COMPOUND SEMICONDUCTOR

May 2008 Volume 14 Number 4

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

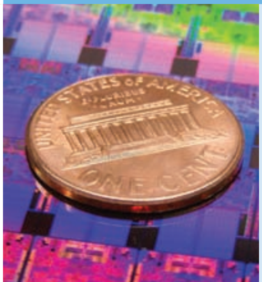
PHOTOVOLTAICS

The sky really is the limit for III-V solar

MARKET REPORT

Wait goes on for killer wide-bandgap application p12

TECHNOLOGY



CMOS future

Compounds and germanium: the saviors of silicon? p21

MATERIALS

Growth prospect

Osaka University team shows how sodium and nitrogen make GaN crystals bigger. p20


Meet Graham. His innovative approach to helping customers large and small starts with identifying the fit between their needs and TriQuint's foundry processes. With the industry's largest in-house GaAs technology portfolio to choose from, he helps customers imagine the possibilities and turn ideas into products. Whether working with a first-time customer or long-term engagement, his commitment to your satisfaction and success is unwavering. Graham is one of the people behind the innovation at TriQuint Semiconductor, and he's on your team.
Visit www.triquint.com/foundry and register for new product and process updates.
LEARN MORE ABOUT OUR LATEST FOUNDRY PROCESSES AT THE 2008 IEEE MTT-S SYMPOSIUM – BOOTH #1027.
TriQuint SEMICONDUCTOR®
Connecting the Digital World to the Global Network®
INNOVATION
BEGINS WITH PEOPLE
Phone: +1-503-615-9000 • Fax: +1-503-615-8900 • E-mail: foundryinfo@tqs.com • Website: www.triquint.com

COMPOUND SEMICONDUCTOR

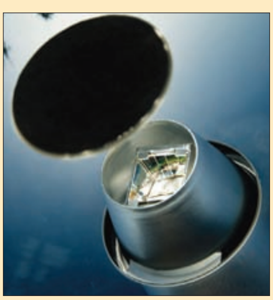
May 2008
Volume 14
Number 4

Connecting the Compound Semiconductor Community

Industry


OSRAM OS

Fab expansion
Osram Opto Semiconductor's huge LED fab in Regensburg is now complete. **p8**

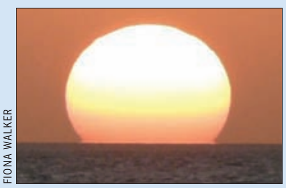

SOLFOCUS

Larger wafers cut costs
The use of larger germanium wafers would cut the cost of triple-junction cells used in concentrator photovoltaic systems. **p10**


ABB

New applications
Switch-mode power supplies are one obvious application area for SiC-based diodes. **p12**

Technology


FIONA WALKER

Setting a trend
Terrestrial photovoltaics is a booming industry and dozens of new companies are hoping to get in on the action. **p14**

INTEL

The future is optical
Future computer chip microprocessors will put demands on the electrical interconnects between processors. Optical interconnects will be needed to replace them. **p25**

Main cover image: *SolFocus is one of a rapidly growing number of companies working on concentrating photovoltaics systems. On the cover is an array of mirror modules that focus sunlight onto III-V semiconductors. See pp 10 and 14. Credit: SolFocus.*

BPA
Compound Semiconductor*'s circulation figures are audited by BPA International*

COMPOUND SEMICONDUCTOR

Editor Michael Hatcher
michael.hatcher@iop.org
Tel +44 117 930 1013. Fax +44 117 925 1942

Features editor Richard Stevenson
richard.stevenson@iop.org
Tel +44 117 930 1192

Reporter Andy Extance
andy.extance@iop.org
Tel +44 117 930 1007

Senior sales executive David Iddon
david.iddon@iop.org
Tel +44 117 930 1032. Fax +44 117 920 0977

Business development manager Rosemarie Guardino
Guardino@ioppubusa.com
Tel +1 215 627 0880. Fax +1 215 627 0879

Sales executive Paul Russo
russo@ioppubusa.com
Tel +1 215 627 0880

Circulation manager Claire Webber
claire.webber@iop.org
Tel +44 117 930 1165. Fax +44 117 920 0984

Publisher Nicola Gulley
Production Louise Unwin
Ad production Mark Trimnell
Art director Andrew Giaquinto
Technical illustrator Alison Tovey

Subscriptions
Available free of charge to qualifying individuals working at compound semiconductor fabs and foundries. For further information visit compoundsemiconductor.net/subscribe. Subscriptions for individuals not meeting qualifying criteria: individual £95/$174 US/€142; library £209/$378 US/€305. Orders to: *Compound Semiconductor*, WDIS, Units 12 & 13, Cranleigh Gardens Industrial Estate, Southall, Middlesex UB1 2DB, UK. Tel +44 208 606 7518; Fax +44 208 606 7303.
General enquiries: compoundsemi@iop.org.

9835 average total qualified circulation*
*December 2007 BPA audit statement

Editorial board
Mayank Bulsara Atlas Technology (USA); **Andrew Carter** Bookham Technology (UK); **Jacob Tarn** OCP/Gigacomm (Taiwan); **Ian Ferguson** Georgia Institute of Technology (USA); **Toby Strite** JDSU (USA); **Mark Wilson** Freescale (USA); **Dwight Streit** Northrop Grumman (USA); **Joseph Smart** Crystal IS (USA); **Colombo Bolognesi** Swiss Federal Institute of Technology (Switzerland); **Shuji Nakamura** University of California at Santa Barbara (USA)

©2008 IOP Publishing Ltd. All rights reserved.

US mailing information: *Compound Semiconductor* (ISSN 1096-598X) is published 11 times a year for $174 by IOP Publishing, Dirac House, Temple Back, Bristol BS1 6BE, UK. Periodicals postage paid at Middlesex, NJ 08846.
POSTMASTER: send address corrections to *Compound Semiconductor*, c/o PO Box 177, Middlesex, NJ 08846. US agent: Pronto Mailers Association Inc, 200 Wood Avenue, PO Box 177, Middlesex, NJ 08846.

IOP Publishing

EDITORIAL

When the going gets tough

Imagine the scene. It's early 1991, and times are hard. The economic gloom that descended in the late 1980s has yet to budge and semiconductor firms are, as usual, in the front line. Talk of lay-offs is in the air and gossip spreads even more quickly then normal. For Bill Pratt and Powell Seymour at Analog Devices, time is running out.

And yet, this difficult time witnessed the birth of a new industry. After being ditched by their long-term employer, Pratt and Seymour started up RF Micro Devices (RFMD). Shortly afterwards they hired Jerry Neal and the three of them set about building the company that became the dominant force in GaAs RF semiconductors, and which now turns over more than $1 billion per year. What's more, they did it without an MBA in sight: all technologists by training, Neal, Pratt and Seymour bought their first business plan from Office Depot for $29.

Last month, the two original founders called time on their RFMD careers, bringing down the curtain after 17 years and no doubt looking back on what they have achieved with a great sense of pride.

> "With the economic fog once again closing in, Neal, Pratt and Seymour should stand out as inspirational figures."

The genesis of RFMD just goes to show how opportunities can arise at the unlikeliest times. And with the economic fog once again closing in, Neal, Pratt and Seymour should stand out as inspirational figures. Back in 1991 the GaAs HBT was a revolutionary technology that was yet to prove itself in the commercial world and which many thought would never succeed. How many other compound semiconductor technologies are waiting to be exploited in the same vein now?

In his book *Fire in the Belly*, Neal points out that there are no magical routes to success, no roadmaps to guarantee success, or easy answers. Hard work, tenacity and sheer good fortune are three of the key ingredients. RFMD has certainly endured some tough times – Neal's book entertainingly recalls many, from incredible disappearing chips and tensions at key customer Qualcomm, through to the technology meltdown of the early 2000s – and will no doubt do so again in the future. Pratt and Seymour may have just cashed in their chips, but there should be no shortage of technologists ready to open their accounts.

Michael Hatcher *Editor*

Emerging Standardization for Sapphire Substrate Inspection

By Frank Burkeen

Senior Product Marketing Director at KLA-Tencor
Frank.Burkeen@kla-tencor.com

KLA-Tencor Accelerating Yield®

The HBLED industry continues to thrive driven by market demand from mobile devices, automobiles, computer screens, and niche exterior and interior lighting applications. As HBLED device technology evolves and fabrication techniques become more advanced, defect detection and process control are critical to improving device yields. Sapphire substrate contaminants such as particles, scratches, pits, bumps, stains and residues from CMP processing are known to impact subsequent epi deposition processes and substantially degrade device performance and yield. As such, the need for higher quality sapphire substrates is of critical concern for HBLED device manufacturers.

The adoption of optical surface analyzer (OSA) technology is gaining momentum for use in HBLED manufacturing, specifically sapphire substrate inspection.

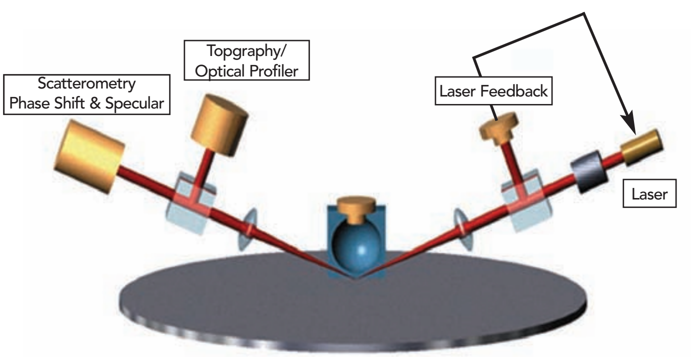


Figure 1: OSA technology combines four signal detection channels, enabling a wide range of inspection applications.

The design of OSA technology combines reflectometry, optical profilometry, scatterometry, and phase shift to measure topographic variations and detect a wide variety of surface defects. The inspection method achieves full surface coverage in minutes to produce high-resolution imaging, wafers maps, and automated defect classification.

At a throughput exceeding 40wph, an OSA system is the only wafer inspection method amenable to volume production and capable of advanced inspection of transparent sapphire substrates. Other inspection tools based solely on scatterometry cannot effectively measure transparent materials due to scattered light interference from the backside of the substrate. An OSA system is designed specifically for defect detection and classification of transparent materials including sapphire, GaN, SiC, and glass.

Figure 2 illustrates a sapphire substrate defect map after OSA inspection. Particles, scratches, pits, and stains are detected and classified in user-defined bins. The defect traceback images show a scratch as detected in the topography channel and two different types of stains as detected in the phase channel.

Scratches are known to transfer to the subsequent epi layer thereby degrading or killing device performance. Substrate stains have been reported to cause poor epi layer adhesion or result in rough epi morphology.

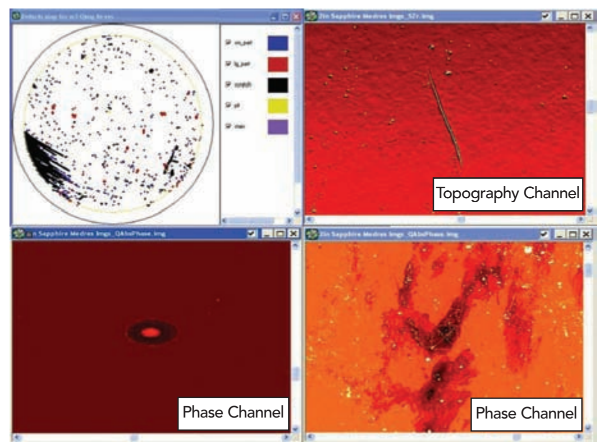


Figure 2: KLA-Tencor's Candela™ OSA defect map and traceback images of scratches and stains as detected in topography and phase channels, respectively.

As HBLED competition tightens and margins are squeezed, manufacturers are relying more on automated OSA inspection technology for process control and yield improvement. The emergence of sapphire substrate reclaim is also driving the need for advanced automated inspection. As supply is strained and material costs rise, the sapphire reclaim business is becoming more prevalent — whether for captive consumption or merchant supply. The reclaim business is even more dependant on OSA inspection as reworked material is highly susceptible to yield impacting defects.

Optical surface analyzer technology is setting the benchmark for automated inspection of sapphire substrates, and is emerging as the industry standard for overall sapphire quality control. HBLED device manufacturers and sapphire substrate suppliers are together converging on OSA inspection specs for quality assurance. Moreover, manufacturer's utilizing OSA technology are the beneficiaries of higher quality sapphire substrates passing distinct inspection specs.

Optical surface analysis technology enables manufacturers and suppliers to automate defect inspection and define objective-controlled process control limits. OSA technology can be employed at incoming substrate inspection, post-clean inspection, and after epi and film deposition processes.

To learn more, go to:
www.kla-tencor.com/candela

Sponsored Editorial. © 2008 KLA-Tencor Corporation.

Your premier choice for III-V and Ge substrates and related strategic raw materials.

axt

VGF

STRENGTH.

PERFORMANCE.

INNOVATION.

OUR VISION

To be the number one advanced semiconductor materials supplier of choice through superior quality, effective cost of ownership, and a customer focused philosophy.

OUR MISSION

To identify and develop growth opportunities that will ultimately result in exceeding customer's expectations, market share enhancement, sustainable profitability, and provide shareholder value.

USA Headquarters
4281 Technology Drive
Fremont, CA, USA 94538

T: 510-438-4700
F: 510-353-0668

E: sales@axt.com
W: axt.com

PHOTOVOLTAICS

Spectrolab nets 350 MW six-year deal

Spectrolab has grabbed the largest terrestrial III-V solar cell order to date, with Australian firm Solar Systems saying that its 350 MW purchase is worth more than $100 million.

The cells will primarily be destined for a 154 MW concentrating photovoltaic (CPV) power plant that Solar Systems is building with the help of an AUS$130 million Australian government subsidy. Although that project will not be completed until 2013, Solar Systems hopes to bring a related demonstrator project that produces 174 kW at peak output online this year.

The order is the third that Solar Systems has placed with Spectrolab since its move away from Sunpower's silicon cells to Ge/GaAs/GaInP triple-junction technology. As the two previous contracts combined only amounted to 10 MW, the big jump in scale represents a significant validation of Spectrolab's CPV technology.

"We moved from silicon to multi-junction III-V cells because it had more legs in terms of efficiency," explained Dave Holland, Solar Systems' managing director. "Also, working with small [III-V] cells makes it much quicker and easier to take them from a hero cell in the lab to production."

The overall deal is for photovoltaic assemblies. These manage heat dissipation and maintain optimum performance conditions for the compound semiconductor cell.

Beyond its work on new power generation projects, Solar Systems is retro-fitting existing power stations to replace silicon cells with Spectrolab technology. At the CPV Today conference held in Madrid, Spain, in April the company said that this process takes only 30 minutes per receiver.

As well as the Australian and Victoria state governments, Solar Systems is backed by TRUenergy, a power company that supplies gas and electricity to 1.1 million homes in Victoria. TRUenergy has promised to spend up to $285 million on a 154 MW solar power station.

Now, armed with a secure supply of high-efficiency cells from Spectrolab and financial backing, Holland is ready to begin the fight to provide economical solar power. "A 100 MW project gives us the critical mass to bring the cost down enough to let us compete with fossil-fuel-based energy that has to account for its emissions," he said.

Spectrolab has also signed a five-year supply contract with OPEL International, whose CPV technology comes from the University of Connecticut and the Canadian National Research Council. So far OPEL has placed a firm order for 10 MW of cells scheduled for 2008.

● The US CPV system vendor SolFocus is the primary mover behind the CPV Consortium, a new industry group that lists Emcore and Spectrolab among its members. SolFocus' vice-president of corporate marketing Nancy Hartsoch said: "What we need is technology that disrupts the way that energy is produced and consumed." The aims of the consortium include educating investors, energy-generating companies and others about the merits of the technology.

EQUIPMENT

Oxford Instruments ventures into epitaxy

Equipment maker Oxford Instruments has broken into the lucrative LED epitaxy equipment market, with a $1 million cash purchase of Technology and Devices International, Inc (TDI). The deal could increase to $6 million, depending on revenues from sales of TDI's hydride vapor phase epitaxy (HVPE) reactors.

Oxford Instruments will also take on debts of $2.2 million, and a business that ran at a $0.8 million pre-tax loss in the year ended June 2007. TDI will continue day-to-day business at its Silver Spring, MD, site with Oxford Instruments providing management, sales and administration support.

The HVPE tool's potential to cut the cost of LED manufacturing through a faster deposition process compared with MOCVD is attracting attention, according to Andy Matthews, managing director of Oxford Instruments Plasma Technology (OIPT).

"A wide range of LED manufacturers support the concept of using HVPE for the growth of the nucleation and base layers in the production of templates," Matthews said. "We will be working with these [wafer] manufacturers, some of whom are existing Oxford Instruments customers, to provide the most cost-effective solutions to their production problems."

TDI also sells GaN, AlGaN and AlN epiwafers and this will continue to provide revenue as the combined company develops the HVPE tool business. Matthews makes the point that TDI's expertise in applying HVPE growth is important for customer support and further refining epitaxial processes.

OIPT says that it previously addressed three of the nine steps needed to make high-brightness LEDs, with existing tools for plasma etching to define the LED structure, device isolation by plasma-enhanced CVD, and substrate etching. Adding epitaxy as a fourth offering will enable the company to capitalize on already established knowledge and contacts in this sector.

WIDE-BANDGAP DEVICES

Raytheon readies GaN for a radar upgrade

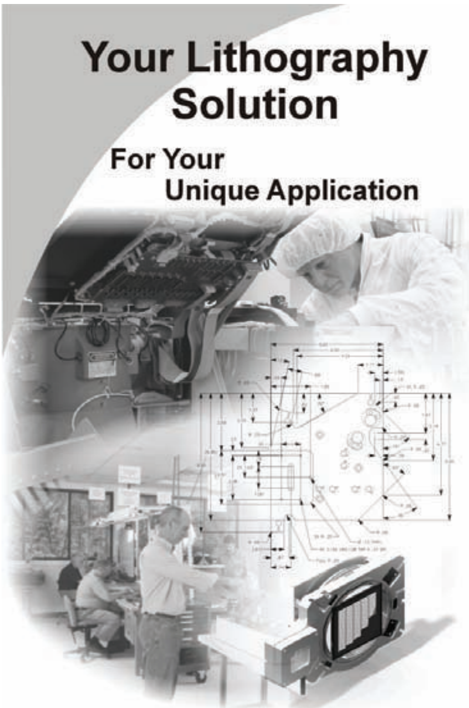
Raytheon says that transmit-receive modules based on GaN semiconductors are proving superior to existing military radar technologies, and are close to being deployed in future system upgrades.

"This transmit-receive module demonstration and parallel reliability testing shows that GaN will soon be ready to take over where increased power and advanced capabilities are needed," said Mark Russell, vice-president of engineering at Raytheon Integrated Defense Systems.

The development is part of an ongoing 42-month, $11.5 million Next Generation Transmit Receive Integrated Microwave Module contract funded by the Missile Defense Agency. Raytheon is demonstrating that transmit-receive modules using GaN provide significantly higher RF power with greater efficiency than current modules.

The GaN technology inside the radar systems has been developed under DARPA's ongoing wide-bandgap semiconductor program, as well as Raytheon's own efforts.

Russell says that GaN technology would increase radar ranges, as well as system sensitivity and search capabilities. Alternatively, the technology can be used to reduce the size of the required RF antenna, making the systems more compact, portable and cheaper without any performance sacrifice.



Beta Squared Lithography Inc. has redesigned the Micralign™ today for tomorrow's compound semiconductor requirements, incorporating BSL's trademark reliability and performance upgrades. We currently have systems throughout the world that are processing these substrates/applications:

- Gallium Arsenide (GaAs)
- Silicon Carbide (SiC)
- Sapphire (Al_2O_3)
- Cadmium Zinc Tellurium (CdZnTe)
- Cadmium Mercury Tellurium (CdHgTe)
- Germanium (Ge)
- Quartz (SiO_2)
- Pyrex
- Solar/HD Heads/Ink Jets
- Gyros/Accelerometers

To find out more information or to purchase a refurbished Micralign™ for your compound semiconductor requirements, email us at: sales@beta2L.com

Beta Squared Lithography Inc.

940 Federal Road, Brookfield, CT 06804
Phone: 203.775.4242 Fax: 203.775.1337
www.betaSquaredLithography.com

FOUNDRY

Kopin explores solar and HEMTs

Kopin is branching out into two currently high-profile compound semiconductor segments to extract greater value from its 6 inch GaAs wafer manufacturing facilities.

The company is developing MOCVD-based HEMT manufacturing processes at its Taunton, MA, facilities at the request of partners impressed by current HBT yields, while solar cells are also on the agenda.

Although the company's III-V business is now focused on GaAs HBT epiwafers, its first products were actually GaAs-based solar cells for powering satellites.

Talking to *Compound Semiconductor*, CEO John Fan downplayed the move to solar cells, saying that they would not be in the marketplace for "a couple of years".

"Solar cells are very involved because demands for efficiency, especially in concentrator cells, are so high," he said. "Also, some of the new ideas that we're exploring are pretty innovative, so it will take some time." But the move into HEMTs should come quickly: "We believe that the HEMTs, advanced structure HEMTs and HBT/HEMTs will be much more immediate."

Kopin still retains intellectual property from its early photovoltaic products, which it developed in conjunction with the US National Renewable Energy Laboratory and manufactured for Boeing. In its portfolio is a method for lifting a GaAs cell off its substrate and stacking it on top of another cell made from a different material, like silicon or copper-indium-selenium films.

"Lift-off technology allows us to make tandem cells much more flexibly," said Fan. "You can do series connect, parallel connect. You can do a lot of different things."

The CEO's comments come on the back of Kopin's results for 2007, in which the company made a $6.6 million loss, compared with losing just $2.1 million in 2006. The increasing deficit was in part due to gradual erosion of the company's selling prices, although the focus on new products will help to combat this trend.

Skyworks Solutions and Advanced Wireless Semiconductor Company, the Taiwanese fab to which Skyworks outsources some of its operations, accounted for $31 million of Kopin's $44 million compound semiconductor revenues in 2007.

● Skyworks has extended its HBT supply deal with Kopin until July 2010. Kopin will deliver all of the 4 inch material and the vast majority of 6 inch wafers to its key customer. The agreement also includes shipments of GaAs BiFET and dilute-nitride HBTs for more advanced RFIC fabrication.

MARKETS

Digital cable increases GaAs market to $100 m

Annual sales of GaAs components for digital cable networks will reach $109 million by 2012, as operators push to deliver high-definition television signals to homes.

Additional network roll-outs will drive an 11% annual growth rate in demand for GaAs chips from the $72 million recorded in 2007, according to a new report from market analysts at Strategy Analytics.

Components sold into the industry fall into one of two areas: those destined for set-top boxes or modems, and those that will be deployed in the network's wider infrastructure. Customer premises equipment (CPE) uses a greater proportion of the sector's discrete GaAs devices, whereas cable infrastructure drives the demand for MMICs.

"Anadigics is regarded as the leading supplier of GaAs components to both the cable infrastructure and the cable CPE market," said Asif Anwar, Strategy Analytics' GaAs market expert. "Other companies targeting this space with GaAs and other components include Freescale, NXP and TriQuint."

The report says that digital cable has increased penetration of GaAs technologies into the cable infrastructure market over the past few years. The compound semiconductor is better able to deal with digital's higher frequencies and the requirement for improved linear performance than silicon.

Infrastructure accounts for 57% of GaAs demand from cable networks, and will grow to 67% by 2012. As well as market-share expansion on the network scale, this is also due to competition from silicon components, which limits GaAs to less than 5% of its addressable market in CPE.

"GaAs demand will grow in set-top boxes, driven by multiple tuners," said Stephen Entwistle, vice-president of Strategy Analytics' strategic technologies practice. "However, silicon technologies will continue to dominate, limiting the overall compound annual average growth rate for [discrete] GaAs devices to no more than 5% over the next five years."

From our newsfeed…

visit *compoundsemiconductor.net* for daily news updates

…€15 million for Norstel
Swedish SiC wafer specialist Norstel has landed €15 million ($24 million) in venture financing as it bids to become a major supplier of the material. "It was a positive reaction from the investment community for the potential of SiC as an energy-saving material," said CEO Iain Jackson.

…Anadigics tools up
Anadigics' wafer fab expansion has seen the company install "multiple" new etch tools from equipment supplier Aviza Technology. The Omega etch systems, which can be used to etch SiN, GaAs backside vias or SiO_2, will help the GaAs chip firm to meet rapidly increasing demand for its products.

…Nitronex meets Merrimac
US firm Merrimac Industries has signed a memorandum of understanding with Nitronex, focused on the development of GaN power amplifiers. Using high-power GaN-on-silicon transistors, Merrimac plans to apply its multilayer circuit technology to develop new products for WiMAX and cellular infrastructure applications.

…Infrastructure gloom
The growing market for high-power RF semiconductor devices will be limited by a sharp decline in demand from the wireless infrastructure industry as 3G network build-out is completed, says a report from ABI Research. However, WiMAX could offer a lifeline to power chip manufacturers, explains report author Lance Wilson: "WiMAX remains controversial," he said. "Although fixed WiMAX is deploying, mobile WiMAX (802.16e) is in a state of flux. There is a potential large upside to mobile WiMAX, but there are no guarantees that this will actually occur. In spite of this possibility, the overall wireless infrastructure segment will decline by a compound annual growth rate of 2% over the 2007–2012 forecast period."

…Rudolph in at WIN
Characterization equipment vendor Rudolph Technologies has installed seven of its NSX series tools at Taiwanese GaAs foundry WIN Semiconductors. The NSX is aimed at back-end process steps and will be used by WIN to inspect RFIC wafers at the probe, bump and dice stages. Its combined defect analysis/yield management software is said to quickly trace patterns back to yield-killing process issues.

PEOPLE

RFMD's original founders retire

Two of the GaAs industry's visionaries, Bill Pratt and Powell Seymour, have retired. As co-founders of RF Micro Devices (RFMD), CTO Pratt and vice-president of strategic operations Seymour set up the company in Greensboro, NC, after they and Jerry Neal were laid off by Analog Devices.

They incorporated the fledgling firm in February 1991 and were joined by Neal three months later. They then set about building it into the compound semiconductor powerhouse that it remains to this day, sealing funding with original investor Kitty Hawk Capital in 1992, launching the HBTs that transformed the mobile phone handset industry the following year and completing its first GaAs foundry in 1998.

Thanks to some crucial deals with Nokia, the company grew rapidly as cell phones became ubiquitous during the late 1990s and subsequently delivered annual sales revenues in excess of $1 billion.

Pratt and Seymour enjoyed a bond as close friends and became in-laws when Carmina Pratt married Chris Seymour. For the full story on them, and on the emergence of one of the foremost GaAs manufacturers, read Jerry Neal's book *Fire in the Belly*.

TRADE DISPUTE

Seoul settles Rothschild dispute

Korean LED maker Seoul Semiconductor and Japan's Toyoda Gosei have become the first major companies to settle the latest dispute involving Columbia University professor Gertrude Neumark Rothschild. In February the academic accused 30 more companies that manufacture or use GaN LEDs and laser diodes of illegally employing semiconductor doping processes that she invented.

Rothschild lodged a complaint with the US International Trade Commission (ITC) against companies making products including blue, violet and ultraviolet emitters. On March 20 the ITC said that it would investigate the alleged patent infringement, with Seoul the first company to state its intention to settle.

"We're not aware of any commercial process other than the professor's that would produce those colors of light," commented Albert Jacobs Jr, the lead litigator representing Rothschild at the ITC.

Jacobs says that, by taking the case to the ITC, Rothschild could tackle many of the companies currently producing GaN emitters in one fell swoop. The list of companies involved reads like a who's who of electronic manufacturing, including global brands such as Nokia and LG down to chip-level companies like Rohm.

"Based on contacts that I've had with the respondents, some will see the wisdom of arriving at an early settlement," Jacobs said, prior to the Seoul and Toyoda responses. "My settlement terms are fair and reasonable, while litigation is always uncertain. The downside of proceeding to trial at the ITC is that the products could be enjoined for importation into the US. It blocks importation at all of the entry points in the US – that's a severe negative in terms of marketing your product."

The dispute revolves around US patents 4,904,618 and 5,252,499, which cover processes for the doping of wide-bandgap semiconductor epitaxial layers using two materials. The first is frequently magnesium and the second hydrogen, but according to the patents the specific dopants may vary.

Rothschild developed these processes during her tenure as a professor of materials science at Columbia University, NY, a post that she has held since 1985.

Jacobs says that the octagenarian professor emeritus has settled federal US patent cases with Toyoda Gosei, Nichia, Osram and, most recently, Philips Lumileds.

Ironically, Rothschild previously worked as a physicist at Sylvania (part of Osram) and Philips. Perhaps this influenced the decision to establish a Philips Electronics chair at Columbia University in her honor as part of the settlement with Lumileds.

Cree, on the other hand, is still battling Rothschild and her legal team. The company wrote in its 2007 annual report: "The patents are invalid and are unenforceable under the doctrine of inequitable conduct."

In response to that, Jacobs said: "Substantial companies have settled. If those companies thought they had wonderful defenses then they wouldn't have."

"There's no prior art that I've seen. Companies can argue over interpretation and whether they infringe, but I don't think there's any validity issue."

● Seoul Semiconductor has claimed victory in a lawsuit with Taiwanese LED firm Advanced Optoelectronic Technology, and signed a license deal with Korea's Itswell.

OSRAM OS

Seven years in the making, following an investment of hundreds of millions of euros and with a workforce now numbering 1500, Osram Opto Semiconductor's huge LED fab in Regensburg is finally complete. Osram chief Martin Goetzeler, Osram Opto CEO Rüdiger Müller and local mayor Hans Schaidinger officially opened the last section of the 55,000 m^2 site on April 4.

The expansion of the facility has boosted chip production capacity by 50% overall, while Osram is also investing heavily at its back-end site in Penang, Malaysia. In addition to manufacturing millions of GaN- and AlInGaP-based LEDs, the Regensburg fab produces laser diodes and detectors.

PRODUCTION EQUIPMENT

Tegal's 'repair' tool set for debut

Following two years of development work with a leading LED manufacturer, Tegal's novel nanolayer deposition (NLD) tool will soon move into volume wafer production.

The Petaluma, CA, company's cluster tool does not just deposit films – it also features a plasma-treatment stage that Tegal CTO Steve Selbrede says "repairs" materials after they are deposited.

Having just signed a beta-site agreement with a leading customer from the HB-LED industry, the Compact 360 NLD will be delivered this summer, with volume commercial production slated for 2009. What the tool will be used to deposit isn't being revealed by Tegal or its customer, but it looks suitable for a number of applications in compound semiconductor fabrication.

Although it does not deposit epitaxial active device layers, the NLD can be used to produce high-quality films for other parts of the wafer-manufacturing process, usually for titanium-containing material but also compounds such as ZrO. "Typically we use MOCVD precursors to deposit the nanolayer film, then plasma treat it to improve its properties," said the company.

One example where this might be advantageous is when the wafer materials are sensitive to high temperatures. Then, instead of directly depositing a high-quality film using MOCVD at 400 °C or more, which could adversely affect the semiconductor wafer, the NLD approach could be used to deposit material at 290 °C, and then be followed by the plasma repair step.

"Lowering the deposition temperature often improves conformality [film thickness variation] by reducing the sticking coefficient, but at the expense of reduced film quality," explained the CTO, adding that the plasma repair step can rescue the film while maintaining good conformality, even within the deep trench structures that are found in high-aspect-ratio chip designs.

According to Tegal, the NLD has an advantage over the related approach of atomic-layer deposition: "We would normally have a higher throughput with the NLD process, especially for thicker films."

Although designed for mainstream semiconductor applications and 300 mm wafers, the NLD can be configured for much smaller wafers used in LED fabrication. For example, 100 mm wafers can be handled directly. Smaller diameters, on which the vast majority of LED manufacturing still takes place, are handled using wafer carriers.

Having worked with its beta-site customer (undisclosed, but described as "the leading company in HB-LEDs" by Tegal CEO Tom Mika) for the past two years on NLD applications, Tegal expects volume commercial production to get the go-ahead in 2009.

FINANCE

Venture firms plunge cash into novel LEDs

Two US companies with novel takes on high-brightness LED technology have reaped $112 million in new venture finance between them within the past month. Massachusetts-based Luminus Devices bagged $72 million in one deal, while California's Bridgelux raised $40 million in a venture-plus-debt transaction.

Each US chip maker is looking to broaden its reach beyond its traditional areas of expertise. Bridgelux, which had initially focused on its GaN epitaxy expertise and large-area, high-power chips, is seeking to move up the industry food chain into lighting products.

Bridgelux CEO Mark Swoboda clarified: "This latest round of funding will enable us to expand rapidly beyond our current LED chip product offerings and move aggressively into LED lighting products, expanding our market reach."

Providing some of the $30 million series D equity capital for Bridgelux was new investor VentureTech Alliance, which has strong links with the Taiwan Semiconductor Manufacturing Company.

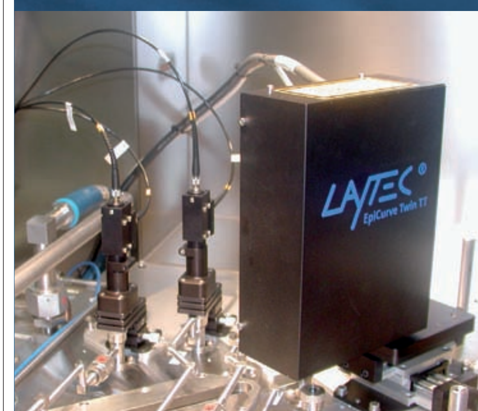
Meanwhile, Luminus, which is best-known for the top-secret photonic lattice microstructuring technique that allows extremely powerful LED emission, is now targeting a broader array of applications beyond its traditional scope of high-end displays and televisions.

Like Bridgelux, Luminus is aiming to penetrate solid-state lighting, from specialist applications in the medical and entertainment industries through to general consumer and commercial uses.

Dennis Costello, managing director at lead investor Braemar Energy Ventures, said: "We are very bullish on LEDs and solid-state lighting, and we are excited to invest in one of the most promising companies in this space."

Every move you make

LayTec's uniquely flexible **EpiTT** in-situ sensor system is adaptable to every MOCVD growth environment. Additional **twin head** and **bowing measurement** options enhance standard growth rate and true temperature parameters, allowing you to create the ideal sensoring system for your specific production or R&D application.



The **EpiCurveTwin TT** uses two EpiTT heads and a bowing sensor for maximum control of multi-ring reactors.

I'll be watching you

LAYTEC in-situ sensors

LayTec GmbH · Helmholtzstr. 13–14
10587 Berlin · Germany
Tel.: +49 (0)30·39 800 80-0
info@laytec.de · www.laytec.de

FIBER-OPTIC COMPONENTS

Quantum-dot lasers prepare for mass-production

QD Laser, the joint venture between Japanese telecom giant Fujitsu and Mitsui Ventures, which specializes in quantum-dot optoelectronics, is poised to become the first company to mass-produce Fabry-Pérot (FP) lasers based on the advanced technology.

Incorporated in Tokyo in April 2006, QD Laser told *Compound Semiconductor* that it already has firm orders from customers in Japan, and it is currently providing engineering samples and testing mass-production. A full production release is scheduled for before the end of 2008.

QD Laser's first products will be FP lasers emitting at 1310 nm. The critical advantage of the InAs quantum-dot nanostructures used in these lasers is that they render the devices almost completely insensitive to changes in temperature over a very wide range (–40 to 100 ºC, claims QD Laser).

At high temperatures, conventional FP lasers require much higher drive currents to generate useful power than they do when either cooled or running at room temperature. The switch-on current required to stimulate lasing is also much higher.

Other advantages of quantum-dot technology, which makes the lasers behave more like individual atoms than bulk materials, include improved efficiency and a smaller package size. All of this is possible because at these atomic scales it is the size of the dot, rather than its material make-up, that controls its physical behavior.

Michael Usami from the company says that QD Laser uses its in-house MBE expertise to grow the FP laser epiwafers on GaAs substrates. External foundries complete the wafer processing and package the lasers into standard TO-cans.

Usami adds that QD Laser expects to be mass-producing quantum-dot FP lasers before the year is out, with a subsequent six-month ramp to reach full production volumes. Lasers based on distributed feedback designs are set to follow.

The new lasers feature between 5 and 12 layers of InAs quantum dots, each one measuring around 20 × 20 × 5 nm. "We have the highest dot density growth in the world," Usami said. "It is about 60 billion [dots] per square centimeter for mass-production."

Controlling the size of the self-assembling quantum dots during the epitaxial growth stage is one of the key problems that QD Laser's engineers have overcome. Until now this had hindered the scale-up to mass-production and restricted the commercial viability of quantum-dot devices, although Germany's Innolume is shipping lasers based on the technology.

At QD Laser, layers of InAs islands are deposited between a stack of intermediate layers of GaAs, with careful control of the growth recipe and temperature proving to be critical. In collaboration with the Arakawa group at the University of Tokyo, the company has introduced antimony into the epitaxial process to increase the dot density to record levels, which delivers additional gain in the lasers. In the past couple of years it has been able to improve control over the laser's polarization and wavelength.

Attempts to grow the InAs dots on InP substrates to make longer-wavelength components are progressing well, and future products will be aimed at longer-reach communications. The company is also working on polarization-insensitive semiconductor optical amplifiers for use in the metropolitan and access levels of fiber-optic networks.

● For more information about quantum-dot epitaxy and laser applications, see "Comb lasers target connectivity", p25.

SUBSTRATES

Solar companies move towards 150 mm wafers

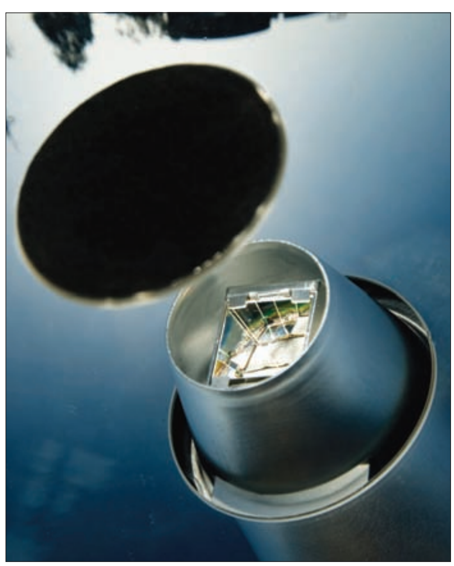
By Andy Extance in Madrid

Solar cell manufacturers Emcore and Spectrolab are working towards device fabrication on larger germanium wafers to help to meet the anticipated growth of the concentrating photovoltaics (CPV) industry.

According to Geoff Kinsey, technical lead for CPV products at Boeing-owned Spectrolab, the Californian firm will move from 100 to 150 mm substrates and aims to use them in production by 2010.

Automated welders and testers are already in place to support the move, Kinsey said at the CPV Today conference in Madrid in early April. Sources at the conference revealed that Emcore will be matching its rival's move, so that both companies will be able to produce more cells per wafer.

However, Spectrolab will only buy the MOCVD reactors that it needs to make triple-junction cells on the larger platform if it receives sufficient orders from manufacturers of CPV modules and systems.



SOLFOCUS

Using larger germanium wafers would cut the cost of the individual triple-junction cells used in concentrator photovoltaic systems, such as this parabolic mirror design produced by SolFocus.

Kinsey says that Spectrolab's cells currently cost its customers around $0.9 per watt of power that is generated. If the process overhaul proceeds as the company plans, the larger wafers will see this figure drop to $0.4/W in 2010.

In response to this, David Danzilio, vice-president and general manager of Emcore Photovoltaics, told *Compound Semiconductor* that his company's cells are already available at $0.37/W, although only if they are purchased in 100 MW quantities.

Emcore has only announced one order approaching that size, but solar module and system makers at the Madrid conference confirmed that Emcore's cells are routinely cheaper than Spectrolab's.

Supporting the switch to the larger wafers is the Belgian conglomerate Umicore, which is shipping engineering samples of 150 mm material and working on even larger substrates in its laboratories. Also present in Madrid was Sylarus Technologies, a recently founded start-up that claims to be a source for the germanium substrates used by Emcore and Spectrolab.

Based in St George, Utah, Sylarus relies heavily on the crystal growth know-how of Grant Fines, the company's director of process engineering. He says that the company is already producing 150 mm germanium.

MANUFACTURING

Laser firm takes stake in Swedish InP foundry

Single-chip tunable laser specialist Syntune has acquired a controlling equity position in Svedice, the InP semiconductor foundry based in Järfälla, Sweden.

Svedice, which provides customized foundry services in its state-of-the-art facility, has expertise in III-V epitaxial growth, materials characterization, etching, metallization and testing for advanced technology products. It is already partnering with Syntune to produce a complete array of widely tunable products, including what the company describes as "the world's first commercially available, widely tunable transmitter on a single chip".

The tunable laser market is a small niche, but is expected to continue its recent rapid growth over the next few years. An estimated 100,000 units are shipping each year, and this figure is expected to grow by between 25 and 30% per year through 2012. It appears that this expectation has convinced Syntune to take firmer control of its semiconductor supply.

"With the tunable laser market continuing to expand, it became imperative that we needed to strengthen our relationship with our chip supplier," said Syntune CEO Patrik Evaldsson. "Syntune has a strong, guaranteed supply chain that is demanded by our expanding customer base, thanks to a controlling interest in Svedice and a co-operative agreement with CyOptics, our packaging partner."

Syntune is in full production of its S3500 C-band tunable laser and its integrable tunable laser assembly. The package can be combined with modulators to reach speeds of up to 40 Gb/s and is small enough to be used in various form factors, including SFF 300-pin transponders and XFP-E packages.

From our newsfeed...

visit *compoundsemiconductor.net* for daily news updates

...QPC gets another patent

High-power laser diode maker QPC Lasers has been issued with US patent 7,342,951 relating to its infrared emitters. Entitled "Laser diode with monolithic intracavity difference frequency generator," the patent protects a new architecture that uses nonlinear optical frequency converters integrated onto the source chip to create new infrared output frequencies.

...Veeco wins Taiwan solar deal

Millenium Communication Co Ltd – known as M-Com – of Hsinchu, Taiwan, has ordered a TurboDisc E450 As/P MOCVD reactor from Veeco Instruments to manufacture high-efficiency III-V compound multi-junction solar cells. Lih-Wen Laih, general manager of M-Com, said: "Adding this tool into production will help us to reduce our cost per chip 10-fold, which is critical as we gain market share in the photovoltaic cell market."

...DOE funds CPV again

Compound semiconductors featured heavily in the US Department of Energy's latest round of research funding under the Solar America Initiative. Included in the 11 university-led projects receiving total funding of $13.7 million are: an Arizona State/SolFocus collaboration on the reliability of concentrator photovoltaics and a CalTech/Spectrolab team working on multi-junction cells deposited on a novel InP/silicon laminate material. In a separate project, Spectrolab is collaborating with North Carolina State University in Raleigh to create a four-junction cell.

...New 980 nm laser from 3S

3S Photonics, the III-V chip maker formerly known as Alcatel Optronics and then Avanex, released its 1999 PLM series: a product family of medium- and high-power 980 nm terrestrial pump laser modules. The launch includes a 365 mW, kink-free module stabilized by fiber Bragg gratings.

...Emcore grabs more of Intel

Emcore has completed a deal with Intel to acquire the enterprise and storage assets of the silicon giant's optical platform division, as well as the Intel Connects Cables business. Albuquerque-based Emcore gains assets including intellectual property, inventory, fixed assets and technology. The transaction, which relates primarily to optical transceivers, closed April 21.

...For sale: detector fab

Employees at CdZnTe radiation detector company eV Products are facing an anxious wait as its owner, II-VI Inc, looks to find a buyer for the subsidiary. II-VI says that Roth Capital Partners is hunting on its behalf for interested parties to buy the vertically integrated maker of detector systems.

8 Reasons to Work with Spire Semiconductor to Develop Your Next Optoelectronics Product...

1 Spire Semiconductor is a **complete compound semiconductor fabrication facility** dedicated to supporting its customers.

2 Spire Semiconductor has its own **MOCVD III-V and II-VI multi-wafer, multi-reactor** capabilities for high volume production requirements.

3 Spire Semiconductor has a **first-class compound semiconductor device fabrication facility** with class 100 cleanrooms.

4 Spire Semiconductor's engineering staff has **extensive experience** in material and device design, process development and testing.

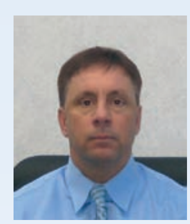
5 **You can work directly** with Spire Semiconductor's engineers.

6 Spire Semiconductor can **manufacture your products** in volume exclusively for you.

7 As a pure play foundry, we do not compete with our customers.

8 Working with Spire Semiconductor will **keep you ahead of your competition**.

Edward D. Gagnon
General Manager,
Spire Semiconductor



spire Semiconductor

Spire Semiconductor, LLC
25 Sagamore Park Road, Hudson, NH 03051
T 603.595.8900 F 603.595.0975
sales@spiresemi.com

WIDE-BANDGAP ELECTRONICS

Desperately seeking applications...

The wide-bandgap electronics market is still looking like a lucrative one, but only if you adopt a "glass-half-full" attitude. **Michael Hatcher** eyeballs the latest reports.

Is your glass half full or half empty? Your relative optimism is probably the most important factor in determining how you view the latest analyses of the emerging market for wide-bandgap electronics.

That's according to Tom Hausken, one of the authors behind a new report from California-based Strategies Unlimited. On the face of it, things look good – devices based on SiC and GaN semiconductors, for growing applications like WiMAX base stations, electronic warfare and hybrid electric vehicle motors, are sure to be in demand. Hausken is expecting the total market for wide-bandgap components to grow quickly, at a rate of at least 30% per year, and to treble in value between now and 2012.

So, if your glass is half full, everything looks good. On the other hand, if you were expecting GaN or SiC to be "the new GaAs", prepare to be disappointed. "They are definitely not the new GaAs," fronted up Hausken, unequivocally. Together, SiC and GaN electronics accounted for a market worth only $40 million in 2007, and Hausken predicts that by 2012 that figure will have risen to something in the region of $170 million. It's a healthy market for a couple of companies, perhaps, but hardly enough to sustain many of the estimated 150 firms that are actively working on these materials, and entirely dwarfed by the GaN LED and laser-diode business.

For a neat comparison, simply look at the GaN-laser sector. To make the blue lasers for its PlayStation3 consoles, Sony is believed to have bought some $50 million worth of GaN substrates from local vendor Sumitomo Electric Industries during 2007. That this supply deal alone was worth more than the entire market for wide-bandgap electronic devices in 2007 illustrates vividly the disparity between electronic and optoelectronic applications.

Hausken is anything but pessimistic about the wide-bandgap sector, however, and says that a successful global launch of the WiMAX connectivity protocol could spark much faster market growth. "Something is finally happening and there is a great opportunity for GaN HEMTs," remarked the analyst. "We are not going to see them in microwave ovens, but GaN is actually getting out there."

At the moment, a lot of the applications that GaN is getting into are being driven by the military, through DARPA-funded development programs and genuine deployments. For example, Eudyna Devices – acknowledged as one of the leading exponents of GaN-based RF technology, and with an estimated 31% share of the current wide-bandgap electronics market – is supplying the US military with devices that are used in Iraq. Here they operate in an "electronic warfare" capacity, where the chips can create enough microwave "noise" to disrupt and jam the cell phone signals with which insurgents attempt to set off roadside bombs. It might seem unlikely at first, but perhaps the declining number of bomb attacks in the war-torn country is, to some degree, thanks to wide-bandgap semiconductors.


ABB

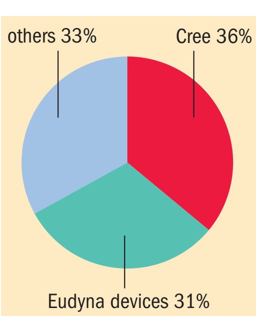
Switch-mode power supplies, such as these from Swedish industrial giant ABB, are one obvious application area for SiC-based diodes. However, manufacturers still need to overcome the problem of their much higher cost compared with silicon.

Useful though they may be for the military's jamming and high-end radar systems, it is the commercial world where GaN and SiC must succeed for these semiconductors to make a real impact. In Hausken's "most likely" scenario, he has factored in a modest degree of success for WiMAX. But, says the analyst, if this technology really takes off – something that is too early to call right now, given the divisions in the wireless industry – it could change everything. In his most optimistic scenario, in which WiMAX breaks through as the 4G wireless protocol of choice, GaN HEMTs get a real boost and Hausken values the 2012 market at $300 million (figure 1, p13).

Even that might not look so good for venture capitalists looking to recoup their investments via a high-value acquisition or stock-market flotation. GaN-on-silicon specialist Nitronex has some great technology and has racked up some $56 million in venture funding since its inception. And in a market worth less than $100 million, a profitable exit in the next five years is hard to envisage.

Hausken forecasts that microwave applications, currently responsible for some 80% of wide-bandgap electronic device sales, will continue to dominate the wide-bandgap scene, with power-management applications likely to be worth only $10 million–$20 million annually over the next couple of years.

However, that split should skew more towards power-management applications in the longer run, and the analyst predicts approximately $60 million in sales for this subsector in his 2012 "most likely"



STRATEGIES UNLIMITED

Cree and Eudyna currently dominate the wide-bandgap landscape, with SiC Schottky diodes and GaN-based HEMTs, respectively.

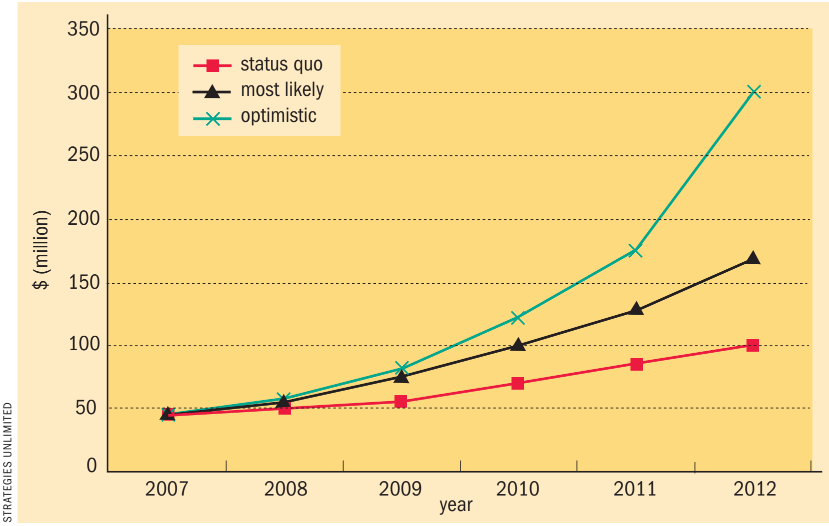


Fig. 1. Hausken's "most likely" future scenario predicts that the market for SiC and GaN electronic devices will increase from $40 million in 2007 to around $170 million in 2012. Microwave components, mostly GaN-based, will dominate initially and demand for these particular chips could grow much more quickly if the WiMAX communication standard becomes widely deployed.

scenario. At the moment, the power-management (as opposed to high-power RF) side of the wide-bandgap industry is dominated by SiC, and largely by Schottky diodes from Cree and Infineon Technologies.

Hausken expects SiC to continue that domination for the foreseeable future, as early adopters begin using SiC diodes and transistors in electric vehicles, and in DC-AC inverters that connect continuous energy sources, like photovoltaics and wind, to regional power grids. The market opportunity here is quite different from that for GaN HEMTs, explains Hausken. While GaN components wait for the opportunity to emerge in high-speed wireless, applications in power management are already plentiful and would potentially support far higher unit volumes than wireless base stations. The key factor holding up SiC here is its current cost, and the big challenge is how to make the wide-bandgap technology competitive.

Though more mature than their GaN equivalents, SiC substrates and processes still need to improve to meet that goal. This can be done by increasing wafer sizes and reducing defect densities to improve manufacturing yields, especially for the larger chips used in power-management applications.

At the moment the power-management market is dominated by applications in computer servers. Although servers only represent a tiny proportion of the wider computer market, they do consume huge amounts of energy upholding internet infrastructure. Hausken estimates that these servers are responsible for something like 3% of all electricity consumption in the developed world. And with companies such as Google running huge server farms approaching a remarkable 1000 MW in power consumption, it is clear that even a tiny improvement in power management to increase the server efficiency would have a very significant impact.

With the general move towards higher-efficiency products from consumers and through government legislation, it is feasible that SiC components might be able to tap into the considerably wider PC market.

"It is much easier to design a new product into a power supply than into a wireless infrastructure network," Hausken said, illustrating that SiC component makers might be able to make an impact much more quickly than GaN specialists. Although GaN-on-sapphire diodes could also be used in power management, as Velox Semiconductor described in the April issue of *Compound Semiconductor*, Hausken believes that the market is much more likely to stick with SiC, unless GaN offers a much cheaper alternative. Velox does have the considerable backing of European electronics giant ST Microelectronics, with which it has a distribution agreement, although ST also has its own SiC-based technology for power applications.

But the single biggest problem with all current wide-bandgap device technologies is their very high cost and, when compared with more mature semiconductors, the low quality of available substrate material on which to produce epiwafers. And, as has been the case with LDMOS technology in the wireless sector, silicon is not standing still. One start-up that has just come onto the radar is Qspeed, based in Silicon Valley. Though at an early stage, it already claims to have a silicon-based 600 V power factor correction technology that can "easily replace SiC Schottky diodes at a fraction of the cost".

Wide-bandgap materials still typically sell for a few thousand dollars per 2 inch wafer. While even this expense can be acceptable in the context of a high-value RF system for military or telecommunications use, a serious drop in cost will be necessary for these devices to penetrate the more commoditized power semiconductor applications, and to hold back the challenge presented by companies like Qspeed.

Part of the problem is that, unlike LEDs, where active-layer defect densities as high as $10^7\ cm^{-2}$ are tolerable and still allow reasonable wafer yields, electronic devices are not nearly so forgiving.

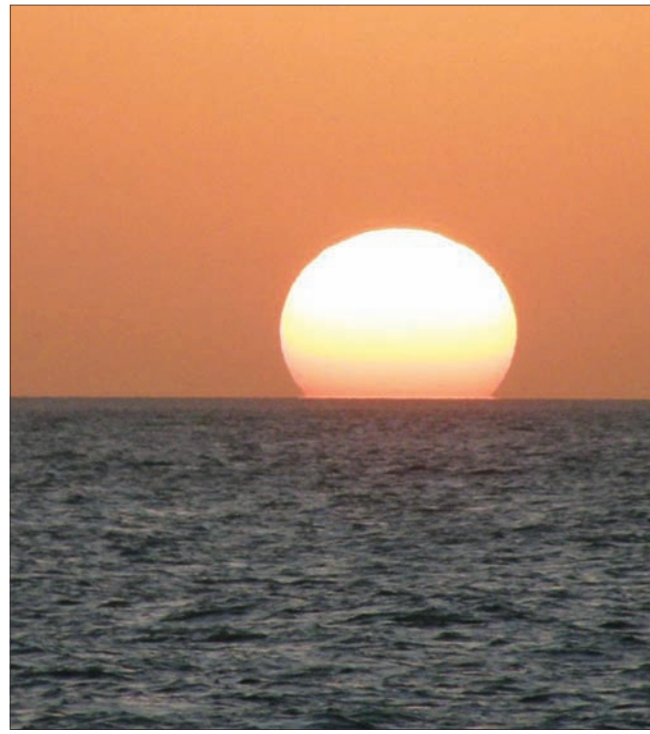
In this respect, wide-bandgap electronic devices are similar to GaN-based blue laser diodes, which are at least now being fabricated in production volumes, thanks largely to Sony. Sony has shown that it is possible to scale up production, albeit at a high cost and not without problems. Sony's lasers are, of course, used internally, and it may be that this is the best way for wide-bandgap electronic devices to make an impact. Some very big Japanese hitters, such as Panasonic, Toshiba and Toyota, are all investigating the technology and could implement it if they wanted to. It is possible that Eudyna, formed by parts of Fujitsu and Sumitomo Electric, will end up as the major beneficiary if that does happen.

So is Hausken's glass half full? The analyst admits that his estimates are based on a currently very small set of data and should not be regarded as a precise guarantee of the future market growth. "It is a ballpark estimate of the opportunity," is how he put it. "It includes many potential opportunities that may not come to pass." But he adds that the total available market for wide-bandgap electronics is itself a growing one, and is set to reach $1 billion by 2012. A breakthrough in any one application could be the spark that is needed to ignite it.

Wide-Bandgap Electronics: Technology Trends and Market Forecasts – 2008 is available now from Strategies Unlimited. Visit strategies-u.com for more details.

Chip makers chase the Su

The rush to invest in and develop clean energy technologies has witnessed unprecedented interest in III-V solar cells for concentrating photovoltaics. However, as **Michael Hatcher** reports from a sunny Key West, huge challenges lie in wait.



The solar energy industry is a curious one. Not yet a cost-effective way to produce electricity without huge subsidies, government support of photovoltaics has been enough to drive steep demand over the past two decades.

According to solar industry analyst Michael Rogol, the production capacity of photovoltaic systems shipped during 2006 reached 2.5 GW, double the 2004 figure and 10 times that recorded in 2000. Winfried Hoffman, president of the European Photovoltaic Industry Association (EPIA) and CTO of equipment giant Applied Materials, recently estimated the 2007 figure at a slightly lower 2.3 GW.

Nevertheless, photovoltaic systems are still responsible for less than 0.1% of global energy production. And despite all of the recent interest in technologies using III-V cells, concentrator photovoltaics (CPV) systems are yet to make any real impact, with estimated shipments of just 18 MW in 2006 – less than 1% of the solar total.

However, everybody agrees that this installed capacity is going to rise – and fast. Sarah Kurtz from the US National Renewable Energy Laboratory (NREL) is credited as co-inventor of the multi-junction cells of which so much is hoped. Extrapolating from industry trends, Kurtz says that, by 2020, 5% of global electricity could be produced directly from the Sun. Already valued at $20 billion per year, that level of penetration would represent a further 100- or even 1000-fold expansion of the solar energy industry. Hoffmann expects annual installations to rise from a peak capacity of 2.3 GW in 2007 to 11 GW in 2012, and Goldman Sachs says that total photovoltaic capacity could meet about 0.8% of global electricity demand in 2011.

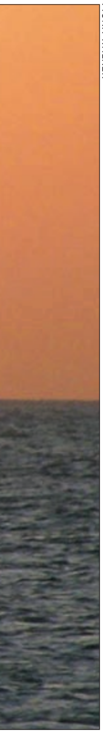
It is this opportunity for expansion that drives venture capitalists (VCs) towards the emerging technologies that might one day see photovoltaics deliver electricity on a utility scale at an economically viable cost. Eric Emmons, a general partner at the Massachusetts Green Energy Fund, told delegates at the 2008 Key Conference organized by *Compound Semiconductor* that venture investment into solar start-ups spiked sharply in late 2007. In North America, venture firms sank $400 million into this sector in the third quarter, funding CPV exponents SolFocus and Greenvolts, among others.

That spike may already have set some alarm bells ringing. As Emmons points out, the biofuels sector showed a similar funding spike in 2006. Already, however, there is overcapacity in biofuel production and a serious question mark about the validity of the technology and its negative impact on food production. VCs can get cold feet very quickly.

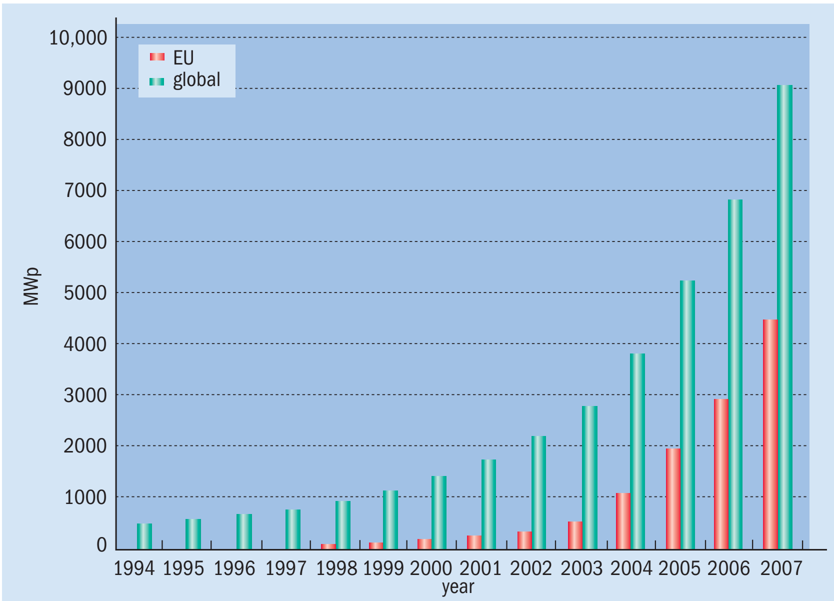
But it isn't all about VCs in the photovoltaics space. Some of the older start-ups are now established public companies and have reaped huge financial gains for their shareholders. The share price of First Solar, the US-headquartered company that manufactures CdTe cells on glass substrates, rocketed 10-fold over the course of 2007. Remarkably, the firm is now perceived by the stock market to be more valuable than the Ford Motor Company.

Michael Molnar, a vice-president at Goldman Sachs and responsible for equity research in the alternative energy and coal sectors, explained why First Solar was causing so much excitement: "They will potentially generate close to $1 billion in revenue at a gross margin of about 50% in 2008. And the stock market has noticed." Despite the optimism, Molnar says that the solar industry must remember that ultimately it is selling nothing but a commodity product – units of electricity. "Photovoltaics needs to be low cost," said the investment analyst. "[Currently] solar energy costs 20–30 cents per kilowatt-hour and the

n as competition hots up



FIONA WALKER



SOURCE: EUROPEAN PHOTOVOLTAICS INDUSTRY ASSOCIATION

Companies working on CPV systems

US
Abengoa Solar
Amonix
Boeing
Concentrating Technologies
Cool Earth Solar
Emcore
Energy Innovations
EnFocus Engineering
ENTECH
GreenVolts
JX Crystals
Menova
Opel International
Pyron
SolFocus
Soliant Energy

Europe
Concentracion Solar La Mancha
Concentrix Solar
Guascor Foton
Isofotón
Sol3g
SolarTec

Australia
Solar Systems
Green & Gold

Asia
Arima Ecoenergy
Daido Steel
Sharp

SOURCE: SARAH KURTZ/NREL

Terrestrial photovoltaics is a booming industry and dozens of new companies are hoping to get a piece of the action. The EPIA says that installed global photovoltaic capacity exceeded 9 GW (peak) by the end of 2007 (above center), although figures on how much of that capacity is being used are harder to find. Half of the installed capacity is in Europe. Future growth of the cumulative total will depend on the specifics of the energy policies implemented in the EU, with the EPIA predicting a maximum cumulative capacity of 44 GW (peak) in 2012. By then, CPV using III-V cells could represent a small but significant chunk of the total.

market [for it] only exists because of subsidies."

For all of the concerns over fossil fuels, coal remains a relatively cheap, reliable energy source that, unlike solar or wind, can be stored easily. The US uses about a billion tonnes of coal each year, and with more than 250 billion tonnes in reserve (according to Molnar's figures), there is no risk of it running out for a long time. So here is the key challenge for solar companies targeting the utility end of the market – achieve a unit price approaching grid parity, meaning 5–10 cents per kilowatt-hour. There are three key parts to meeting this challenge: driving down the cost of the cell materials, installation and system construction; improving cell efficiencies; and, crucially, scaling production to large volumes while maintaining high efficiencies and yields.

First Solar aside, silicon is the dominant material on the photovoltaics scene. But, because of their low conversion efficiency, there is a barrier to driving down the cost of photovoltaics with silicon cells. This is especially pertinent in utility applications, where the unit cost must be even lower than the retail price used as a guide for residential photovoltaic installations. Combined with the constrained silicon supply – huge amounts are needed for panels, and the solar industry gets through more of the material than the semiconductor industry – this has created a window of opportunity for high-efficiency III-V cells and CPV systems to make their mark on the industry with a low-unit-cost, utility-scale solution.

However, while there is potential for economic electricity production with III-V cells, its deployment will be restricted to geographies with clear blue skies. High-quality tracking systems that can follow the path of the Sun precisely and reliably are key.

In the US, the Solar America Initiative (SAI) is funding the development of all kinds of photovoltaic technology. Its key goal is to deliver solar energy at a cost equivalent to conventional grid prices by 2015. Prior to forming the SAI, the target year had been 2020, and Kurtz says that the project has added "a real sense of urgency" to the photovoltaic sector. Within III-V cells and CPV, its incubator has funded six projects, the most recent being headed up by EnFocus, MicroLink Devices and SolFocus.

Along with its involvement in the SAI, SolFocus is one of the companies leading the effort to commercialize CPV. It is concentrating on the parts of the world where energy costs are high – places like Italy, Japan and California. This seems to be paying off, with recent deals to equip the ISFOC demonstration project in Spain and to power radio transmitters used by the San Francisco radio station KGO. Mark MacDonald from the company reports that the mirror system used by SolFocus can tolerate tracking errors particularly well – crucial when the

Table 1. Companies with III-V cell manufacturing capabilities

Company	Available data
Emcore (US)	Typical efficiency 36% at 470× concentration
Spectrolab (US)	Minimum average efficiency 36% at 50 W/cm^2
Spire Semiconductor (US)	Typical efficiency 35% at 500× concentration
Delta Electronics (US)	Receivers only
Bandgap Engineering (US)	No data sheet available
Global Communication Semiconductors (US)	No data sheet available
Kopin (US)	No data sheet available
Microlink Devices (US)	No data sheet available
Cyrium (Canada)	No data sheet available
IQE (UK)	No data sheet available
IMEC (Belgium)	No data sheet available
Azur Solar (Germany)	No data sheet available
Centro Elettrotecnico Sperimentale Italiano (Italy)	No data sheet available
Arima (Taiwan)	No data sheet available
Epistar (Taiwan)	No data sheet available
Millenium Communication (Taiwan)	No data sheet available
VPEC (Taiwan)	No data sheet available
Sharp (Japan)	No data sheet available

SOURCE: SARAH KURTZ/NREL/GOLDMAN SACHS

Copies of the 2008 Key Conference proceedings are now available to purchase from our website. Visit compoundsemiconductor.net/key for details.

intense beams of light created by CPV could damage other components if they are directed anywhere but directly at the center of the III-V cell.

Over in Europe, Spanish company Isofotón has been in pilot CPV production for just over a year and expects to have an annual module assembly capacity of 10 MW in place by the end of 2008. Founded in 2001, Isofotón is one of the best-known solar energy companies in the region and, thanks to a succession of projects funded by the European Commission, it has wide-ranging expertise in optical technologies. "We are committed to getting to 1000-sun concentrations with III-V cells," said Vicente Díaz, manager of the company's CPV business unit, adding that the impending commercial realization of CPV would represent the culmination of a decades-old dream since the approach was first postulated in the 1970s. "Terrestrial applications are now, finally, creating demand," he said. Raising concentration to the 1000-sun level would help the drive to reduce the cost-per-unit figure, although it would present even greater challenges for the cell manufacturers and system integrators.

One of the difficulties is with the uniformity of wafers containing the III-V cells. As a result, Isofotón has developed its own SAMCEL test equipment. Based on a flashlamp set-up, it allows engineers to test the uniformity of 4000 III-V cells per hour, although Díaz says that this crucial part of the production process still needs to be improved.

Díaz also shed some light on the likely volumes of germanium wafers that would be required to support the broader deployment of CPV. He reckons that as much as 100 MW may be realized annually just 2–3 years from now. This would demand 150,000 4 inch germanium wafers per year.

At the moment, however, Isofotón's CPV projects remain relatively small, with a 16.2 kW (peak) system recently completed and installations in Barcelona, ISFOC and Malaga University in progress.

Something that has characterized the III-V solar cell industry thus far is the relative paucity of cell producers, with only Spectrolab and Emcore manufacturing in anything like production-scale volumes. This now looks certain to change, despite the high level of expertise required. Speaking in Key West, Kurtz listed new US entrants, including Spire Semiconductor and MicroLink Devices, and a whole host of other potential suppliers from as far afield as Japan, Italy and Taiwan (table 1). More recently, MOCVD epitaxy foundry Kopin has thrown its hat into the ring too, marking a return to one of the first applications that the company targeted, back in the late 1980s. Kopin CEO John Fan said: "We have substantial intellectual property and manufacturing know-how around this technology."

Kurtz also highlighted some major challenges specific to III-V cell makers. For space applications, with small volumes and large-area cells, manual testing and mounting is the norm. But for terrestrial CPV, with far smaller cells and higher expected volumes, automated production will be essential. Cells must also be attached to heat sinks and optical components, demanding high-performance bonding materials. For this, the photovoltaic cell makers may be able to learn from the high-brightness LED industry, which has had to go through a similar learning curve to solve such thorny issues.

The LED industry's use of flip-chip and substrate removal processes could also be useful for a new type of triple-junction cell pioneered by Emcore and NREL. The technique, which uses an inverted semiconductor material stack to achieve a cell efficiency of up to 38.9%, also involves removing the GaAs substrate, leaving behind a very thin cell that must be mounted and bonded carefully.

Further challenges are certain to emerge, but, as the list of companies involved in CPV grows (see box "Companies working on CPV systems", p15), the collective expertise should grow, and the emerging community should ensure that it benefits from the experiences of LED and RFIC manufacturers.

What seems to be required is a healthy awareness of the challenges that remain. Molnar said: "Many start-ups have been able to produce interesting photovoltaics at a pilot scale but have found it challenging to scale their technology to commercial size without problems with efficiency and yields."

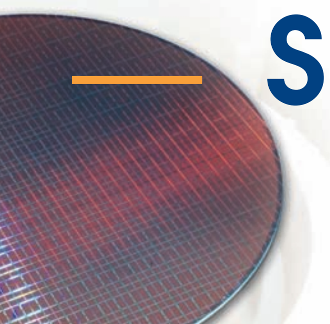
However, he is confident that, with so many companies and so much venture finance now at stake, the probability of a handful of them emerging successfully from the current wave of new entrants is very high. With a collaborative effort from cell makers, CPV companies and the existing III-V industries, at least one of those successes ought to be based on compound semiconductors.

umicore
materials for a better life

Umicore Electro-Optic Materials is the recognised world leader for the supply of Germanium substrates and offers epi-ready, dislocation free wafers ranging in diameter from 2" to 300 mm. Our material is the substrate of choice for the growth of the world most efficient solar cells used on space satellites and in terrestrial concentrator photovoltaic (CPV) systems.

Under concentration, the most advanced solar cells on Germanium have a conversion efficiency of over 40% and pave the way for cost-effective and sustainable energy generation. Umicore is ready to address the growing CPV market needs both in terms of large volumes and larger diameter material.

Umicore Electro-Optic Materials: Watertorenstraat 33, BE - 2250 Olen, Belgium
Tel +32 14 24 57 02 - Fax +32 14 24 58 00 - substrates@umicore.com - http://substrates.umicore.com



SSEC Single Wafer wet processing

SSEC 3310
10 Processing Stations

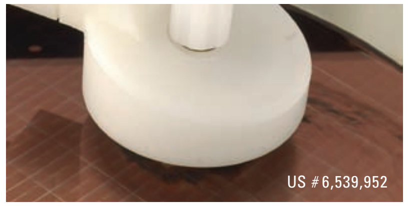
SSEC 3307
7 Processing Stations

Dual SCARA robotics can address all stations in any sequence.

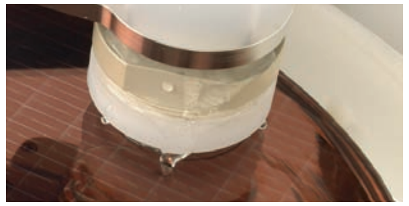
Clean

99% Particle Removal Efficiency at the 88 nm, 65 nm, and 45 nm Nodes

High Velocity Fan Scrub



Single Wafer Megasonic Scrub

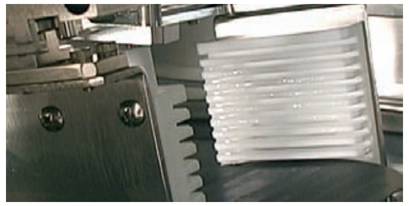


Rotary PVA Brush Scrub

With advanced single wafer non-contact and contact cleans, SSEC systems can be configured exactly to your cleaning requirements. Using dilute chemistries, such as SC-1 1:1:300, SSEC cleaning processors have 99% particle removal efficiency at the 88 nm, 65 nm, and 45 nm nodes, with 30 nm particle size in development.

Solvent Strip

Immersion and Single Wafer Processing

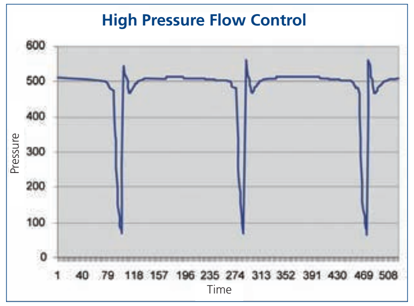


Solvent Immersion

High Pressure Spray

High Pressure Needle Dispense

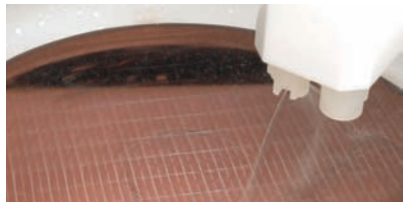
Using only milliliters of solvent per wafer, SSEC solvent processors combine batch immersion and single wafer spray technology in one SEMI® safety compliant, dry-in/dry-out system. High pressure sprays are entirely under closed-loop control for flow, temperature, and dispense arm motions.



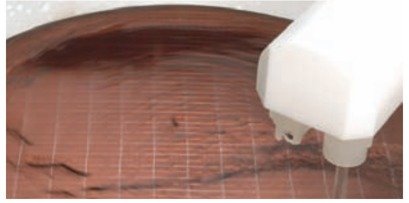
Etch

Uniform, Selective Etching on Multiple Process Levels

Backside/Bevel Cleaning

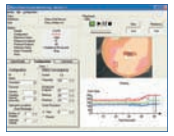


Spray Etch

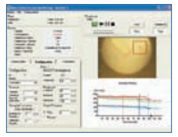


Stream Flow Etch

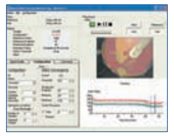
Whether your requirements are for Under Bump Etching, with almost no undercut, or for wafer thinning, SSEC's patented single wafer tools achieve more controlled results and substantial COO reduction, compared to batch or alternative single wafer systems. SSEC's exclusive WaferChek™ in-situ adaptive process control ensures an optimum etch on every wafer.



Ti Etch



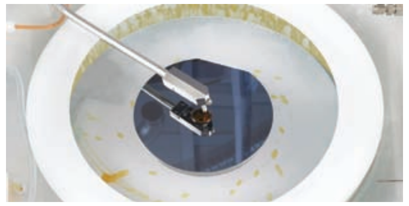
Al Etch



Cu Etch

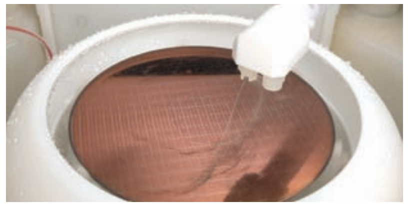
Coat/Develop

Photolithography Clusters



Spin Coating

Hot Plate Bake Processing



Spray Coat

Application-specific coat and develop clusters are configured for your exact process requirements, including thick resist processing. SSEC systems provide standard 95% uptime. The advanced machine control technology enables superior uniformity within wafer, wafer to wafer, and lot to lot, including complete data tracking and operation with programmable robotic sequencing.

Single Wafer Processing

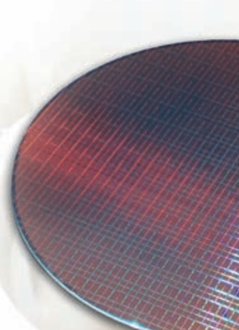
SSEC Systems are configurable in strip, etch and clean process stations with up to 12 stations in a system. In a Class 1 mini-environment, dual SCARA robotics can operate in any sequence to any station according to recipe selection. SSEC's applications laboratory will assist you in configuring a tool around your exact process and manufacturing requirements.

Come visit SSEC and learn what is new in single wafer processing.

SSEC Compliance

SEMI S2-0703aE Safety
SEMI S8-0705 Ergonomics
FM 4910 Materials
SECS GEM CCS 200 & 300
CE Marked
ETL Listed

SSEC 3300

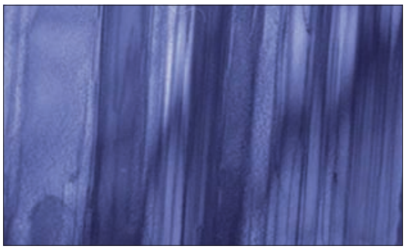


Solid State Equipment Corporation
Phone: **215-328-0700**
Email: info@ssecusa.com
www.ssecusa.com

SUBSTRATES

Sodium flux scales up GaN crystals

Adding sodium to a gallium melt that is fed with nitrogen gas promises to scale up minuscule GaN crystals to 4 inch diameters, according to Osaka University's **Fumio Kawamura**, **Yasuo Kitaoka**, **Yusuke Mori** and **Takatomo Sasaki**.



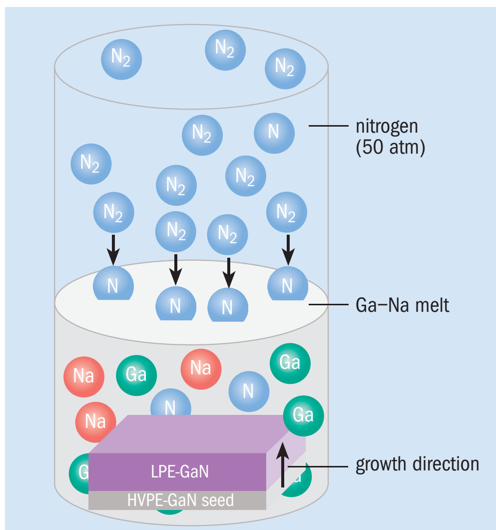
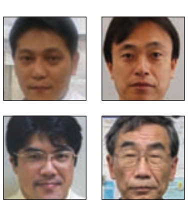


Fig. 1. (top left) Current methods for producing GaN substrates, such as MOCVD growth of GaN on sapphire, lead to material plagued with atomic-level line defects. **Fig. 2.** (bottom left) Sodium-flux LPE is relatively free from atomic-level line defects, thanks to the bundling of defects at the interface with the seed crystal. **Fig. 3.** (bottom right) Osaka University's sodium-flux LPE approach scales GaN crystal dimensions through the addition of 2 inch HVPE-grown GaN into the gallium melt. The thermal convection currents of the melt are controlled to prevent GaN crystals from forming. **Fig. 4.** (top right) The method can produce single GaN crystals that are 3 mm thick.



About the authors
Fumio Kawamura (top left), **Yasuo Kitaoka** (top right), **Yusuke Mori** (bottom left) and **Takatomo Sasaki** (bottom right) are researchers at Osaka University.

Wide-bandgap electronic devices combine high efficiencies with good temperature- and current-handling capabilities, which makes them very desirable for a variety of applications. These include deployment in hybrid cars and trains to convert DC output into an AC signal to power the motor, and installation in base stations for the amplification of wireless signals.

Ideally these devices would be manufactured on a native material platform because this minimizes epilayer strain. With SiC this is possible, but substrate prices are high and different polytypes can form in the epilayers, impacting device reliability. However, these drawbacks are far less severe than those for GaN. It is very difficult to make this material in large sizes and it also suffers from dislocations that cause premature device breakdown (figure 1).

To address the problems with GaN, we have been developing a solution-based method for crystal growth at Osaka University, Japan. This process is based on an established technique – sodium-flux liquid phase epitaxy (LPE) – which can produce high-quality GaN crystals in a vessel that contains a gallium–sodium mixed metal melt and nitrogen gas pressurized to 50 atm (figures 2 & 3).

Sodium's role in this process is to drive the dissociation of nitrogen molecules at the gas–liquid surface. The nitrogen radicals that are formed dissolve easily in the metal melt at 800 °C. Without the presence of sodium, forcing nitrogen into a solution requires pressures of at least 10,000 atm.

GaN crystals were first produced from a gallium–sodium mixed metal melt over a decade ago by Hisanori Yamane and co-workers from Tohoku University. However, the pieces of GaN were 1 cm or less across. Since then, one of the primary goals for researchers in this community has been to increase the crystal dimensions to a more commercially useful scale.

We have done just this by inserting seeds of 2 inch GaN crystals into the metal melt. These seeds have high dislocation densities because they are grown by HVPE or MOCVD. However, the dislocations are not transferred to the LPE-grown material as they tend to annihilate close to the interface with the seed.

In 2005 we produced the first 2 inch GaN using this technique. This had a dislocation density of 2.3×10^5 cm^{-2} – more than an order of magnitude less than typical commercial GaN substrates. Scaling to this size demanded control of the thermal convection currents, alongside optimization of the crystal's growth conditions. If a 2 inch piece of GaN was dropped into the metal melt, nitrogen would not reach the crystal surface and would be lost to the growth of polycrystals around the gas–liquid interface.

We have recently developed proprietary apparatus and techniques that can increase the crystal sizes and growth rates. If many GaN wafers can be sliced from large single crystals, this could dramatically cut the manufacturing costs of these substrates. Last year we focused on improving the growth rate and tripled it to 0.6 mm/day. This is suitable for the mass-production of substrates for lasers, but faster growth is required to make a platform for LED manufacture.

With this new apparatus we have produced the thickest 2 inch GaN crystal ever made by sodium-flux LPE (figure 4). We are now working to extend the technique to 4 inch crystals by developing another, faster tool. If it is successful, this will be a major step towards the development of affordable GaN devices that can be grown on a native material platform.

III-Vs and Ge look to help CMOS

Scaling down silicon CMOS nodes is getting harder and harder. However, help is on the horizon in the form of III-V and germanium MOSFETs that can improve the performance of n- and p-type channels, say **Matthias Passlack**, IMEC's **Marc Heyns** and **Iain Thayne** from the University of Glasgow.

Cracks are starting to appear in silicon CMOS. Although the International Technology Roadmap for Semiconductors states that MOSFETs with strained silicon channels will be suitable down to the 22 nm node and possibly beyond, projections of device performance indicate otherwise. Studies show a gap will appear between projected and actual performances as node sizes fall to less than 65 nm, and this will only get wider with increased scaling (figure 1).

To make matters worse, history suggests that one of the main sources for transistor improvement is an increase in channel carrier velocity. Recent work by MIT's Ali Khakifirooz reveals that this depends more strongly on low field mobility than was previously believed, which will make it even harder for silicon CMOS to stick to its roadmap.

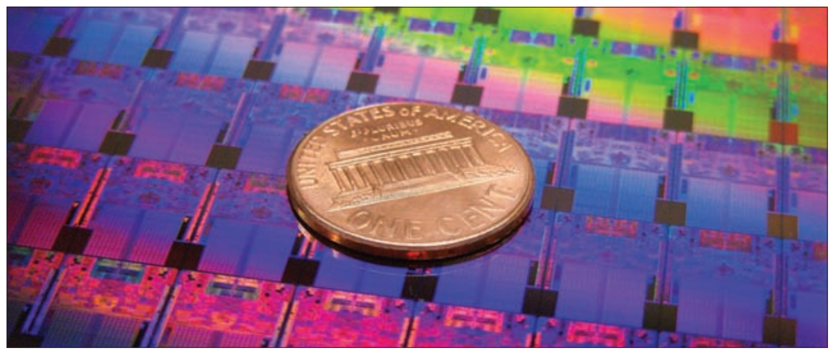
Fortunately, it should be possible to improve channel mobility significantly by switching to other materials, such as III-Vs and germanium. III-Vs promise to increase electron mobility by 10–30 times, which makes them great candidates for high-speed, low-power n-channel transistors. However, they cannot make good p-channels, which are also needed for CMOS, because their hole mobilities are relatively low. This is where germanium comes in – it has a hole mobility four times that of silicon.

Turning to other materials is not a new idea. In 1986, prototype 16- and 32-bit GaAs RISC processors were developed by Vitesse Electronics Corporation and Texas Instruments. These delivered fast clock speeds of up to 200 MHz, but they were a commercial failure due to high costs and high power consumption. The history of germanium dates back even farther, but this element hasn't been used in mainstream FETs for decades. However, there is good reason to believe that the time has come for III-Vs and germanium to make a lasting impact.

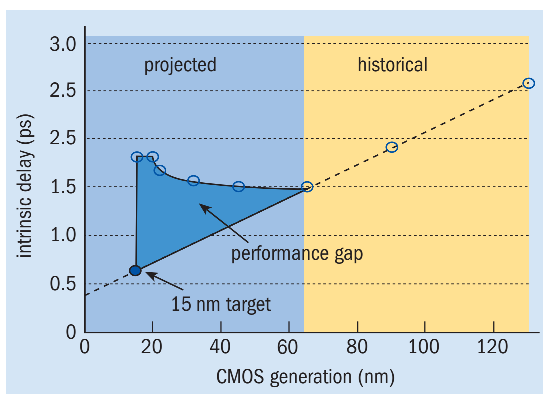
For one thing, the industry is very short of options. It would prefer to steer clear of even more immature technologies, which rules out transistors employing graphene as the channel material and FETs operating via impact ionization or quantum mechanical tunneling. This means that germanium and III-V MOSFETs will be the only real alternatives to silicon in the coming years. Encouragingly, research by Jesús del Alamo's group at MIT, as well as a partnership between Intel and QinetiQ, has delivered some promising results with III-V n-channel HEMTs. These efforts have shown that III-V FETs can be less power hungry and faster than their silicon counterparts at the low supply voltages required for billion-transistor integration.

However, before we get carried away, it's important to realize that there are some massive hurdles to overcome before we can fabricate non-silicon channels in CMOS. These dwarf those that were faced by the industry when it made the recent transition from traditional SiO_2 to high-k dielectrics.

Dictated by economics, FETs with non-silicon channels will have to be realized on large-area silicon substrates. This presents a tremendous challenge because it is difficult to unite materials into a near-perfect single-crystal epistructure when they have different thermal expansion coefficients, lattice constants and, in the case of III-Vs, crystal types. Many hours have been thrown at this problem and, although there has been an intensified effort in recent times, potential roadblocks still remain.

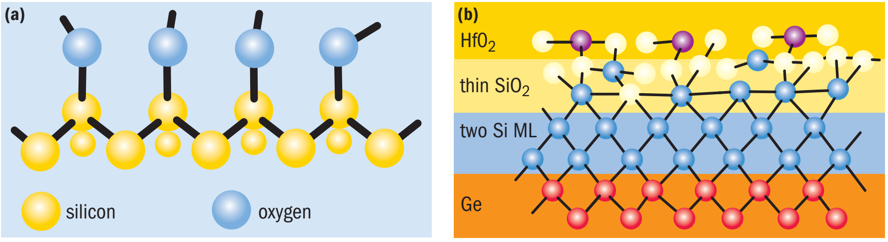


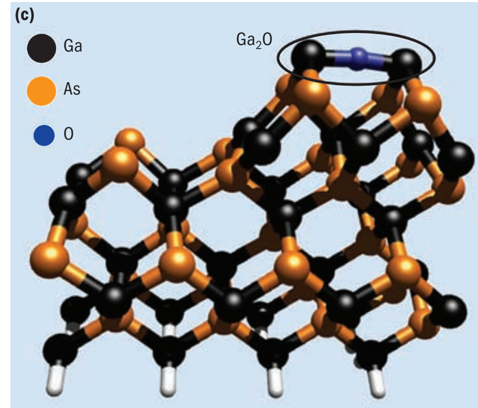
INTEL



SOURCE: D ANTONIADIS

The latest CMOS processes from Intel are producing devices at the 45 nm node (above). **Fig. 1.** (left) Dimitri Antoniadis from MIT has calculated that as CMOS nodes head to dimensions of less than 65 nm, a gap is emerging between the performance expected by the silicon roadmap and that actually delivered. A switch to III-V and germanium MOSFETs promises to close this gap.





SOURCE: A KUMMEL, UCSD

Fig. 2. Silicon CMOS's success stems from the high interface quality of silicon with its native oxide **(a)**. A stack of thin films comprising silicon, silicon dioxide and hafnium dioxide can produce oxides for germanium **(b)**. In this case the silicon layer must be no thicker than eight monolayers, otherwise it produces strain-related defects. Deposition must take place at lower temperatures to prevent germanium surface segregation. The silicon layer is partly oxidized to form about 0.4 nm of SiO_2, prior to deposition of the high-k dielectric. The deposition of Ga_2O can form a high-quality oxide interface for GaAs MOSFETs **(c)**.

Non-silicon transistors are also susceptible to poor off-state performance resulting from the narrower bandgap of the material employed – InGaAs, InAs, InSb or germanium. This increases band-to-band tunneling at the high electric fields that exist at the drain side of the gate of scaled devices, which increases leakage current and cuts the transistor's I_{on}/I_{off} ratio. The density of states available for conduction in high-mobility III-V channels is also less than one-hundredth of that for silicon equivalents.

Some of these changes in material characteristics hinder the performance of inversion-type MOSFETs, the standard workhorse of silicon CMOS. Minority carrier mobilities in surface inversion channels are relatively low. Large surface potentials are needed to produce the surface inversion required for transistor operation, leading to a narrowing of surface quantum wells with large energy quantization, which further reduces the density of states and leads to an increase in the proportion of electrons scattered into satellite valleys. In short, inversion-type MOSFETs may not be the best option for III-Vs.

However, recent work at various groups, including Freescale, the University of Glasgow, UK, and Interuniversity Microelectronics Center (IMEC), Belgium, has shown that it is possible to address some of the problems associated with non-silicon MOSFETs. For example, efforts at Freescale have revealed that progress can be made on the III-V side by turning to flatband- or accumulation-mode MOSFETs, which are promising high-mobility devices.

Flatband MOSFETs

Although the flatband MOSFET is similar to its inversion-mode equivalent – it shares planarity, enhancement-mode terminal characteristics and the ability to be implemented as either a surface or a buried channel device – there are fundamental differences in device operation. The flatband-mode MOSFET, unlike its inversion-mode cousin, is a majority carrier device in the on state and a minority carrier device in the off state. This means that the transistor is able to benefit from the higher majority carrier mobility and increased on-state current, in addition to the potentially lower off-state leakage current. This reduction in the leakage current can result from both deep depletion within the device and minority carrier extraction measures.

"FETs with non-silicon channels will have to be realized on large-area silicon substrates".

All non-silicon MOSFET developers face the challenge of fabricating a satisfactory oxide interface. For decades the only material capable of producing a good enough interface for device operation was a combination of silicon and oxygen. Even today the leading CMOS manufacturers insert a thin SiO_2 interfacial layer between silicon and a high-k dielectric. However, promising contenders are emerging for device quality interfaces on germanium, such as ultrathin fully strained epitaxial silicon layers and thermally grown GeO_2 with *in situ* deposited high-k dielectrics. It is also possible to make device-quality oxide–semiconductor interfaces for GaAs-based MOSFETs by depositing Ga_2O molecules into the arsenic dimers of a clean GaAs surface. Conventional oxidation – the process used for elemental semiconductors – is not an option because it produces a high density of trap levels within the GaAs bandgap.

Heterogeneous integration is clearly an important challenge but it is not the only criterion for judging the progress of non-silicon FETs. After all, it is not just the device's performance that matters but also its suitability for incorporation into CMOS.

The Intel and MIT groups have built some high-performance n-channel III-V PHEMTs that have a gate length of less than 100 nm, high-channel electron mobilities of 10,000–20,000 cm^2/Vs and a superior gate delay and power-delay-product compared with state-of-the-art silicon NMOS transistors. However, their Schottky contact gate electrodes limit scalability and progress in this area will require the addition of oxide layers to address CMOS requirements.

One device that shows promise for fulfilling CMOS requirements is the GaAs-based n-channel MOSFET that we have developed at Freescale and the University of Glasgow. This flatband-mode device, which features a $Ga_2O/GaAs$ interface and an $In_{0.3}Ga_{0.7}As$ channel, has been developed for radio-frequency applications and delivers a superior performance to PHEMTs (figure 3, p24). More important is that it has the potential to usurp BiHEMT and BiFET technologies and kick-start a new era of RF front-end integration in applications such as mobile handsets. Success in this market would be driven by the

iscs 2008

35th International Symposium on Compound Semiconductors

ISCS2008 will be held September 21 - 24, 2008 at the Europa-Park Rust near Freiburg, Germany.
The conference addresses compound semiconductors and their applications as well as emerging materials, e.g. carbon, oxides, and organic semiconductors.
Scientific program starts on Sunday, September 21, 2008 at 2:00 pm.

Invited Speakers

David Awschalom, UCSB
Erik Bakkers, Philips
Lucien Besombes, CNRS Grenoble
Zhihong Chen, IBM
Nicolas Grandjean, EPFL Lausanne
Ken Nakahara, ROHM
Tomás Palacios, MIT
Reinhart Poprawe, RWTH Aachen
Alberto Salleo, Stanford Univ.
Thomas Schäpers, Forschungszentrum Jülich
Zlatko Sitar, North Carolina State Univ.
James Speck, UCSB
Martin Wegener, Univ. Karlsruhe
Hiroshi Yamaguchi, NTT
Seikoh Yoshida, Furukawa

Abstract submission

Authors are invited to submit a two page camera-ready abstract by Email.

Important Dates

June 6, 2008 Submission of Abstracts
July 4, 2008 Notification of Acceptance
July 15, 2008 Conference Pre-Registration
July 15, 2008 Hotel Reservation

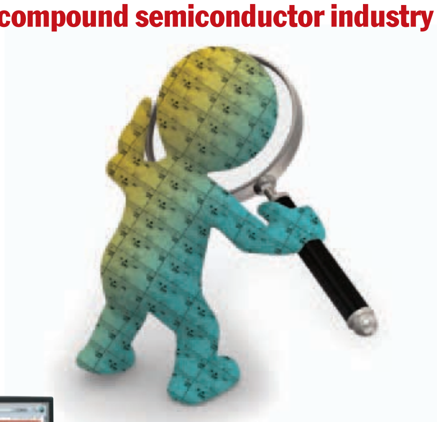
visit www.iscs2008.com

ISCS2008, Fraunhofer IAF, Tullastrasse 72, 79108 Freiburg, Germany, Email: iscs2008@iaf.fraunhofer.de

compoundsemiconductor.net
Connecting the compound semiconductor community

Take a closer look behind the headlines

for the inside stories in the compound semiconductor industry



Follow Mr Chip to register free today to get access to industry news and reports on current developments in compound semiconductors. Visit **compoundsemiconductor.net**.

IOP A community website from Institute of Physics Publishing

Blue Photonics, Inc.

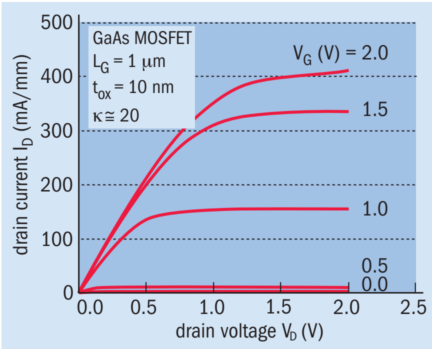
a dedicated GaN epi supplier

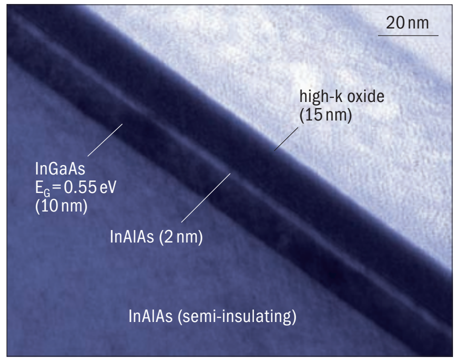
We supply the state-of-the-art GaN epi wafers

- **GaN/InGaN on sapphire (2” to 4”) for blue LED, LD and UV detectors**
- **GaN/AlGaN HEMT on Si (2” to 6”)**
- **Special Custom GaN epi wafers**

Blue Photonics, Inc.
679 Brea Canyon Road,
Walnut, CA 91789
Tel: (909) 839-2678
Fax: (909) 839-2677
Email: info@bluephotonics.com
http://www.bluephotonics.com

Total GaN Solutions





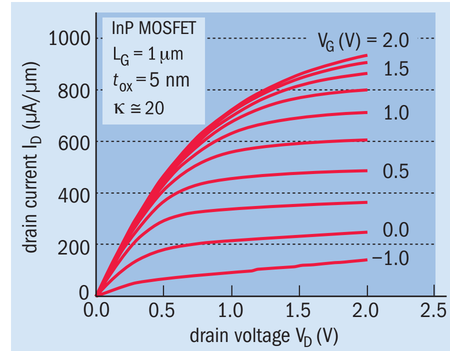


Fig. 3. (left) I-V characteristics for a 1 µm gate length GaAs MOSFET with an $In_{0.3}Ga_{0.7}As$ channel and 10 nm thick high-k oxide. This device has a peak transconductance of 477 µS/µm, a threshold voltage of 0.26 V, an on-resistance of 1.9 Ω mm and a gate current of less than 20 pA. **Fig. 4.** (center) This TEM image shows a CMOS proof-of-concept thin-body layer structure with a 10 nm $In_{0.75}Ga_{0.25}As$ channel, 2 nm AlInAs barrier layer and 15 nm high-k dielectric. A mobility map of this epiwafer reveals an average electron mobility of 8000 cm^2/Vs. **Fig. 5.** (right) Freescale and the University of Glasgow have built a thin-body 1 µm $In_{0.75}Ga_{0.25}As$ channel MOSFET with a source-drain distance of 3 µm and a physical oxide thickness of 5 nm (the equivalent oxide thickness including the AlInAs barrier layer is 1.7 nm). The I-V characteristics reveal the difficulty in turning the device off, which is attributed to a high density of donor-type states in the lower part of the semiconductor bandgap at the oxide–semiconductor interface. Peak transconductance is 737 µS/µm, on-resistance is 530 Ω µm and gate current is less than 1 nA.

About the authors
Joining Motorola in 1995 from AT&T Bell Laboratories, **Matthias Passlack** (left) led and contributed to R&D efforts at Motorola and Freescale Semiconductor in the field of III-V MOS materials, processes, characterization, devices and physics. He left Freescale in March. **Marc Heyns** (center) joined IMEC in 1986. He became an IMEC fellow in 2001 and a professor at the KU Leuven in 2005. His current research topics include novel high-k dielectric materials, advanced cleaning and surface preparation, and novel devices made on high-mobility substrates, such as germanium and III/V, nanowires, carbon nanotubes and graphene. **Iain Thayne** (right) has worked on III-V materials and transistors for 23 years, initially at Philips Research Labs and since 1998 at the University of Glasgow, where he is professor of ultrafast systems. He coordinates III-V MOSFET research funded by the UK EPSRC, the US SRC and the EU.

planar MOS configuration, which employs a common epitaxial layer structure allowing single-chip integration of power amplification, RF switching, and digital and analog functions.

These MOSFETs are of limited relevance for CMOS due to their lower mobility compared with higher indium mole fraction InGaAs channel layers. Introducing indium into this layer with a mole fraction of 50% or more requires a switch from a GaAs to an InP substrate. At Freescale we have done this and built a thin-body structure that contains an $In_{0.75}Ga_{0.25}As$ channel by MBE (figure 4). This epiwafer has a mobility of 8000 cm^2/Vs, but other MOSFET wafers with similar layer structures have shown electron mobilities of more than 10,000 cm^2/Vs – 20 times as great as silicon NMOS.

Our flatband-mode InP MOSFETs deliver an impressive on-state performance – transconductance exceeds 700 µS/µm for a 1 µm gate length. This compares favorably with InGaAs MOSFETs built by both Peide Ye's group from Purdue University and a collaboration between IBM and Princeton. They feature gate oxides deposited by atomic layer deposition, and they have electron mobilities and a transconductance of 1200 cm^2/Vs and 230 µS/µm, respectively.

Germanium inversion-mode MOSFETs with a thin epitaxial silicon layer are being developed by IMEC. Such devices can deliver peak hole channel mobilities of more than 350 cm^2/Vs on unstrained p-channel devices. Mobility increases to more than 640 cm^2/Vs on strained devices – three times as high as the peak value for silicon. Optimizing implantations and silicon passivation leads to good control of short channel effects and enables devices with a peak transconductance of 800 µS/µm for a 125 nm channel length. At 1.5 V drain voltage this transistor delivers 722 µA/µm – more than double that of a p-channel silicon MOSFET with a 120 nm channel.

If III-V and germanium channel MOSFETs are to provide a viable future beyond silicon CMOS then they will have to scale to diminutive CMOS dimensions. However, it's not just a question of physical miniaturization as these transistors must deliver enhanced electron or hole transport properties. In addition, and in contrast to GaAs MOSFETs, there is still the problem of making a high-quality oxide–semiconductor interface for III-V channel materials with CMOS relevance. This problem plagues all of today's high indium mole fraction channel technologies, and it is evident from the difficulty associated with turning the device off (figure 5).

"Everything can be done in silicon" is a claim that our community contests. And with the scaling of CMOS feature sizes delivering diminishing returns, there is reason to believe that with a collaborative spirit the compounds and germanium can gain a solid foothold. Indeed, it is possible that the saying "everything can be done on silicon" will eventually find universal acceptance. But whatever the outcome for non-silicon MOSFETs for CMOS, one thing is certain: the semiconductor community has some exciting and challenging years ahead.

Further reading

A Khakifirooz *et al.* *IEEE Transactions on Electron Devices* **55** (in press).
J R Lineback 1986 *Electronics* June 9 **21**.
B C Cole 1986 *Electronics* September 18 **57**.
S Datta *et al.* 2005 *IEDM Technical Digest* 763.
D-H Kim *et al.* 2007 *IEDM Technical Digest* 629.
R Metzger 2007 May *Compound Semiconductor* 16.
M Passlack 2006 *IEEE Transactions on Electron Devices* **53** 2773.
A Delabie *et al.* 2007 *Appl. Phys. Lett.* **91** 082904.
M Hale *et al.* 2003 *J. Chemical Physics* **119** 6719.
R J W Hill *et al.* 2007 *IEEE Electron Device Letters* **28** 1080.
R J W Hill *et al.* 2008 *Electronics Letters* **44** 498.
Y Yuan *et al.* 2007 *IEDM Technical Digest* 637.
G Nicholas *et al.* 2007 *IEEE Electron Device Letters* **28** 825.
M K Hudait *et al.* 2007 *IEDM Technical Digest* 625.

Comb lasers target connectivity

Today's quantum-dot lasers operate in niche markets. However, significant laser shipments could soon materialize thanks to Fabry-Pérot designs that offer the ideal source for optical links in next-generation computer systems, according to **Alexey Kovsh** and **Greg Wojcik** from Innolume.

Today's computers are rarely stand-alone machines. Instead, they are hooked up to the information superhighway where they exchange data in the form of e-mails, webpages, pictures, music and video.

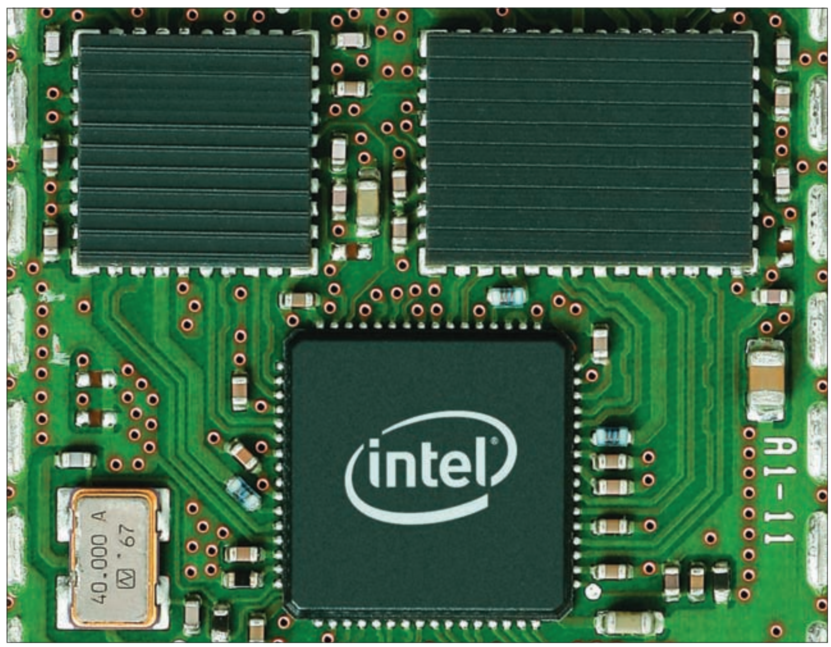
The transfer of information involves optical fiber networks, which provide medium- to long-reach data communications via wavelength-division multiplexing (WDM) transmission. However, as the reach gets shorter, there is a switch from optical to electrical links, such as interconnects used in mainstream computing applications. Here the electrical link infrastructure is being pushed to its limit, thanks to the proliferation of server farms, high-performance computing and chip-level multiprocessors.

To address the impending data-rate crunch over these short distances, researchers are developing techniques to unite silicon photonics and fiber optics. These technologies should equip silicon with tools to couple, route, (de)multiplex, detect and modulate light for short-reach needs. However, silicon cannot provide the laser. This means that there is a massive potential market for III-V lasers at wavelengths of at least 1.2 μm, which can provide the optical sources for short-reach communication.

Unfortunately it is difficult to make optical systems that can replicate the levels of integration found in silicon ICs. Arrays of VCSELs and, to a lesser extent, edge-emitter lasers are two of today's best options, but their excessive cost and complexity make them impractical for very-high-volume computer applications. So alternatives are needed, such as single Fabry-Pérot quantum-dot broadband comb lasers that produce a collection of equally spaced emission frequencies. We are developing such a device at Innolume, which is specifically designed for short-reach WDM.

The WDM approach that we are pursuing isn't the most popular method for transferring information over short-reach interconnects. Parallel optics approaches are preferred, which are based on directly modulated VCSELs and multiple fibers, waveguides or free-space optics. However, WDM, which involves the coupling, modulating and multiplexing of light from multiple continuous wave lasers into a single fiber or waveguide, is equally capable of satisfying the need for multiple light source integration on a single chip.

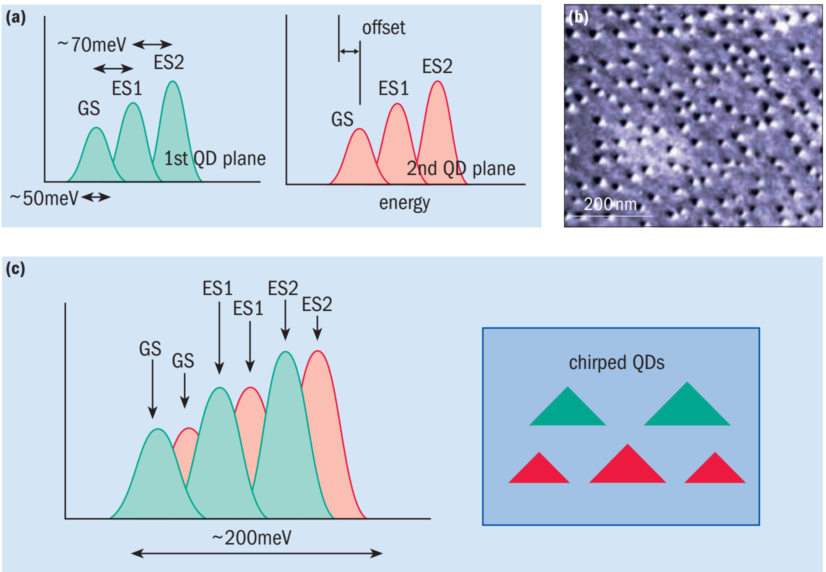
WDM technology also has an advantage over VCSEL arrays: it doesn't require coupling to multiple waveguides or fibers. The VCSEL-based approach fails to offer a clear path for the migration of the optics to the IC because the device has to be placed next to the silicon chip and connected electrically. To eliminate inefficient electrical links, the optics must be brought close to, and eventually onto, the processor or memory, which could lead to direct communication between cores in multicore chips.



INTEL

Today's computer chips use an electrical link infrastructure to transfer data. But future chip microprocessors will put greater demands on the electrical interconnects between processors, which may eventually have to be replaced with optical interconnects in an optical layer.

Our lasers will target deployment in systems delivering data rates of at least 1 Tbit/s, because this will be the likely tipping point for transition from electrical to optical interconnects. Obviously the crossover point is a moving target because electrical engineers will continue to extend this technology's capabilities. There will come a time when the engineers are defeated by power issues at ever higher speeds, such as greater distortion of electrical signals (skin effect), dielectric losses and reflections caused by impedance mismatch. However, higher speeds alone can't guarantee success because compelling cost advantages are also needed to drive the switch to optical



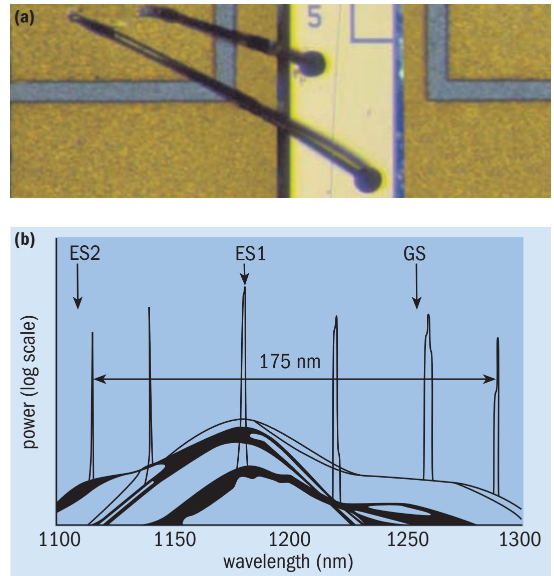


Fig. 1. (left top and bottom) **(a)** The emission from quantum dots under high-excitation pumping results from transitions between ground states (GSs) and two excited states (ESs) within the dot. The energy of these transitions can be shifted by altering the dot's size. **(b)** TEM reveals that variations in the sizes of quantum dots across a layer are fairly small. **(c)** However, a broad emission spectrum can be produced by building a stack that features layers with different quantum-dot sizes. **Fig. 2.** (right top and bottom) Innolume's quantum-dot gain chip **(a)** can form part of a tunable laser with continuous-wave powers of more than 200 mW across the whole spectral range and a peak of more than 500 mW **(b)**. Vertical arrows indicate the spectral position of the optical transitions from ground and excited states.

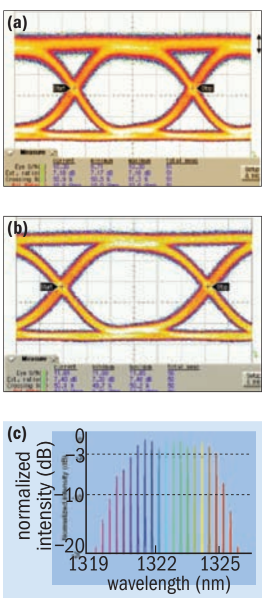


Fig. 3. Eye diagrams can be used to compare the quality of the modulated signal from a single Fabry-Pérot mode of a quantum-dot comb laser **(a)** and a commercially available 1300 nm external cavity laser **(b)**. Bit error rates of less than 10^{-13} were obtained for more than 10 Fabry-Pérot lines of the comb laser with continuous-wave powers of more than 1 mW **(c)**.

signal distribution. This change-over will not be trivial, but a disruptive and expensive transition for the IC, computer, PCB and packaging industries.

We believe that our WDM links should employ signal modulation speeds of 40 Gbit/s or less. Using faster external drivers for these lasers is prohibitively expensive, and employing lower speeds and more channels offers better value for money.

Laser connections

This approach requires optical coupling of the laser to the silicon chip, or the photonic integrated circuit chip in the case of III-V substrates. In our opinion, the best way to do this is to locate the laser assembly off-chip and connect this with an optical fiber/ribbon or integrated waveguides. This is not a cheap solution, but it does deliver manufacturing advantages, as the laser and silicon ICs can be brought together during motherboard or package assembly.

The alternative to this approach is based on the bonding of laser array chips to silicon or silicon photonic ICs. However, IC manufacturers may not favor this cheaper method because they will be reluctant to relinquish chip real estate and will want to avoid making disruptive architectural changes to their highly evolved and very valuable jewel – the CPU. Bonding approaches are restrictive because the single-frequency emission needed can only be produced by distributed feedback and microring laser designs. However, Intel and UCSB have shown that gratings in the silicon waveguides can provide feedback.

Bonding technologies also hamper the laser's operating environment. High-performance chips, such as dual-core CPUs, idle at 30–40 °C but work at 70, 80 or even 100 °C under heavy loads. High temperatures and large temperature swings degrade the device and drive variations in quantum-well laser emission wavelengths. Quantum-dot lasers are immune to this – the Fujitsu spin-out QD Laser Inc recently announced a 1310 nm emitter for passive optical network uplinks that is insensitive to temperatures between –40 and 100 °C.

Regardless of whether the laser chip is mounted externally or onto either the silicon photonics chip or the photonics integrated circuit, it must mimic the performance of an array of distributed feedback lasers producing up to hundreds of channels. This means that each channel should deliver at least 1 mW with very low relative intensity noise to ensure low bit error rates at high modulation speeds. On top of all of this, the laser chip must command a price tag of about a dollar for high-volume IC applications.

The quantum-dot lasers promise to fulfill all of these requirements. They take advantage of the intrinsic variations in quantum-dot sizes, which lead to a broad lasing envelope. By intentionally producing structures of up to 10 layers of quantum dots with different dot sizes in each layer (figure 1), we can make a device with a very wide optical gain that delivers broadband lasing at high power (figure 2). The quantum-dot lasers that we have fabricated include a device with a 75 nm wide emission spectrum and only 3 dB intensity variation.

Our broadband laser does not produce continuous emission over a wide spectrum – such a device would be too noisy for high-speed external modulation. Instead we have built a broadband comb laser, which emits a collection of single Fabry-Pérot lines. The relative intensity noise of each line (longitudinal mode) is the critical parameter, and calculations show that this must be less than 0.3% for 10 Gbit/s transmission with a bit error rate of less than 10^{-12}.

Guaranteeing modal intensity stability in any conventional Fabry-Pérot laser is not just a matter of maintaining overall power stability, as different longitudinal modes compete for optical gain. Noise associated with this, known as mode partitioning, prevented engineers from using quantum-well lasers as a simple comb spectrum source several years ago. However, we have solved this problem with proprietary quantum-dot engineering. Also, experiments conducted by the Heinrich-Hertz-Institut in Berlin have revealed that individual lines of a comb laser support error-free 10 Gbit/s transmission using external modulation (figure 3).

Our best results to date include 10 mW per channel over 16 channels and more than 1 mW per channel over 100 channels, for channel spacing of less than 50–140 GHz (<0.28–0.8 nm). Although emission is centered between 1250 and 1320 nm, which overlaps the O-band (1260–1360 nm), we have performed our benchtop experiments with standard discrete C-band components (figure 4).

We are now attempting to demonstrate our comb laser's feasibility for short- to medium-reach WDM transmission, such as 100 Gbit/s Ethernet and passive optical networks. To this end we are co-developing transmitters on photonic integrated circuits in III-Vs and on silicon photonic chips using silicon-on-insulator technology. In each case the transmitter comprises a laser fiber-coupled to a demultiplexer that separates the comb input channels, modulators for each of the channels, a multiplexer that combines the modulated channels and a coupler into the output fiber. We expect III-Vs to deliver the first successes and enable moderate-cost, low-volume production. The SOI project is more challenging but should set us on the path towards eventual high-volume CMOS production.

In these types of application, our comb laser transmitter promises to deliver several advantages over a laser array. It simplifies the component count by replacing an integrated array of lower-yield DFB lasers with a single comb laser plus a demultiplexer. It also offers more channels at negligible cost, which allows lower modulation speeds to deliver similar or greater bandwidth. These properties should make the comb WDM transmitter more scalable because it is cheaper to raise the channel count of (de)multiplexers and modulator arrays than to increase the number of lasers in the integrated array.

We are also evaluating driver electronics for electroabsorption and Mach–Zehnder modulators, and paying attention to layouts, packaging and timelines for integration and cost. 1.2 mm GaAs, 10 Gbit/s dies are available today from GigOptix, and SiGe 10 Gbit/s drivers may show up soon, perhaps with four drivers per die. CMOS versions offering many drivers per chip could also appear on the market within a few years, once the high-volume WDM interconnect market becomes a reality.

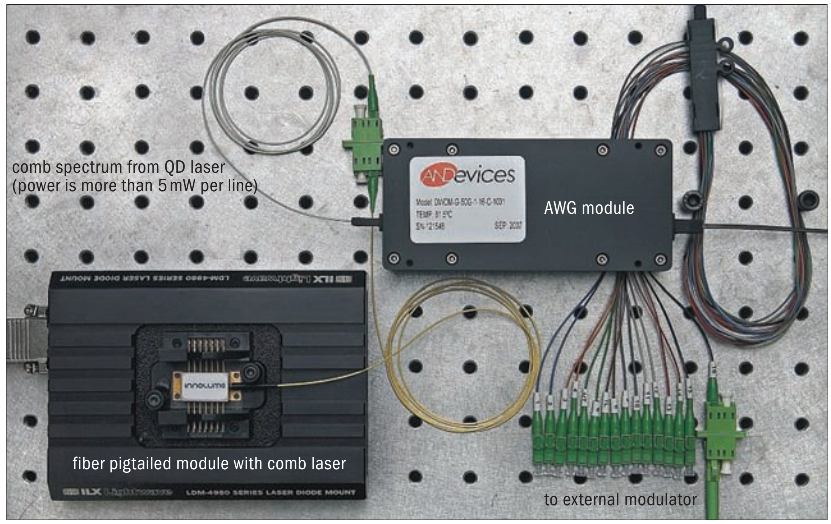


Fig. 4. Many of Innolume's initial optical experiments involved the demultiplexing of a comb laser by a commercial C-band (1550 nm), 50 GHz spacing arrayed waveguide. The O-band arrayed waveguide grating output of combs centered at 1280 and 1310 nm shows negligible power loss.

Comb laser WDM transmitters offer the compound semiconductor industry several challenges and opportunities related to materials, processing and new device fabrication. Just as erbium-doped fiber amplifiers have unlocked the door to long-reach 1550 nm WDM in telecom networks, broadband quantum-dot semiconductor optical amplifiers for coupling and tap losses could spur the deployment of 1310 nm WDM networks. This could lead to relatively short terahertz ring networks on boards, or in facilities and vehicles, such as ships and planes.

Niche opportunities, such as surgery and therapy, also exist for quantum-dot lasers because their wavelength range can't be covered by mainstream quantum-well lasers. Pricing structures are especially attractive and quantum-dot lasers are already penetrating these medical markets because of their high power, excellent reliability and lifetimes in excess of 100,000 hours. These qualities are also enabling this type of source to be used in flow cytometry, and to form gain chips for spectroscopy and optical coherence tomography.

Computer optical interconnects would be the big win – a potentially very-high-volume market where novel devices like the diode comb laser can offer terahertz speeds at commodity pricing. Our strategy to penetrate this market begins with the co-development of a prototype transmitter photonic integrated circuit for short-reach WDM communications in tangible, near-term applications. This will allow us to "put our flag in the ground". It will also enable us to evaluate and quantify scaling issues, and the true WDM potential of the GaAs quantum-dot comb laser and its supporting photonics infrastructure. Self-sustaining niche businesses, technology developments and forthcoming comb-laser transmitter applications will prepare us, suppliers and market partners alike for the future battle over commodity computer communications.


About the authors

Alexey Kovsh (left; alexey.kovsh@innolume.com) is Innolume's CTO. He is responsible for laser technology development and oversees operations. His background includes MBE growth of III-V alloys and self-organized quantum dots, and the development of quantum-well and quantum-dot edge emitters and VCSELs. **Greg Wojcik** (right; greg.wojcik@innolume.com) is vice-president of engineering. He develops and implements strategies for laser commercialization in emerging markets. He has a PhD from Caltech, and an engineering and mathematics career that spans 30 years.

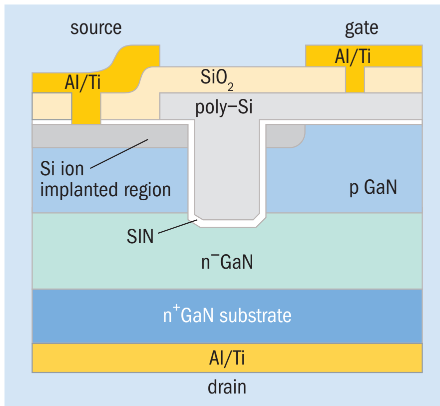
POWER ELECTRONICS

Non-polar face fits for Toyota MOSFET

Using non-polar GaN, Toyota researchers have made high-power transistors with electronic behavior and a chip design that pave the way for volume manufacture.

GaN HEMTs are widely touted for power switching but frequently fail to exceed the threshold voltage of 3 V that they need to qualify as normally off. Now Toyota has produced a trench-gate MOSFET with a threshold voltage of 10 V, which fulfills their preference for normally off switches currently embodied in silicon.

Trench-gate transistors are widespread in silicon power electronics, so this method is desirable for delivering the efficiency and robustness benefits that GaN promises. “The formation of GaN trench-gate power transistors is a simple process, with GaN making higher-temperature device operation possible,” explained Masahito Kodama of Toyota Central R&D Laboratories.



The U-shaped trench in the epitaxial structure is pivotal in the production of a normally off device.

In conjunction with Toyota Motor Corporation, Kodama and his colleagues produced their normally off device by starting the growth of the transistor’s polysilicon gate on non-polar (1$\bar{1}$00)-plane GaN, thereby reducing the impact of the polarization-induced charge.

Starting with a standard, free-standing (0001)-plane n-type GaN substrate, they grew a 6 μm n-type GaN layer by MOCVD, followed by a 1 μm p-type GaN layer. Inductively coupled plasma etching produced V-shaped trenches with rough sidewalls unsuitable for gate growth. Further chemical etching with trimethylaluminum hydride then broadened the trench into a U-shape.

Sloping walls at the base of the trench then provided the non-polar (1$\bar{1}$00) surface on which the polysilicon gate could be grown by low-pressure CVD.

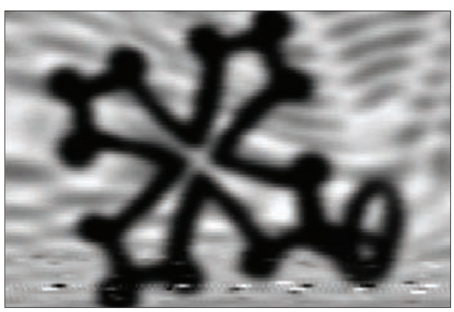
Journal reference
T Kachi *et al.* 2008 *Appl. Phys. Express* **1** 021104.

TERAHERTZ IMAGING

GaAs HEMTs provide hope for detectors

Off-the-shelf GaAs chips from Fujitsu have offered a straightforward solution to one of the biggest challenges for terahertz imaging by showing themselves to be promising detectors for terahertz radiation.

“Terahertz imaging will only break through into mainstream applications if low-cost non-cryogenic multipixel detector arrays become available,” said Hartmut Roskos of Frankfurt University. “Monolithic integration of planar microelectronic detectors is the most promising path to follow.”



A commercial Fujitsu GaAs chip was used to detect this image, created by focusing terahertz radiation on a cross-shaped charm in a paper envelope.

Roskos’ German group teamed up with researchers from Montpellier, France, to scan items, hidden in paper envelopes, with 0.6 THz radiation from a 0.5 mW source, collimated and focused with plastic lenses. For detection, the radiation modulates carriers in the Fujitsu FHX05X GaAs HEMT to generate currents that can form images.

Roskos and his colleagues are currently investigating which type of transistor will offer the ideal detector. “High electron mobilities are desirable, which speaks well for GaAs or InP,” Roskos said. “Silicon, however, seems to have an advantage in terms of noise performance.”

Journal reference
H G Roskos *et al.* 2008 *Electron. Lett.* **44** 408.

WHITE LEDs

Lateral quantum wells challenge phosphors

A white-light-emitting GaN chip containing alternating quantum-well strips ordered side by side and produced by a Korean group avoids the need for phosphors that are ever-present in today’s white LEDs. The different quantum wells emit at 431 and 511 nm, producing a very cool overall white color.

However, research team leader Seong-ju Park emphasizes that color temperature can be varied in different epitaxial structures. “The color can be controlled by changing the emission wavelengths of the two multi-quantum wells [MQWs] from blue/green to blue/yellow light,” he said.

Starting with a sapphire substrate, the team from Gwangju Institute of Science and Technology, South Korea, used MOCVD to grow a 2 μm thick n-GaN layer. It deposited five pairs of InGaN/GaN layers on top of this to make a blue-emitting MQW.

A 100 nm thick SiO_2 covering layer was deposited and patterned into lines by a combination of photolithography and wet etching. The group etched the strips of uncovered blue MQW down to the n-GaN layer using inductively coupled plasma etching. In the gaps between the columns, the team then deposited another five pairs of InGaN/GaN layers, this time to produce green MQWs.

Removing the remaining SiO_2 produced a flat surface – indicating that the MQWs were the same thickness – and Park deposited a 2 μm thick p-GaN layer on top.

The electroluminescent emission of this device showed very little variation in the ratio of blue to green emission. According to Park, this contrasts with the few examples of stacked MQW LEDs that have produced white light without phosphors.

Journal reference
S-J Park *et al.* 2008 *App. Phys. Lett.* **92** 0921110.

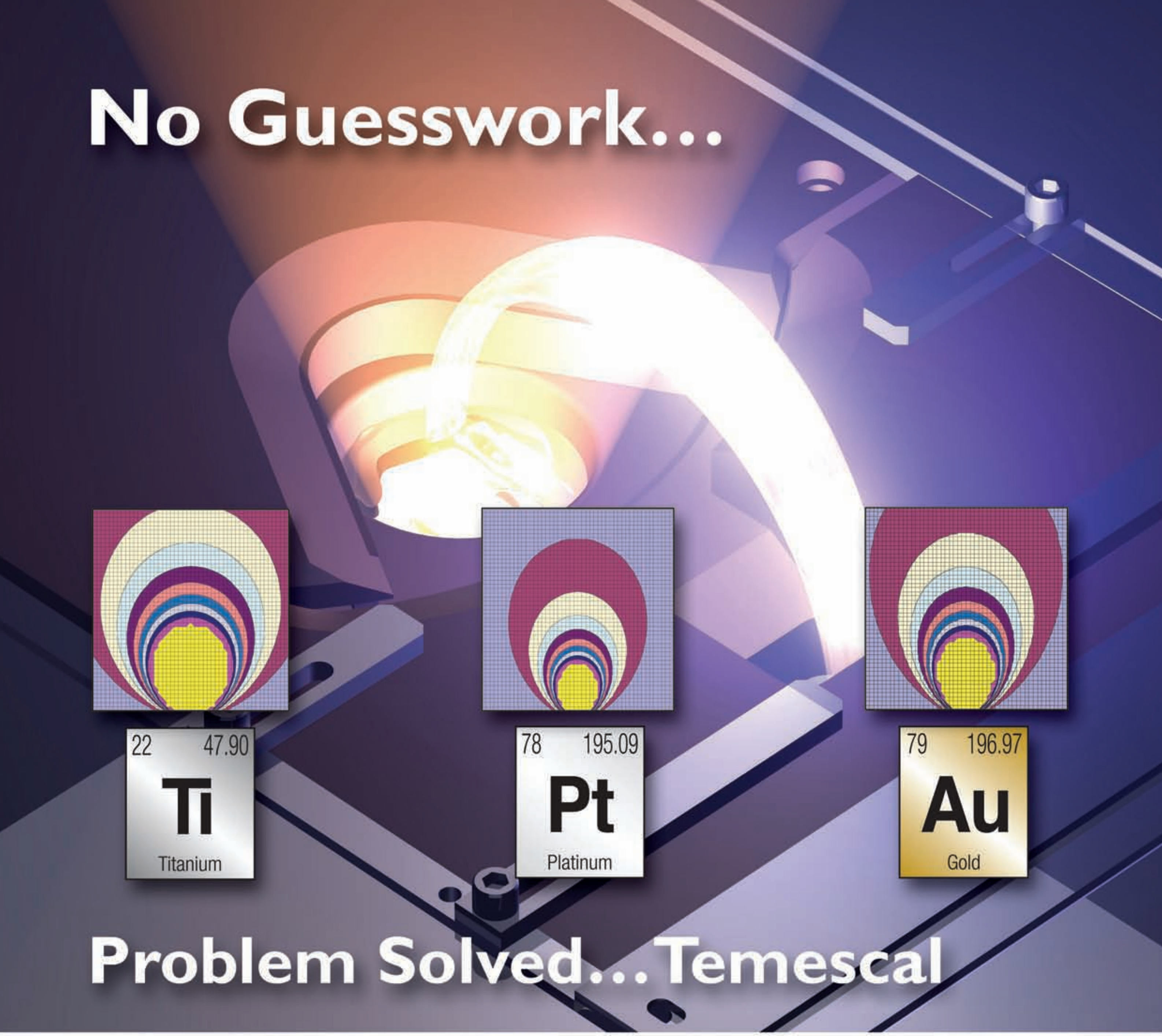
AIXTRON

Our leading technology. For highest quality in your products.

Innovators in production of highly complex materials use cutting edge technology!
Our CVD systems with highest performance and best economy.

AIXTRON

AIXTRON AG · Kackertstraße 15–17 · 52072 Aachen, Germany
info@aixtron.com · www.aixtron.com



Compound Semi

Experts in ^ Metallization

Temescal process scientists have developed a library of *Elemental Knowledge*™. This has led to 3D modeling of metal vapor clouds that enables Temescal to build tools that will optimize your process. A Temescal tool is more than just an Evaporator: the TCS (Temescal Control System) provides the Process Engineer unique control transforming the tool into a simple push-button system.

We've done your EVAPORATION homework for you™

Temescal

www.temescal.net