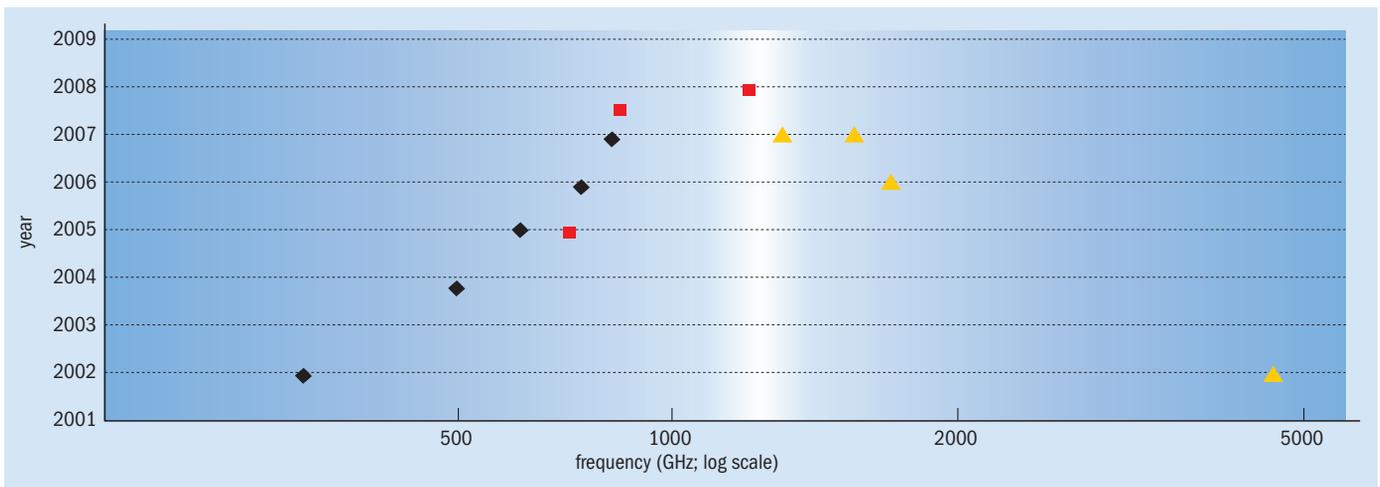


About the author

Harumasa Yoshida is a senior researcher at Central Research Laboratories, Hamamatsu Photonics KK, Japan. He is joint head of research and development of nitride materials and applied photonic devices.

III-Vs squeeze the terahertz gap

The terahertz gap is on the way out. Transistors are speeding up, quantum cascade lasers are stretching farther into the microwave domain and the window that's left is shrinking, reports **Richard Stevenson**.



This decade has witnessed steady improvements in the two figures of merit for transistor speed, f_T (diamond) and f_{max} (square), and has seen the construction of the first device capable of operating at more than 1 THz. Quantum cascade lasers (triangles) have made progress from the other direction and Jérôme Faist's team from the University of Neuchâtel, Switzerland, has fabricated 1.2 THz emitters. These devices can reach 850 GHz when they are placed in a strong magnetic field.

It's the simple goals that tend to capture our imagination, such as the breaking of the four-minute mile and the first ascent of Everest. In our community we also have a similar goal – the building of the first semiconductor chip that can operate at 1 THz. This target is particularly interesting because it is being attacked on two fronts by strikingly different technologies. Quantum cascade lasers (QCLs) are making gains from the optical side as researchers build new structures to operate at longer wavelengths, while engineers are moving closer from the electronics domain with ever faster transistors.

In recent years, advances in transistor speed have been led by Milton Feng from the University of Illinois at Urbana Champaign (UIUC), who has raised his HBT's top speed to almost 800 GHz at room temperature. But he was pipped at the post in December when Richard Lai from Northrop Grumman Space Technology announced that his team's InP HEMTs had passed 1 THz.

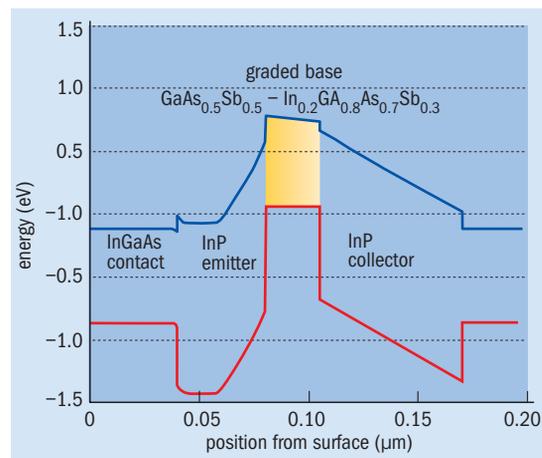
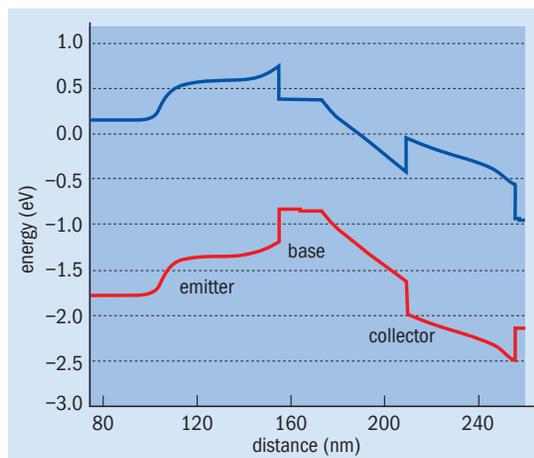
Lai, the leader of the company's microelectronics products, reveals that his team has been working under the radar for the last few years, admitting: "This result is not something we focused on to achieve as a goal." Instead, the researchers have been aiming for the targets of a Sub-millimeter Wave Imaging Focal-plane Technology (SWIFT) program, funded by the US Defense Advanced Research Projects Agency (DARPA).

Northrop Grumman's role in this project is to build an amplifier operating at 340 GHz. But to provide amplification at this frequency, you need to produce transistors that are two to three times as fast, which explains why this team has been developing such high-speed devices. The researchers concentrated on characterizing the amplifier and only went on to measure their HEMT's speed when DARPA's program manager, Mark Rosker, asked if the researchers could claim a terahertz transistor. Measurements showed that this was the case and Lai was told to write this up and present the results, which he did at last December's International Electron Devices Meeting (IEDM).

The record-breaking speeds are the result of several modifications to Northrop Grumman's previous HEMT designs. Gate sizes have shrunk to 35 nm and adjustments have been made to the epitaxial structure, including a switch to an InAs channel with very high mobility.

Northrop Grumman's approach to measuring the speed of its HEMTs reflects its target application – microwave devices. Here the key figure of merit is f_{max} , the frequency that produces a unitary power gain. Measuring this frequency with reasonable accuracy is a tricky task because it involves the extrapolation of data obtained at far lower frequencies (see box "Determining the speed of ultrafast transistors", p19). Lai accepts that extrapolation-

Fig. 1. One of the disadvantages of type I DHBTs is the barriers formed at the base-collector junction. These can be smoothed with grading layers, but this modification comes with the penalty of increased scattering and reflection of electrons at the interface. These drawbacks have led Milton Feng's team at the University of Illinois at Urbana Champaign to develop type II DHBTs. These structures don't have an energy barrier at the base-collector junction and electrons can be ballistically launched into the collector, leading to faster transit times. This device also benefits from a lower turn-on voltage.



based methods can undermine claims of terahertz records, but he counters this criticism by saying that all of the currently accepted methods for testing produce an f_{\max} of more than 1 THz for his team's transistor. Applying the unilateral gain technique produced a value of 1.2 THz, and figures of 1.1 and 1.4 THz, respectively, were obtained by extrapolating maximum stable gain and making circuit model calculations.

Lai claims that the ultimate validation for f_{\max} extrapolation above 1 THz comes from the performance of the team's three-stage low-noise amplifiers that have also been built from these HEMTs. At IEDM he unveiled the results for a 0.65×0.35 mm MMIC chip, which can produce 21 dB of gain at 285 GHz, 18 dB at 300 GHz and 15 dB at 340 GHz. And he believes that amplifiers operating at much higher frequencies are also within his grasp. "We have devices with 1.4 THz f_{\max} , so you should have some decent gain at 600 and 700 GHz. This is not our primary thrust but we are working on it." At these frequencies the difficulties are not associated with the chip itself but with the coupling of signals in and out of the transistors. Simulations have shown that this can be done, but his team is still to follow this up with a real demonstration.

Lai is also very keen to emphasize that his results are not just one-offs. "In industry my objective is not to try to demonstrate one terahertz transistor. This has to be a technology that can be manufactured, so yield and reliability are very important." Northrop Grumman has already produced tens to hundreds of wafers with this process and yields are encouraging. In particular, the process is producing T-gates with 99% yields that are also robust, according to temperature cycling and vibration tests.

One of Northrop Grumman's next steps will be the transition from prototype fabrication to genuine deployment. "We've got to get to the next level where we can make [our HEMTs] into blocks and start putting things together. We're still at the fundamental technology stage, trying to get the basic components and understand them."

Lai believes that the shipments of modules

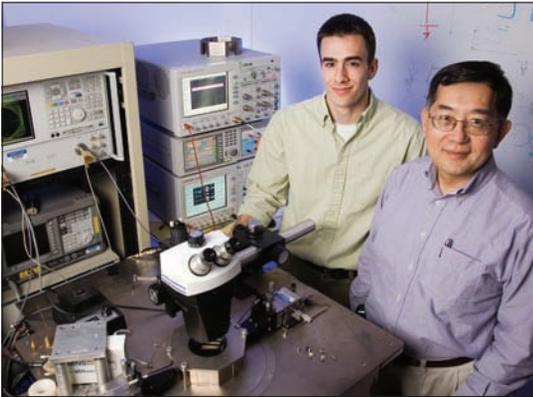
employing high-speed HEMTs for military applications, such as radar, will start on a very small scale. However, a lot of arrays will need to be built, and this could translate into substantial chip volumes.

From HEMTs to HBTs

Feng, meanwhile, has a very different application in mind for his high-speed HBTs – mixed circuits such as analog-to-digital converters. This application has a different key figure of merit, f_T , the frequency at which current gain is equal to unity. (However, a high f_{\max} is needed for a wide dynamic range.) At IEDM, Feng's team reported a speed of 683 GHz for its double-heterostructure HBT (DHBT), which increased to 745 GHz at -37°C . "The device is not optimized," said Feng, "and we are expecting something even better to come out soon." He hopes that this structure can operate at more than 1 THz and believes that he can achieve that this year.

Up until very recently, many of Feng's IEDM papers focused on the development of conventional single-heterostructure HBTs, but increasing the speed of these transistors has come at the penalty of a very low breakdown voltage. These devices could achieve terahertz operation at a marginal breakdown voltage, says Feng, but this is not good enough for mixed-signal applications. "In order to achieve [a breakdown voltage of] about 2 V in the terahertz regime, the technology requires the collector to be a larger bandgap," he added.

Switching to DHBT structures allows just this, and the UIUC team has been developing a type-II design that features a pure InP collector layer (figure 1). Feng claims that this is a superior structure to type-I versions, which have a transition layer in the collector section that causes current blocking. In comparison, type-II structures have a base layer with an energy band above the collector, which gives an advantage known as velocity overshoot. "Fundamentally, that gives you a fast transport through the collector," said Feng. His type-II designs also deliver better thermal conductivity, thanks to binary material in the collector, which is said to improve I-V characteristics and allow the



Milton Feng's research team at the University of Illinois at Urbana Champaign has been developing high-speed InP transistors since 1995. His fastest HBTs have an f_T of almost 800 GHz at room temperature and 845 GHz at -55°C .

HBT to operate at lower temperatures.

Like Lai and his team at Northrop Grumman, if Feng wants to make circuits that can operate close to 1 THz, he will have to build HBTs with top speeds that are way beyond that value. However, he thinks that will be possible with his current structure. "The problem right now is that we have a 400 or 350 nm emitter. If you look at silicon, it's 130 or 65 nm, but if we can get to that level we will cross over into the terahertz range."

One of the major players operating on the other side of the terahertz gap, and hoping to come down in frequency, is Jérôme Faist from the University of Neuchâtel, Switzerland. He and his team currently hold the record for the lowest frequency for a QCL, which stands at 1.2 THz for a GaAs/Al_{0.1}Ga_{0.9}As-based heterostructure. However, this laser can emit at just 850 GHz when a strong magnetic field is applied with a superconducting solenoid.

The emission from this type of device results from transitions between extended states that are similar to those found in superlattices, and growing such a structure is not easy. "If you were just to scale linearly all of the dimensions with wavelength, you would end up having unreasonably thick layers," explained Faist. He says that this can be overcome by using metal-metal waveguides, a common solution for many researchers in this field: "It's conceptually simple. There is some [process] know-how that you need to acquire, but in the end it turns out to be quite straightforward."

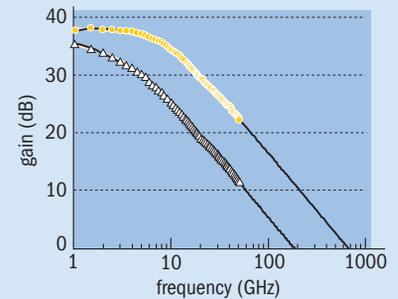
Designs must also combat potential losses from free-carrier absorption. This absorption process is predicted to be proportional to the square of the emission wavelength, but Faist found that the loss did not follow this trend and only showed a small increase between 2 and 1.2 THz. "It's a good surprise and it gives hope that we can proceed [to shorter wavelengths]."

Avoiding the problems associated with free carrier absorption has not been down to good luck and is the outcome of work with theoretical models that

Determining the speed of ultrafast transistors

The circuits used for measuring the response of ultrafast transistors are unable to operate at these really fast speeds. So f_T and f_{max} are determined by measuring gain over a certain range of lower frequencies and then extrapolating the performance at far higher frequencies (see figure for example, which shows the gain for a type-II DHBT from Milton Feng's research group for frequencies of up to 50 GHz).

Northrop Grumman is working on increasing the maximum speed of its testing rig and has got up to 200 GHz. However, a Jet Propulsion Laboratory



team is working on an even more advanced set up, which will hopefully enable testing at up to 500 GHz.

consider free-carrier absorption as a tail of intersubband absorption. "If it's intersubband absorption, you can't completely eliminate it, but you can push it to the places where you can tolerate it and remove it from the places where you don't want it."

One of the major weaknesses of all terahertz QCLs is their low operating temperature. The University of Neuchâtel's 1.2 THz QCL, for example, can operate in pulsed mode at temperatures of up to 69 K, but it can only produce a continuous-wave output at up to 50 K. However, Faist believes that progress can be made by switching the quantum well from GaAs to InGaAs. "We will benefit from a slightly lower optical phonon scattering rate, and since optical phonons are the main scattering mechanism at high temperature, this should really help us."

Friends or foe?

If we assume that transistor and QCL technologies both continue to extend their spectral coverage, then there could come a day when you have a choice of device for a terahertz source. Feng is adamant that at that stage the transistor will win because it operates at room temperature and doesn't require cooling. However, Faist believes that a marriage of the two technologies could lead to even better performance characteristics.

"One of the problems that we have with QCLs is tuning," explained Faist, who says that these devices actually have the potential to tune over a broad range, thanks to their wide gain bandwidth. Electronic components can easily provide a tunable source, however, and Faist believes that using this device in combination with a QCL providing amplification would be a great solution.

Lai is also enthusiastic about the possibility of uniting the two technologies. "It could probably be a hybrid solution in the end, depending on what you're trying to do." And it definitely looks like Northrop Grumman is keen to invest in this new field, as the company is planning to set up a lab dedicated specifically to terahertz research. ●

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Groovy nitrides could light up silicon

Devising a monolithic approach to making a silicon light source has been fraught with difficulty, but the fabrication of lattice-matched GaNAsP lasers on CMOS-compatible substrates is showing a great deal of promise, according to **Wolfgang Stolz** from the University of Marburg and NAsP III/V.

The silicon industry dwarfs our own but it does have a few weaknesses. These include silicon's inability to emit light with any great efficiency, which rules out the construction of lasers and optoelectronic ICs built from only this material. But such circuits are of great importance as they could offer a solution to overcoming the data-transfer bottlenecks in ICs and help to cut fiber-to-the-home deployment costs.

The benefits of equipping silicon ICs with a laser source have already motivated a tremendous amount of research, including attempts to build GaAs- and InP-based designs on silicon substrates. However, producing monolithic chips from these combinations of materials is incredibly challenging because the significant differences in lattice constant lead to a high density of misfit dislocations that act as non-radiative recombination centers. This has prevented the fabrication of any optoelectronic devices using these material systems that can deliver long-term stability, and it has driven researchers to look for possible alternative solutions.

Two approaches that have generated considerable interest are erbium-doped silicon and low-dimensional silicon systems, which include porous silicon, silicon nanocrystals and nanopillars, and specific silicon-interface structures. Remarkable progress has been made in the basic understanding of the light-emission process of these systems, including optical gain in silicon nanocrystals, but nobody has been able to build a laser.

Greater success has come through the study of nonlinear optical processes, such as stimulated Raman scattering in a silicon-based waveguide structure. In 2005, Intel demonstrated that it is possible to produce a continuous-wave silicon Raman laser in a specifically designed reverse-biased p-i-n diode embedded in a silicon waveguide. However, this technique still needs an efficient laser source to pump and to initiate the nonlinear process. This obstacle may have encouraged Intel to develop other approaches because it recently announced a technology that involves the bonding of small InP laser chips onto silicon substrates.

At the University of Marburg, Germany, we have been developing a new process that promises to unite III-Vs and silicon monolithically via the novel material system GaNAsP. This dilute nitride can be grown epitaxially and lattice-matched to silicon by using the nitrogen content to tune the lattice con-



Fig. 1. A dark-field transmission electron microscopy image of the heterostructure containing GaNAsP wells and GaP barriers reveals no dislocations or inhomogeneous strain relaxation.

stant of the compound to the underlying substrate.

We have laid the groundwork for this technology by growing a variety of dilute nitride laser structures on an Aixtron AIX 200-GFR tool designed for research and development. Film growth was performed using a reduced reactor pressure of 0.05 atm, hydrogen as the carrier gas, and the metal-organic precursors triethylgallium, tertiarybutylarsine, tertiarybutylphosphine, 1,1-dimethylhydrazine and triethylboron. We chose these because they efficiently decompose at 575°C – a relatively low growth temperature that is needed to produce dilute nitrides with significant amounts of nitrogen. (Arsine, phosphine and ammonia – the more common group-V sources for MOCVD growth – hardly decompose at this temperature and would lead to a very inefficient growth process.) After growth, our epiwafers are annealed in the reactor for an hour at 750°C. This improves the optoelectronic properties of the active region without compromising structural integrity.

Our GaNAsP/GaP multiple quantum-well

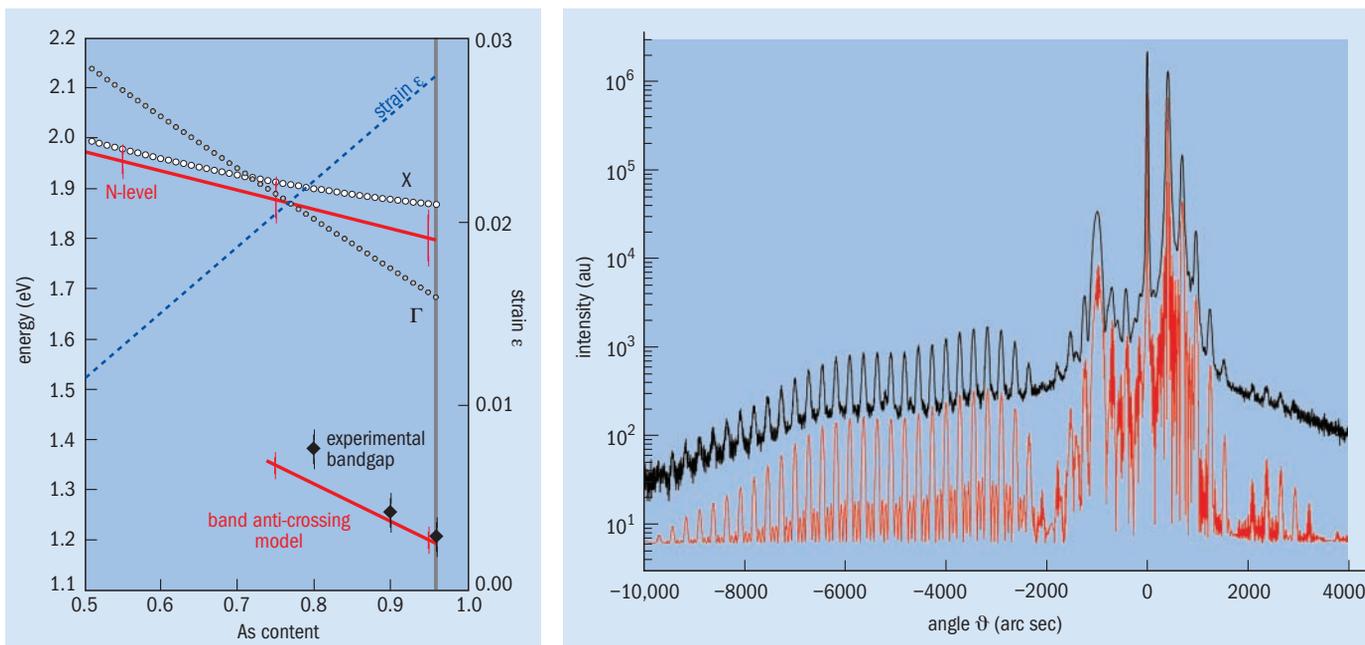


Fig. 2. (left) Calculations have mapped out the bandgap of the GaNAsP-material system, which are based on the well established band anti-crossing model. The positions of Γ , X and nitrogen energy levels are plotted as a function of arsine concentration for a fixed nitrogen content of 4%. To obtain a real direct band structure in this dilute nitride, the Γ level has to be lowest in energy with the nitrogen state positioned in between the Γ and the X levels. This condition is fulfilled for arsine concentrations of more than 75%. **Fig. 3.** (right) High-resolution X-ray diffraction measurements ([400]-reflection) reveal the excellent crystal quality of the laser structure. This design contains a quadruple quantum-well heterostructure comprising 4.3 nm GaNAsP wells and 65.7 nm BGaPAs barriers, which is embedded in 1 μ m thick BGaP separate confinement heterostructure layers. Boron is used to adjust the lattice constant of this quaternary. There is almost perfect agreement between the theoretical model for the X-ray spectra and the recorded data. The measurements show that there is no relaxation of the material, due to careful balancing of the strain in this structure. Compressive strain results from the GaNAsP quantum-well, tensile strain comes from the BGaPAs barrier and BGaP separate confinement heterostructure, and additional strain is caused by the differences in thermal expansion coefficient between the heterostructure and the silicon substrate.

heterostructure's (MQWH) high crystal quality is revealed by X-ray diffraction spectra and by transmission electron microscopy images (figure 1, p21). These don't provide any evidence for either dislocation formation or any related inhomogeneous strain relaxation in the MQWH. We have also studied our active region's direct-bandgap characteristics by using photoluminescence-based techniques, which show excellent agreement with our theoretical model (figure 2).

To allow us to assess the capability of our GaNAsP/GaP-MQWH for various optical devices, we have also grown a range of structures on GaP substrates that integrate this active region in AlGaP/GaP-separate confinement heterostructures. GaP substrates can easily be cleaved to form simple cavities and, because they have a similar lattice constant to silicon, the process is compatible. Silicon substrates, in comparison, are harder to cleave and laser facets have to be formed by more complex dry chemical etching processes.

We began our device development by studying the optical gain in simple structures that can cover the 850–950 nm wavelength range used for data communication applications. Measurements of the modal gain curve revealed that our structure's spectral width and peak modal gain were similar to those produced by standard III-V material systems.

These promising results have encouraged us to

fabricate broad-area devices that can deliver room-temperature laser emission when driven in pulsed mode. The typical threshold current density for these pulsed devices is 40 kA/cm², which is very high. However, these are early-stage results and the threshold current will come down as we optimize the growth and annealing conditions for our structure, and improve the optical and electrical confinement of our waveguide.

We believe that the proof of concept provided by these simple laser structures, which are built on GaP substrates, underlines the enormous potential for applications integrating III/V-based optoelectronics with silicon-based microelectronics. We are now starting to work towards this goal by developing a technology for the full monolithic integration of our GaNAsP material system with silicon microelectronics. Such a process must be as compatible as possible with existing standard CMOS-process technology so that it delivers the full benefits of integration. This means that it must be designed with the most common form of silicon used by this industry – (100) substrates.

CMOS processing demands the exactly orientated form of this substrate, which has typically been overlooked by many research groups developing heteroepitaxial processes for the growth of III-Vs on silicon. Instead, these groups have used off-axis wafers that improve material quality and

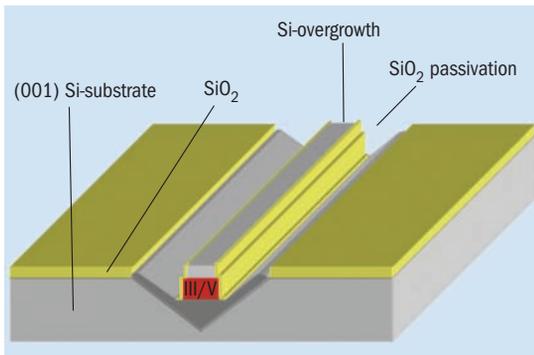


Fig. 4. The University of Marburg's technology features the fabrication of lasers in grooves in the silicon substrate. This means that once the laser has been defined and passivated, this III-V element of the device is "hidden", and conventional CMOS processes can be applied to the wafer without any threat of cross-contamination between the different types of material.

feature a series of atomic steps. However, with our proprietary process, we can deliver the benefits of an off-orientated substrate from an exactly orientated form of this platform (see box "Double stepping on a flat surface").

The high-quality buffer layers produced by this approach have been used as the basis for growing our GaNAsP-based laser structures, which have excellent crystal quality according to high-resolution X-ray diffraction measurements (figure 3, p22).

We plan to deposit this laser structure in recessed stripes of silicon substrates, which are formed by selective-area growth (figure 4). Such an approach guarantees the planarity of the wafer for subsequent process steps and is compatible with a 750°C post-growth anneal that improves the structure's optoelectronic properties. This anneal would take place before CMOS processes are carried out that cannot stand such high temperatures.

Once the laser has been deposited, its sides will be passivated with SiO_x and SiN_y , and high-reflection and anti-reflection coatings applied to the device's end facets, the latter formed by dry-etching processes. Heavily doped p-type and n-type silicon layers can then be used as contacts, thanks to the use of lattice-matched material for the laser. This avoids all of the problems associated with the use of non-CMOS-compatible metallization schemes, and it also "hides" the III-V material, thus allowing CMOS processing without any threat of cross-contamination.

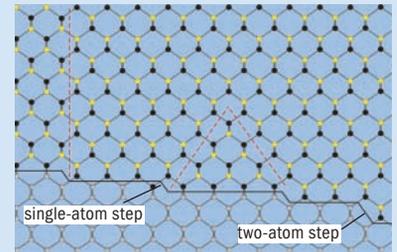
Our progress has enabled us to secure €8.5 million (\$12.3 million) to continue to develop this technology, through funding from Germany's federal ministry of education and research High Technology Initiative program. This three-year venture, called MonoLaSi, will run until 2010 and has two main aims: to fabricate prototype monolithic continuous-wave ridge waveguide lasers on silicon for data communication applications, and to develop a bespoke growth tool.

The partners involved in this project come from

Double-stepping on a flat surface

Research groups developing processes for the growth of III-Vs on silicon have tended to focus on off-axis (100) silicon substrates. These platforms feature steps in their surface that are one or two atomic layers high (top figure). Annealing prior to GaAs or InP nucleation promotes the formation of silicon two-atom steps. This reduces the proportion of unwanted single-layer atomic steps that cause charged defects at anti-phase boundaries, which are formed when two group-III atoms, or two group-V atoms, bond.

At the University of Marburg, researchers have developed a proprietary process that can produce double steps on exactly orientated (100) silicon substrates. Employing this approach with optimized GaP nucleation conditions terminates the small number of anti-phase boundaries that are



formed, leading to high-quality GaP buffer layers. These layers are free from anti-phase domains after just 30–40 nm of GaP growth, according to dark-field transmission electron microscopy images (bottom figure).

industry, publicly funded research institutions and academia. They are led by NAsP III/V, our spin-off from the University of Marburg. NAsP III/V will carry out the MOCVD deposition of the monolithic-ridge waveguide laser structures on silicon wafers with recessed stripes. Aixtron will develop a growth tool capable of depositing III-Vs and silicon on 300 mm wafers, Dockweiler Chemicals will provide specifically purified group-V precursors and Osram Opto Semiconductors will offer expertise in qualifying the technology and laser manufacture.

The Fraunhofer Institute for Applied Solid-State Physics, Freiburg, will perform processing, develop chip technology and characterize the lasers, which includes lifetime testing. Among the players from academia, the Ruhr-University Bochum will carry out experimental characterization of the gain and the laser properties of our dilute nitrides, and Philipps-University Marburg will be analyzing the MOCVD growth process and performing first-principle calculations of the gain and lasing characteristics.

We believe that our monolithic III/Vs-on-silicon laser will be a key component for delivering future on-chip, chip-to-chip and/or backplane optical interconnects. However, this is not the only sector that will benefit from such a device. This technology promises to deliver low-cost devices for fiber-to-the-home connectivity and terrestrial high-efficiency III/V-multijunction solar-cell stacks on germanium and silicon substrates, as well as the development of novel n-channel III/V-layers for CMOS-transistor devices. Our consortium will provide research and development results and technology processes for all of these applications, as well as the production tool for the manufacture of all of these types of device.



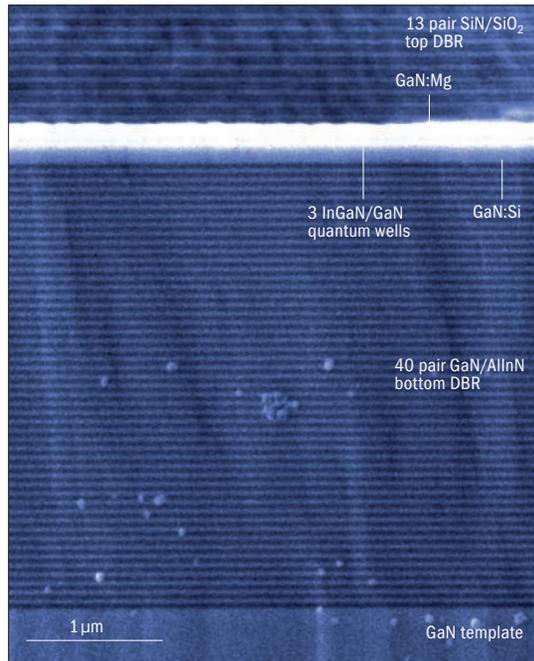
About the author

Wolfgang Stolz is the CTO of NAsP III/V and an academic at the University of Marburg.

AllInN mirrors spur VCSEL progress

Electrically pumped GaN VCSELs are just round the corner, thanks to the development of AllInN-based distributed Bragg mirrors and ring-shaped intracavity contacts, says EPFL's **Eric Feltin**.

Fig. 1. This scanning electron microscopy image of a GaN-based VCSEL made by EPFL reveals excellent uniformity in the lattice-matched AllInN/GaN distributed Bragg reflector.



Our community has produced several types of nitride device that offer better performance characteristics than their GaAs equivalents. GaN HEMTs can produce far higher power densities, while nitride LEDs can emit at shorter wavelengths that allow single chip, high-brightness white-light sources.

However, there is a gaping hole in the nitride portfolio – a GaN VCSEL. Such a device does not exist because it is very difficult to produce highly reflecting mirrors that operate in the blue-violet spectral range with good electrical conductivity. But a GaN VCSEL could offer several desirable attributes over a GaN edge-emitting laser including a lower threshold current, a circular emission profile that simplifies coupling into optical fibers and a reduced price, thanks to higher yields and on-wafer testing.

Despite these advantages, it is highly unlikely that a GaN VCSEL would replace an edge-emitter in today's Blu-ray and HD DVD players. That's because it would need to be in the form of an array to deliver sufficient power, and major changes would be needed in the technology employed for reading/writing functions. However, this device could enjoy success in a variety of other applications. Xerox has built some very high-quality 2400 dpi printers with infrared VCSEL arrays, and even higher resolutions may be possible by switching to GaN-based equi-

valents. These shorter-wavelength arrays could also serve in small laser-based projectors, and single GaN VCSELs could offer an alternative to their red-emitting cousins employed in optical mice.

All VCSELs feature a pair of high-quality mirrors with a reflectivity of at least 99%, which compensate for the small active volume that is a consequence of this emitter's vertical design. The mirrors for conventional arsenide-based VCSELs are relatively easy to manufacture because they can be produced by making distributed Bragg reflectors (DBRs) from alternating layers of GaAs and AlAs. These two materials have good conductivity, very similar lattice constants and a significant refractive index contrast, which means that high-reflectivity defect-free mirrors that are capable of good carrier injection can be produced from an acceptable number of mirror pairs. Nitride-based VCSELs, however, can't call on an equivalent pair of nitride materials that are so well matched for making mirrors.

Up until now, research into nitride-based DBRs has focused on AlGaIn and GaN, but it has proved impossible to produce mirrors of sufficient quality with this pair. The combination has a good refractive index contrast, but this comes at the expense of a lattice mismatch of up to 2.4%, which causes the epiwafer to crack and prevent laser manufacture. Sophisticated strain-engineering solutions can overcome this cracking, but even free-standing GaN substrates can't prevent the high dislocation densities that result from plastic relaxation.

Dual-purpose mirrors

The mirrors employed in an infrared emitting VCSEL are not just there to reflect light back into the device – they also transport carriers from the metal contacts to the central part of the active region. Injecting these carriers is relatively easy for arsenide-based VCSELs, but it is a major stumbling block when designing a nitride equivalent. The problems can be bypassed with intracavity contacts, but these can hinder lateral current spreading, which is needed to transport the carriers to the device's center.

A high current must be confined within an area of a few microns to produce the current density required for lasing. In an arsenide VCSEL, this confinement is produced by partial chemical oxidation of an AlAs layer inserted in the active region. However, this process is incompatible with GaN-based VCSELs, because AlN increases the structure's strain and defect density, and it can't be oxidized.

“Our quality factors are the highest reported values for a nitride VCSEL under current injection and we believe that lasing is within our grasp.”

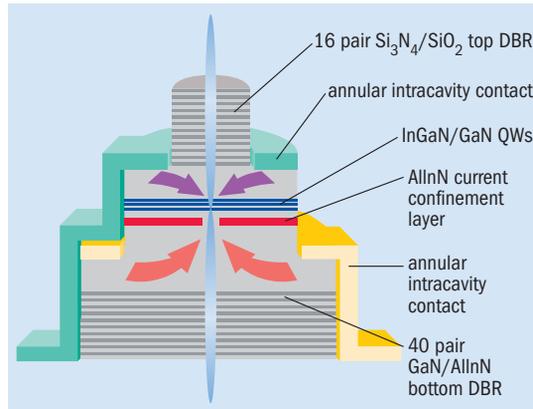
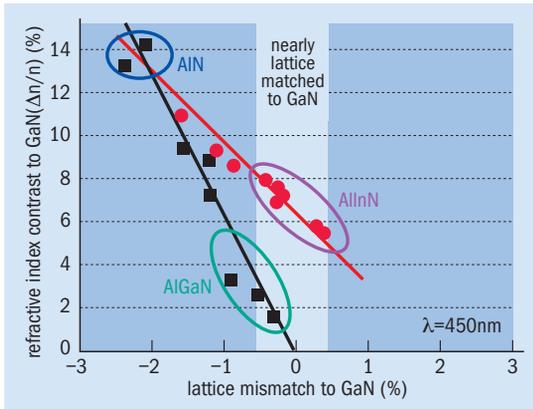


Fig. 2. (far left) GaN VCSEL development has been held back by AlGaIn/GaN mirrors that tend to crack due to the difference in lattice constant between the two materials. However, these problems can be overcome by switching to AlInN, which can be matched to GaN. **Fig. 3.** (left) Researchers from EPFL have fabricated GaN VCSEL structures that feature a bottom mirror with 40 pairs of alternating AlInN and GaN layers, alongside a dielectric 16 pair DBR with SiO₂ and SiN layers. Photoluminescence from this device has a linewidth of just 0.30–0.35 nm. **Fig. 4.** (bottom) Ring-shaped contacts produce a circular emission pattern from the LEDs (**a**) and lasers (**b**). The contacts are 10 μm in diameter, but the light is localized in the non-oxidized part of the device, which is 3 μm in diameter.

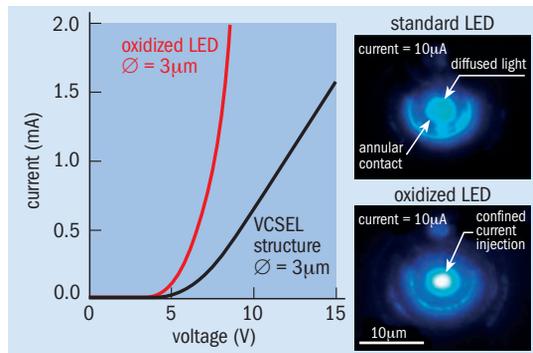
Current confinement from selective oxidation or etching of a nitride alloy could be a solution, but this requires sophisticated processes, such as photochemical etching and electrochemical oxidation.

To overcome some of the difficulties associated with AlGaIn-based mirrors, our team headed by Nicolas Grandjean from the Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, has developed microcavities based on the Al_{1-x}In_xN alloy (figure 1, p24). This material has a perfect lattice match with GaN at an indium content, *x*, of 17%, and a far higher refractive index contrast than that of AlGaIn-based mirrors (figure 2).

AlInN is difficult to work with because it is thermodynamically unstable. The Al–N and In–N covalent bonds have a large mismatch, which drives phase separation and compositional inhomogeneity. Incorporating indium into the AlN matrix is very challenging because InN prefers growth temperatures below 600°C and AlN is grown at 1100°C.

Despite these difficulties, we have developed an MOCVD process that can routinely produce high-quality Al_{1-x}In_xN layers with an indium content of less than 30%. This is done using growth temperatures between 800 and 850°C, a pressure of less than 100 mbar and nitrogen as a carrier gas that prevents indium desorption. This growth temperature window prevents the degradation of AlInN's crystalline quality, which would occur at lower temperatures, and allows sufficient indium to be incorporated, which is not possible at higher temperatures. Reducing the growth rates to 0.2 μm/h prevents surface roughening and the formation of indium clusters, and there is no variation in indium content, according to X-ray diffraction measurements.

Thanks to this lattice-matched growth, we can produce AlInN/GaN DBRs on sapphire substrates that are free from any additional dislocations. These structures typically have 40 mirror pairs and 99.4% reflectivity, and microcavities built from them have a quality factor (the cavity mode's wavelength divided by its linewidth) of 2800. This key figure of merit for any VCSEL – which is inversely proportional to its optical losses – is a big improvement over the previous best value for AlInN microcavities of 800, but it is still considerably less than the high-



est figure for planar GaAs microcavities – 11,000.

As mentioned, VCSEL mirrors have a second purpose – providing electrical injection into the active region. Unfortunately, the Al_{1-x}In_xN and Al_yGa_{1-y}N layers hamper electron and hole transport due to the large band-offsets between these alloys. In addition, the layers with high aluminum content have a low conductivity that leads to a fairly high series resistance and poor vertical injection through the DBRs.

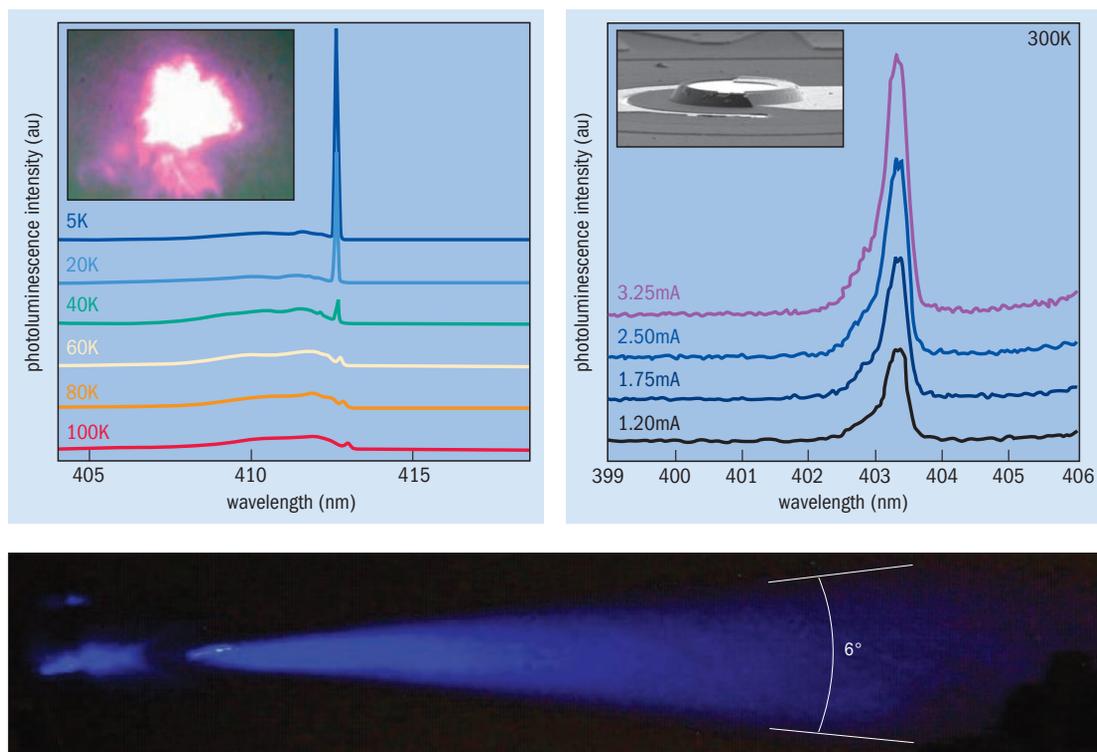
Switching to dielectric DBRs is not a solution because this structure is not conductive. However, success is possible by turning to a VCSEL design that injects carriers from intracavity contacts, which are metallic rings inserted between the mirrors and the active region (figure 3). Producing such a device is not straightforward because sufficient hole injection for lasing cannot be produced at acceptable levels of optical loss from either tunnel junctions or semitransparent contacts, such as ITO or thin metallic films. It is also tricky to implement a ring-shaped geometry that prevents contacts from reabsorbing the emitted light, because the nitride's poor hole transport prevents carriers moving from the rings to the center of the active region. This is a major concern because lasing requires high current densities in the very center of the device where optical confinement is optimized.

However, we can get round all of these problems by replicating the current-confinement technology found in arsenide VCSELs. In our case, we oxidize part of an AlInN layer that is inserted close to the quantum wells. This confines the carriers in the cavity's non-oxidized region, which enables the



EPFL has overcome the problems of epiwafer cracking (left) by switching to lattice-matched materials.

Fig. 5. (right) Continuous-wave optical pumping with a 351 nm Ar⁺ laser with an excitation density of 60 kW/cm² produces narrow emission lines at low temperatures. **Fig. 6.** (bottom) Emission from optical pumping is a singlemode beam with a linewidth of just 0.025 nm. **Fig. 7.** (far right) Destruction of the p-contact prevents the lasing of GaN VCSELs, but these devices do exhibit line narrowing as drive current increases.



use of electrical contacts with a ring geometry.

The first device that we built with this technology was an LED that had a circular emitting area with a 3 μm diameter. It had a current density of 20 kA/cm² and an output power of 400 kW/cm² (figure 4, p25). We followed this up with a crack-free VCSEL structure on sapphire, which featured an active region with three InGaN/GaN quantum wells and a hybrid microcavity – a 40 pair lattice-matched AlInN/GaN bottom DBR and a 16 pair SiO₂/SiN top DBR mirror. A fully epitaxial structure was not used, even though it would have offered better optical quality, because processing would have been challenging. Hole injection through a nitride DBR is not possible, so mirror etching would be required before the contacts were defined, but this step demands an unattainable precision without an etch-stop layer.

Before we processed our wafers, we measured the microcavity's quality factor and found that it peaked at more than 3000. This high value enabled a lasing threshold for pulsed optical pumping of just 300 kW/cm² at room temperature and allowed us to observe lasing under CW excitation with a power density of 10 kW/cm² at temperatures of more than 50 K (figure 5). The emission from this structure is a high-quality singlemode beam with a linewidth of just 0.025 nm and a divergence angle of 6° (figure 6).

We then measured the electrical characteristics of our lasers, which have a thinner cavity than our LEDs. This adjustment increases the device's resistance and cuts its typical maximum current density. Under pulsed operation the p-type contact of these VCSELs fails at less than 10 kA/cm². Unfortunately, this is just below the theoretical value for the onset

of lasing. However, we did see some electroluminescence from this device, which had a 0.3–0.35 nm linewidth that corresponds to a quality factor of 1200–1600 (figure 7).

The values for the quality factor are lower than those obtained on unprocessed wafers, which we attribute to “edge effects”. These impact the deposition of the top dielectric DBR over the structured surface, which takes place after mesa etching and the deposition of the electrical contact. Nevertheless, these quality factors are the highest reported values for a nitride VCSEL under current injection and we believe that lasing is within our grasp. Typical threshold currents for edge-emitting laser diodes on sapphire substrates are a few tens of kiloamps per square centimeter. Taking into account the vertical geometry of our VCSELs, we expect to reach the lasing threshold at a similar current density when the microcavity quality factor approaches 3000.

We have definitely made a great deal of progress, but there are still several obstacles to overcome before we make the first GaN VCSEL that delivers lasing via electrical injection. Refinements in the process used to form the intracavity ring contacts are needed because the existing approach seems to reduce the microcavity's quality. In particular, deposition of a more uniform top dielectric DBR is needed to cut optical losses, boost the cavity's quality factor and ultimately decrease the threshold current density to a sustainable value. A switch from sapphire to free-standing low dislocation GaN substrates should complete the list of improvements required, as this will increase VCSEL quantum efficiency and thermal management capability. ●



About the author

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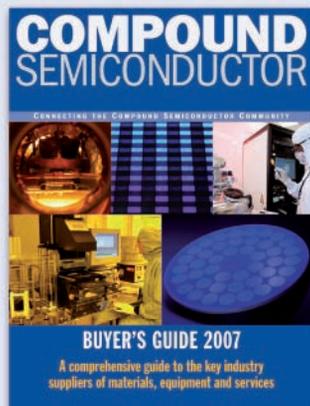
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LASERS

QCLs stretch to shorter wavelengths

Quantum cascade lasers (QCL) can now emit at even shorter wavelengths, thanks to the efforts of Alexei Baranov and colleagues at the University of Montpellier, France.

The team has fabricated an InAs/AlSb device that can operate in pulsed mode at 80 K and produce 0.3 W per facet at 2.75 μm . A second device that is made from the same material system can operate close to room temperature and deliver 1.5 W per facet, but at a longer emission wavelength of 2.97 μm .

Baranov says that both of these lasers could be useful for spectroscopic applications because the spectral region near 3 μm contains absorption lines corresponding to stretching vibrations of some diatomic molecules. In particular, nitrogen–hydrogen and

oxygen–hydrogen bonds have strong absorption lines between 2.7 and 3.3 μm .

To produce such short emission wavelengths requires the pairing of two materials with a very large conduction band offset. InAs and AlSb are a great combination because their offset is 2.1 eV.

Baranov says that the difficulties associated with MBE growth of these materials are comparable to those of other III-Vs, but he points out that care must be taken over the growth conditions at the interface. There are no common atoms at the interface and any InSb or AlAs bonds formed will introduce a high degree of strain into the epiwafer. This degrades crystalline quality and hampers the device's electronic performance.

The researchers are currently using rapid processes to form their lasers so that they can quickly compare device and modeling results. However, this approach leads to lasers with poor thermal dissipation, which means that continuous-wave (CW) operation can only occur at low temperatures.

The team is aiming to address this weakness and one of its next goals is to produce a QCL capable of room-temperature operation under a high duty cycle or CW operation. Improvements will be made to the laser design and the processing, says Baranov.



Journal reference

AN Baranov 2007 *Appl. Phys. Lett.* **91** 251102.

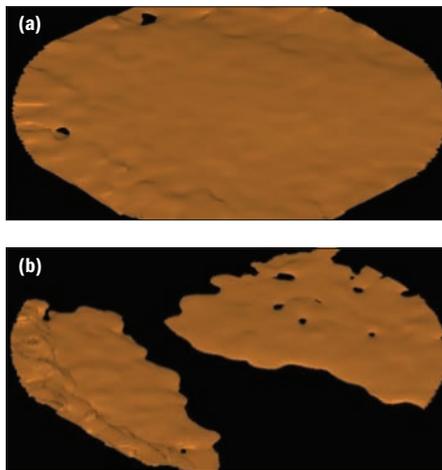
LEDs

Atom probe uncovers gross inhomogeneity

Colin Humphreys' group at the University of Cambridge, UK, has found that UV-emitting InGaN/GaN multiple quantum-well (MQW) structures can contain gross discontinuities and compositional variations within the wells on a 20–100 nm length scale.

These findings, observed with the 3D atom probe technique, will help to unravel the relationship between the structure of InGaN and its luminescent properties, which is a hot topic in the scientific community.

The variation seen in a 10-period InGaN/GaN quantum-well structure that emits at 380 nm is in contrast to the high degree of uniformity observed in blue-emitting quantum-well structures. This difference is down to the growth temperatures employed. The UV structure uses different growth temperatures for the wells and barriers while the active region of the blue-emitting sample was grown at a fixed temperature.



Cross-sections from the 3D atom probe map show regions (brown) with an indium content in the InGaN layer exceeding 2.8%. **(a)** A quantum well with relatively uniform indium content. **(b)** A quantum well with gross fluctuations in indium content.

Atomic force microscopy measurements determined the compositional variations in the UV structure on a longer length scale.

Measurements on a single InGaN epilayer, which has the same thickness and composition as one of the wells of the 10-period MQW structure, revealed a discontinuous but interconnected network structure.

A similar morphology was previously observed in green-emitting InGaN/GaN single quantum-well structures, which have the majority of their threading dislocations passing through gaps in the layers. The researchers believe that a similar arrangement occurs in their 380 nm sample, which accounts for its high efficiency of 67%.

The atom probe will now be used to look at samples emitting over a wider range of wavelengths and thicker, relaxed epilayers of InGaN. "It is important to understand whether epilayers and quantum wells behave in a similar way, since much work aimed at understanding quantum wells is performed on epilayers," commented team member Mark Galtrey.



Journal reference

MJ Galtrey *et al.* 2008 *Appl. Phys. Lett.* **92** 041904.

EPITAXY

Low pressures boost growth rate of 4H-SiC

The fastest growth rate of high-quality 4H-SiC has been increased from just over 100 $\mu\text{m}/\text{h}$ to 250 $\mu\text{m}/\text{h}$, according to researchers at Japan's Central Research Institute of Electric Power Industry.

This hike should ultimately speed up the

fabrication of bipolar devices operating at 10 kV or more. These devices, which could be used for electrical switching in national grid networks, require SiC layers that are at least 100 μm thick.

The faster growth rates result from a very low system pressure and high flow rates for hydrogen and silane gas. This combination prevents silicon clusters, which limit the SiC growth rate, from forming.

The team used a vertical hot wall reactor

with a 175 mm susceptor. Silane, propane and hydrogen were fed into the reactor and deposition took place at 1650 $^{\circ}\text{C}$ and 15 Torr. A hydrogen flow of 70 l/min was used alongside a carbon:silicon ratio of 1. The fastest growth rate for good-quality material occurred at a silane:hydrogen ratio of 0.005.



Journal reference

M Ito *et al.* 2008 *Appl. Phys. Express* **1** 015001.

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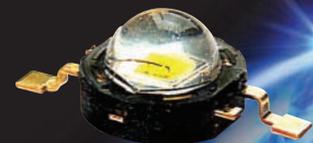
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