

COMPOUND SEMICONDUCTOR

September 2008 Volume 14 Number 8

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

NANO-IMPRINT LITHOGRAPHY

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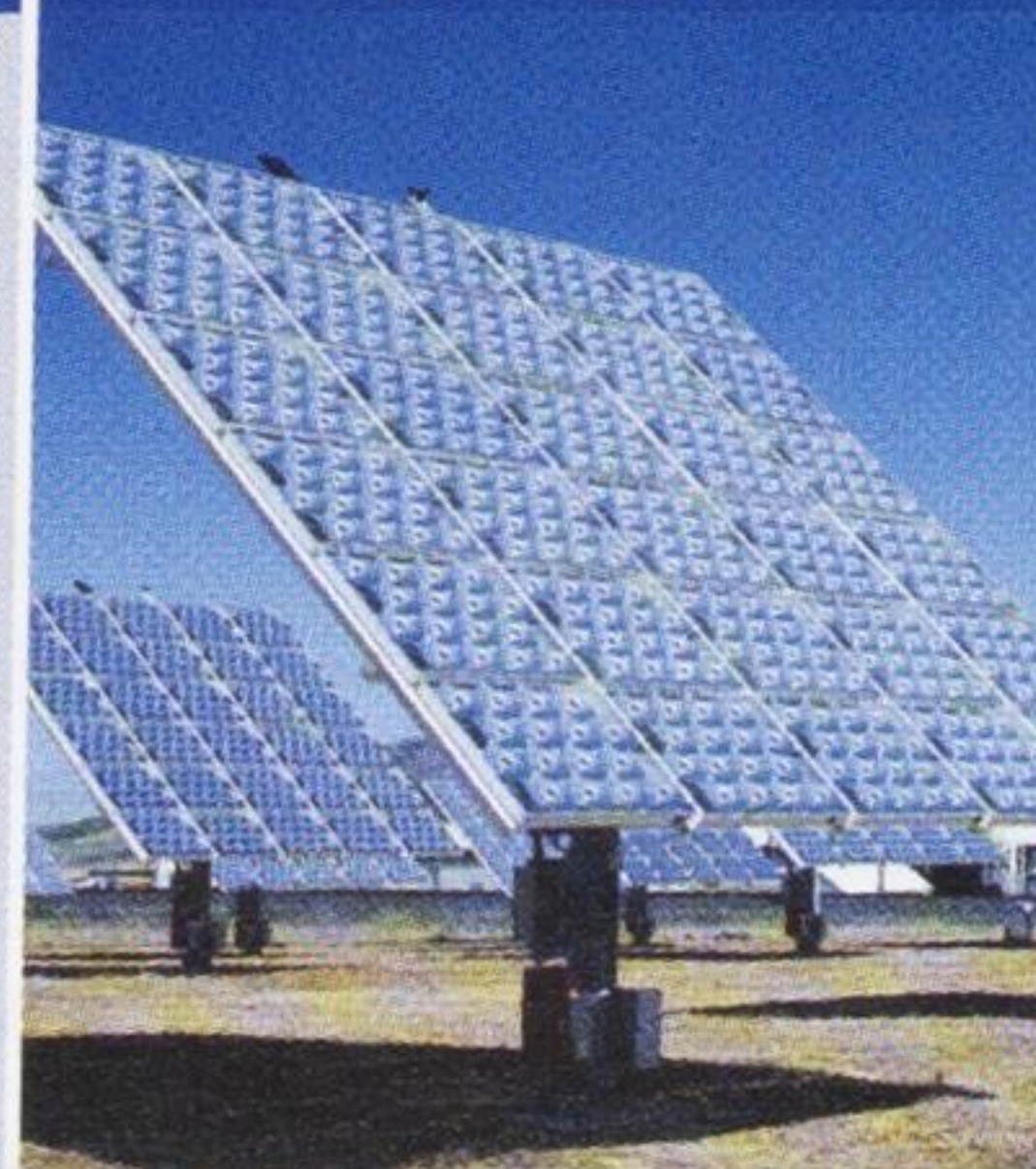
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Catching some rays

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Meet Gailon. With nearly 30 years experience in the MMIC industry, Gailon is dedicated to working closely with his team to deliver customers world-class technologies. His career experience includes helping develop GaAs MMICs for the earliest active-element phased array radars and the TriQuint technology which helped the Mars Rover communicate with scientists on Earth. He combines technical expertise, honesty and integrity to exceed customer's expectations and deliver projects on-time and to-specification. Gailon is one of the people behind the innovation that has made TriQuint the world's leading GaAs foundry and he's on your team.

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INDUSTRY

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Presidential visit

German president Horst Köhler visited Osram Opto Semiconductors in August in recognition of its continued LED innovation. **p9**

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Auto manufacturing

Fiber lasers from IPG Photonics will soon be welding car doors on BMW assembly lines. **p10**

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TECHNOLOGY

16 **Cadmium-based boules prepare to ignite the detector market:** Security services could get a massive boost from cadmium-based detectors that can identify plastic explosives in a suitcase's contents. Although it's tricky to make these II-VIs, a novel deposition tool and growth on GaAs offer a promising route to making high-quality CdTe and CdZnTe boules, say Max Robinson and Arnab Basu from Kromek.

20 **CRIEPI spearheads Japan's SiC assault:** From its position linking Japan's power companies, the Central Research Institute of the Electric Power Industry is on a mission to exploit SiC devices' efficiency. Andy Extance reports.



Power links

In Japan, electricity companies sponsor research into cutting-edge semiconductor devices, which is largely undertaken at CRIEPI. **p20**

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27 **Equipment Update: Cyclical process improves film quality** If you want to put down robust and highly conformal films for LED and radio-frequency electronic device manufacture, then you ought to consider a novel nanolayer deposition tool that features a plasma film treatment step in each deposition cycle, say Steve Selbrede, Michael Studendorff and Paul Werbaneth from Tegal Corporation.

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32 **Research Review:** GaN shapes up for multispectral imaging...New barriers enable longer wavelengths...Hybrid growth improves gate-oxide quality.

Main cover image: Photonic crystal LEDs that are being developed by researchers in the UK should help to improve the efficiency of backlighting units in LCD TVs. See p25. Credit: Ian Watson, Erdan Gu and Martin Dawson, University of Strathclyde.

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9428 average total qualified circulation*
*Updated December 2007 BPA audit statement

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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.

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Record breakers



It's not just in Beijing where world records are falling this month. OK, so the Olympics does enjoy a slightly higher profile than the compounds business, but the remarkable Michael Phelps is far from alone in setting world bests.

That said, whereas the six-foot-five swimmer tore chunks off the previous records, chip developers have been making progress at a more incremental pace. Researchers at the National Renewable Energy Laboratory (NREL), for example, have just shaded the new efficiency record for solar cells, thanks to their latest inverted metamorphic design for a III-V cell.

Beating the previous world mark of 40.7% – which was based on a cell design from the same laboratory – by just 0.1% might not seem like such a massive achievement. However, every improvement helps to take concentrator photovoltaics a step closer to economic viability. We should take nothing away from the marginal improvements by John Geisz's NREL team. After all, Jamaican sprinter Usain Bolt “only” shaved 0.03 s off his own record when he ran the 100 m final in just 9.69 s, but it still makes him the fastest man in history.

“Chip developers have been making progress at a more incremental pace.”

Chips are getting faster too. A team from the Massachusetts Institute of Technology (MIT) has just produced transistors with the highest combined f_t and f_{max} figures, in research that could pave the way for III-V materials to feature in future logic applications.

Other technologies are improving more rapidly. The most obvious area is white LEDs, where a team from Osram Opto Semiconductors recently made prototype 1 mm² chips delivering 155 lm and 136 lm/W under standard conditions – no wind assistance or banned substances here.

Which brings us onto one of the more obvious connections between the Olympics and compounds. The aquatic center hosting Phelps' amphibian-like efforts has stood out as one of the architectural highlights of the games. And that is in no small measure thanks to the LEDs that illuminate the so-called water cube, supplied by Cree among others.

The motto of the games – faster, higher, stronger – could apply just as easily to semiconductor research, even if “more efficient” doesn't scan quite so nicely. Congratulations to the MIT, Osram and NREL teams (and Phelps) on their record-breaking feats.

Michael Hatcher *Editor*

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Emerging Standardization for Sapphire Substrate Inspection

By Frank Burkeen

Senior Product Marketing Director at KLA-Tencor
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A growing demand for GaAs substrates and epitaxial wafers is being driven by two major device industries: (1) LED devices used in automobiles, signs, and flat-panel displays, and (2) MMIC devices for mobile electronics and Wi-Fi stations. As a result, industry experts are forecasting 16% CAGR for GaAs material by volume over the next 5 years. While volume demand for GaAs materials will continue at a healthy pace, overall demand will be counterbalanced by decreasing die sizes as GaAs device manufacturers improve fabrication processes. To date the use of automated defect inspection has been much less pervasive in compound semiconductor processing than in silicon wafer processing, however this is changing with the increasing need to increase yield and reduce costs.

With tighter design limits, substrate and epi defectivity is more critical than ever. A number of global manufacturing facilities are employing an Optical Surface Analysis (OSA) inspection technique that combines the power of scatterometry, ellipsometry, reflectometry, and topographical analysis to detect and classify defects in substrates, epi-layers, and process films. OSA technology is being used by industry leaders to monitor production lines, identify mission critical defects of interest, and create process-specific recipes to detect and classify yield killing defects while ignoring nuisance defects.

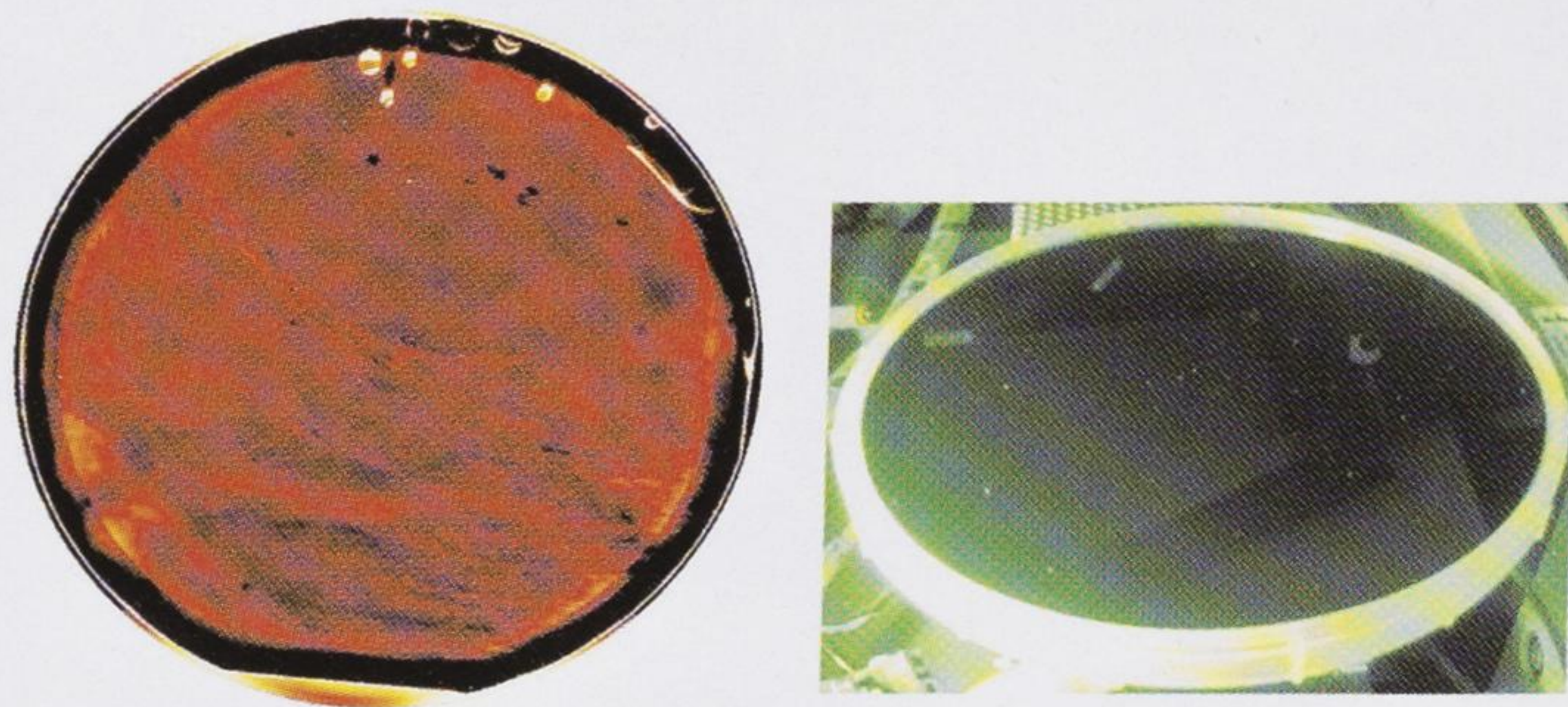


Figure 1: Candela Qphase™ image of GaAs substrate stains showing various water stains, wipe stains, edge defects and dark spots. Stains have been identified as killer defects resulting in rough epi morphology and poor epi-layer adhesion. Substrate stains cannot be seen under microscope or bright light inspection

Substrate stains on bare GaAs wafers are one such killer defect and frequently result in full wafers scraps after epi deposition. Historically GaAs substrates have been monitored with optical microscope or bright light inspection. However these inspection techniques are ineffective at detecting these killer stains and other thin film defects like some CMP residues. Many of these stains are only tens of angstroms thick and are not detectable with microscope or bright light inspection.

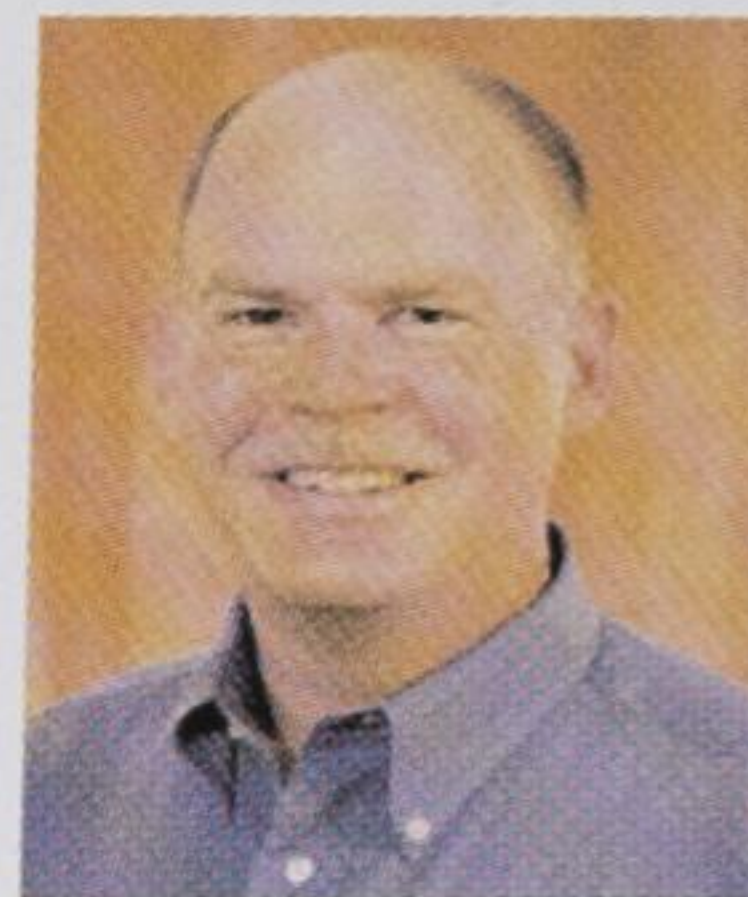


Figure 1 shows the OSA Qphase™ (digital image analysis application) image of GaAs substrate stains highlighting various water stains, wipe stains, edge defects and dark spots. Certain stains have been identified as killer defects resulting in rough epi morphology and poor epi-layer adhesion. Failed epi is causing full-wafer scraps throughout the supply chain creating turmoil between substrate suppliers, epi OEMs and device manufacturers as incumbents investigate whether the resultant wafer scraps are due to growth conditions or substrate quality. The Candela OSA has proven effective at root cause analysis of GaAs substrate stains and real-time defect detection and classification.

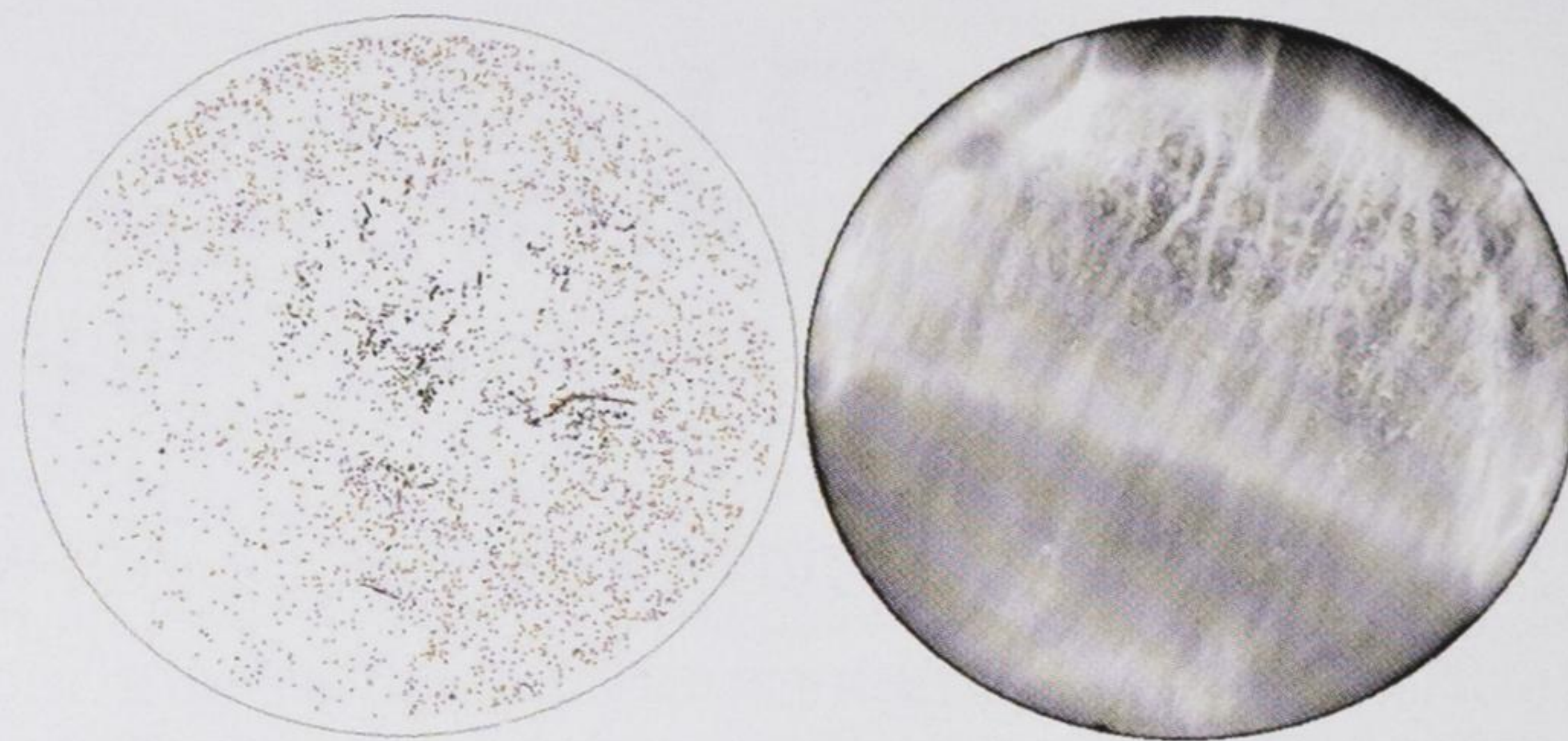


Figure 2: OSA Defect Map and Qphase™ image of same bare silicon wafer

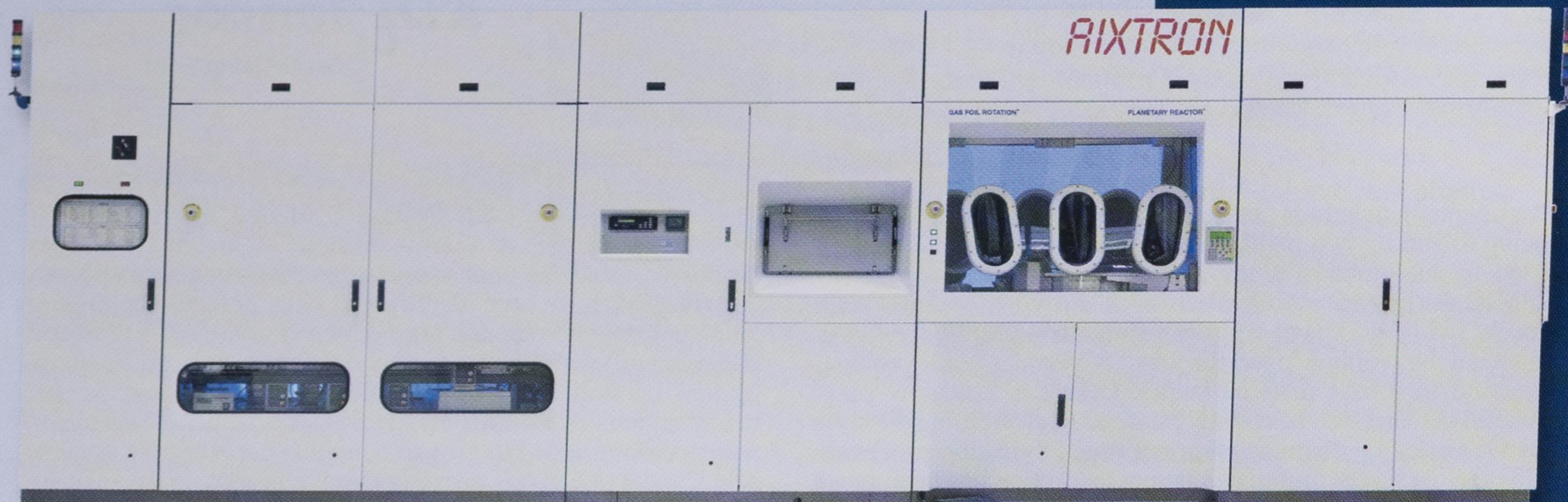
The long-standing industry standard in the semiconductor industry has been the report of Light Point Defects (LPDs) and surface haze. LPD defect maps are commonly used for process control and tool monitoring but a growing number of manufacturers are recognizing that some killer defects do not necessarily scatter light and scatterometry alone is not enough to meet their quality control needs. Figure 2 shows an LPD defect map and OSA Qphase image of the same bare silicon wafer. The substrate stains seen in the Qphase image are not detected using scatterometry.

Optical surface analysis technology enables manufacturers and suppliers to automate defect inspection and define well-controlled process control limits. OSA technology, as found in KLA-Tencor's Candela™ CS20, can be employed at incoming substrate inspection, post-clean inspection, and after epitaxial growth and process film deposition to improve yield.

To learn more, read about the Candela CS20 at:
www.kla-tencor.com/CS20

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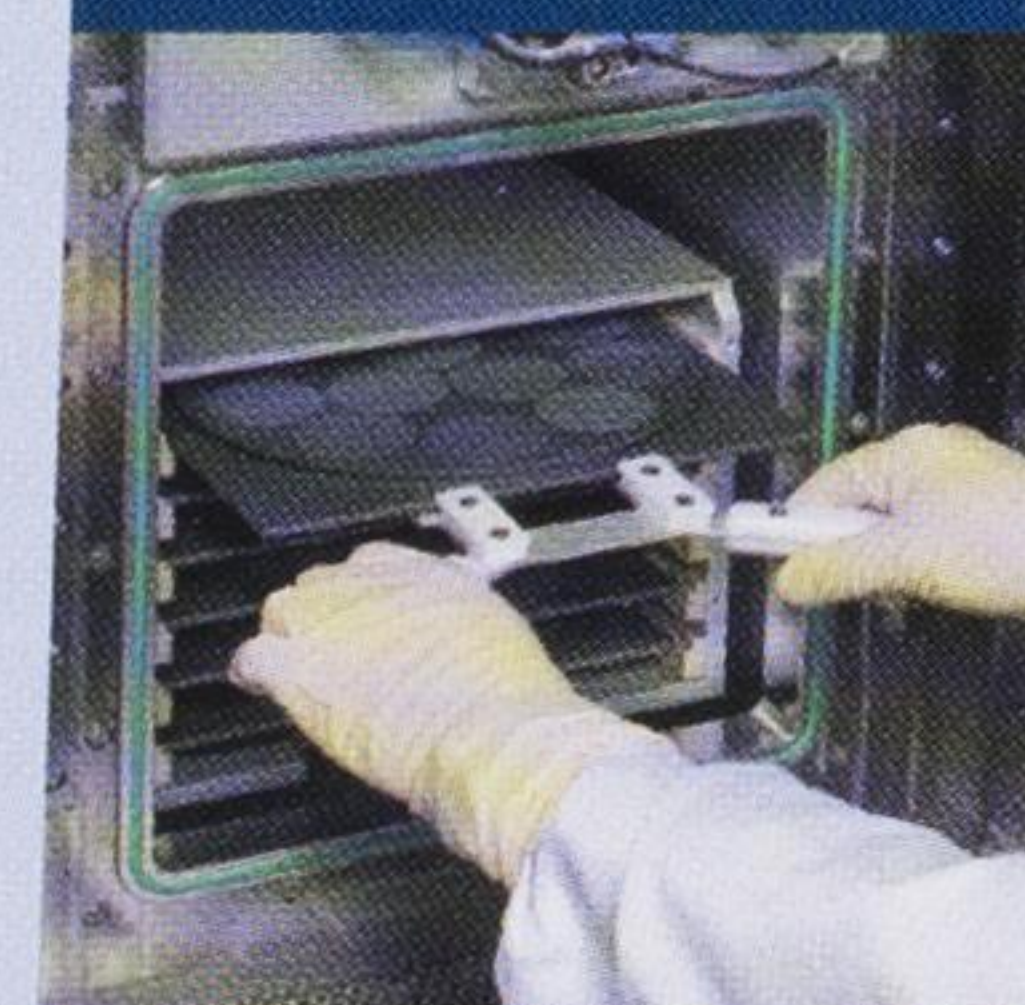
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RF CHIP MANUFACTURING

Sales shock checks Anadigics' fab plans

Anadigics has reversed its decision to boost its China fab investment by \$50 million after a drastic loss of handset power amplifier business to its rivals.

The GaAs chip maker axed 20% from its revenue prediction for the third quarter of 2008 after meeting its phone-manufacturing customers at the beginning of the period. The company says that it will make \$62–65 million in sales, down from the \$75–81 million that it estimated just three weeks before.

According to Anadigics, the lower expectations come from a mixture of market share loss and inventory build-up caused by capacity problems at the end of 2007. Then, demand for the company's chips exceeded its ability to supply.



Although Anadigics has decided not to invest as much in equipment to populate it, this Kunshan, China, facility should be completed in late 2009.

"Because they were concerned about receiving the number of power amplifiers that they needed, they were building a buffer

of our inventory," explained Bami Bastani, Anadigics' CEO. Bastani says that these problems have now lost Anadigics business at several phone manufacturers, with Samsung the one named customer switching to other power-amplifier makers. "It's a natural reaction by the customer to say 'I can't wait for the product, therefore I'll get it from someone else,'" said CFO Tom Shields.

Since the end of 2007, Anadigics has upgraded its Warren, NJ, fab to a level where it can support \$90–100 million production per quarter. With that level of demand now some way off, and the upcoming quarter looking financially difficult, the company has decided to postpone growing its total Chinese investment to \$100 million.

LED PRODUCTION

Silicon players come to Aixtron for LED entry

Companies from outside the traditional LED sector are enquiring about buying MOCVD reactors from Aixtron, which says that the newcomers will end up reshaping the industry. This is assuring the German equipment maker that demand for the technology driving the vast majority of its sales is solid, despite falling order activity.

"Companies that have traditionally operated in the parallel silicon sector have expressed interest in investing in LED equipment," said Paul Hyland, Aixtron's CEO. "It's actually a healthy sign that we're getting new players coming in. It reflects

the view that the industry is going to be sustainable over some time."

During the second quarter of 2008, the company's revenues were up by 45% over the same time in 2007, at €65.6 million (\$100 million). Yet in the same period the previous strong order intake driving these sales slackened to €72.5 million from €85.5 million in the prior quarter.

Aixtron's LED revenues currently come from five of the industry's top manufacturers, along with around 80 small players, but only one of what Hyland calls the "tier two" firms. That company is Epistar, and

Hyland anticipates that within a few years the potential new LED arrivals will be operating at this intermediate level.

LCD display manufacturers have already begun the tectonic shift in the industry's make-up. However, Hyland says that their LED production is at a very early stage, refuting reported deployments of hundreds of reactors.

What is attracting companies to the sector is the increasing size of the displays that LEDs are used to backlight, Hyland says. "Laptops, monitors and TVs will sustain the industry for several years," he prophesized.

III-V SOLAR

Emcore purges record order from its books

III-V solar-cell manufacturer Emcore has cancelled all production slots relating to its supply agreement with controversial customer Green and Gold Energy (GGE), after the Australian company revealed that it was negotiating the sale of its business.

In a call to discuss the US firm's latest financial results, Emcore CEO Hong Hou said that GGE would make no more purchases under the agreed \$79 million supply deal. "We want to wipe the slate clean," said Hou, even though the firm in talks to buy

GGE's assets has indicated that it intends to negotiate a new supply contract for concentrating photovoltaics (CPV) components.

Credibility concerns surfaced earlier this year, prompting Emcore to refute negative claims about GGE circulated in an internet blog as "seriously misleading". This came just a few weeks after GGE placed an additional \$39 million order. Although Hou did not say what proportion of these had been honored, he did say that products shipped to GGE to date had been paid for.

However, even with GGE wiped from Emcore's books, Hou says that demand for its CPV components and cells is mounting, ahead of a crucial six months in the development of the technology. It has just signed

another \$40 million supply contract destined for GreenVolts' solar farm near San Francisco and Soliant's roof-top installations. A source close to Emcore suggests that it is the single source on these deals.

"Emcore will be the first to benefit from the ramp of the CPV business," Hou said. If the CPV technology is deemed viable, he sees a major production ramp ensuing.

● Overall, Emcore reported a sharp increase in revenue to \$75.5 million for its third fiscal quarter ended on June 30. Boosted by the acquisition of Intel's optical platform division, sales of fiber-optic components accounted for \$53.6 million of the total, with photovoltaics sales registering a \$5.1 million year-on-year increase to \$21.9 million.

MOBILE HANDSETS

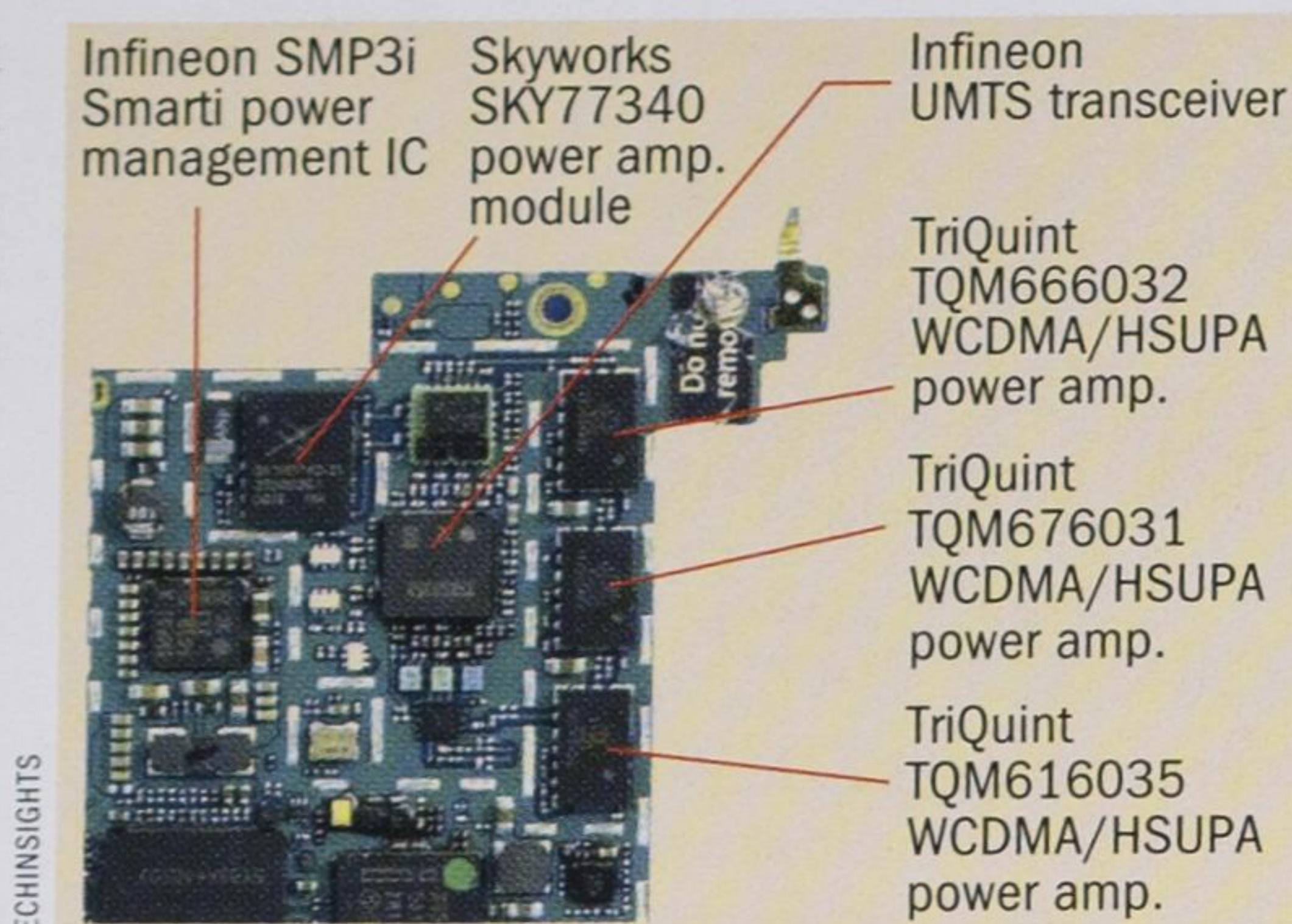
iPhone win sends 3G signal for TriQuint

As cellphone power-amplifier makers begin the run up to Christmas, TriQuint and Skyworks Solutions have stolen a march on the competition with their inclusion in the iPhone 3G. The much anticipated handset included three power-amplifier modules from TriQuint and one from Skyworks when it went on sale in 22 countries on July 11.

TriQuint is supplying its Tritium wide-band CDMA power amplifier/duplexer modules into the latest iPhone, which also includes Skyworks' SKY77340 quad-band GSM/EDGE PA module.

Greg Quirk of TechInsights, which has published its efforts at dismantling the iPhone 3G, says that he has never seen TriQuint in such a high-profile phone before. "While it is almost impossible to guarantee that a company is a single source for a component, every iPhone 3G that I've seen has them designed in," he told *Compound Semiconductor*.

The summer marks the beginning of the third quarter, in which companies enter their big annual production ramp-ups and



All five iPhones that Greg Quirk has seen feature Skyworks and TriQuint. The phones came from New Zealand, Canada and three from Austin, Texas.

hope that their design wins will give them reason to be jolly come December.

For TriQuint, this process in 2008 is particularly focused on 3G GaAs technologies, which are now the largest part of its handset business. The company has just reported its most recent quarterly results, in which revenues from wideband CDMA and EDGE

products leaped to \$21.5 million, up from \$12.3 million just three months previously.

However, sales for the quarter fell below original projections due to problems in increasing the output of these products.

Now TriQuint is estimating at least a \$28 million jump to revenues of \$155 million, and possibly up to \$170 million, for the next quarter. 3G ramps will account for a large part of these forecast gains.

Normally the company would calculate these estimates so that firmly booked orders make a strong 80% foundation for the midpoint of its projected revenue range. This quarter, however, booked orders constitute 95% of its estimate. "We are being more deliberate and respectful of these ramps now," said Steve Buhaly, TriQuint's CFO.

Although it has not yet directly mentioned its inclusion in the iPhone 3G, TriQuint says that the kind of modules that it uses sell for around \$1.50 each.

Apple says that a million iPhone 3G handsets were sold over the first weekend that they were available.

FINANCIALS

RFMD and Skyworks increase share of GaAs market

RF Micro Devices (RFMD) says that it has wrestled share of the cellular front-end market away from its competitors, despite recording a \$24.1 million net quarterly loss.

RFMD terminated its research into GPS and silicon-based transceivers at a cost of \$26.5 million in the period ended June. It is now talking up its regained GaAs focus.

"GaAs usage is going to increase over the next few years," pointed out Dean Priddy, RFMD's chief financial officer. "We're looking at an \$8-10 billion total addressable market for RF components and compound semiconductor-related products. Some are going to benefit more than others and obviously we think we fall into that category."

The Greensboro, NC, firm says that sales of front ends grew by 10% in the quarter. "Our business at Sony Ericsson doubled, Samsung tripled and LG grew significantly," said Priddy. "We also grew with one of the other top-five handset vendors. RFMD was clearly a share gainer."

Revenues from its multimarket product group grew by more than 20%, and it believes that these figures show that it is strengthen-

ing its position in both segments.

These trends combined to push RFMD's overall sales to \$240.5 million, up 9% sequentially and 13.7% year on year.

Transceivers were responsible for dragging the strong quarterly sales growth seen in other product lines back down below 10% overall. However, RFMD does expect to see a small increase in its sales of Polaris transceiver lines through the rest of 2008.

The company says that it has completed the 10% overall reduction in headcount that arose from ceasing GPS and transceiver development. The cost-reduction process is now around 95% complete, says Priddy.

● Skyworks Solutions also says that it grabbed a greater share of the GaAs wireless semiconductor market in the second quarter of 2008, and it expects this to continue.

This helped the Woburn, MA, company to nearly double its profits for the period to \$20.5 million, up from \$11.4 million for the equivalent quarter in 2007.

Some of that growth comes from the acquisition of Freescale's GaAs business, which has positioned Skyworks as the

number-one power-amplifier supplier to Blackberry-maker Research In Motion. Nevertheless, increased sales elsewhere also helped the company to beat its own guidance to record revenues of \$215 million – a 23% gain year on year.

"Our performance represents further progress towards realizing our stated vision of becoming the worldwide leader in mobile connectivity semiconductor solutions," said CEO David Aldrich.

With that success behind it, Skyworks' optimism could not be restrained as it predicted further sales growth in the third quarter, setting a \$225 million target.

Aldrich claims that Skyworks is unique in counting each of the top-five handset makers as customers, and these look to be a major driver in the chip-maker's growth.

Currently, Samsung and Sony Ericsson are the only two companies that account for more than 10% of Skyworks' revenues. The company says that ramps across the phone manufacturers will mean that four of them will contribute a 10%-plus proportion of its sales by the end of 2008.

SUBSTRATES

AXT shrugs off GaAs setbacks

Compound semiconductor substrate specialist AXT has posted a solid financial quarter, despite the difficulties posed by three separate setbacks. In the three months ended June 30, the north Californian company, with operations in China, delivered a net profit of \$0.7 million on total sales of \$19.9 million.

This slight increase in sales revenue masked a \$0.4 million sequential decline in shipments of 6 inch GaAs material – down to \$5.5 million.

Although the market for large semi-insulating GaAs substrates remains strong, thanks mostly to increased GaAs content in the latest generations of mobile handsets, AXT's CEO Phil Yin points out that three unexpected events in the quarter dented 6 inch material sales.

First an unspecified US customer closed operations at its West Coast GaAs fab, before a key Asian chip maker shut down operations for two weeks for routine maintenance. That same customer also switched to a new epiwafer process during the quarter, the change seemingly causing some manufacturing problems.

Yin says that, with the customer moving to a new set of epitaxy reactors, any problems should be resolved shortly.

However, with strong growth in other key accounts, the CEO says that the market for compound semiconductor materials stayed solid and he is hopeful that the remainder of 2008 will see a return to stronger growth.

AXT's sales remain dominated by GaAs, which accounted for \$13.1 million in revenue – a figure that includes 6 inch and 4 inch semi-insulating material, as well as 4 inch semiconducting substrates used in red-LED manufacturing.

The company is currently expanding its 6 inch manufacturing capacity, with the 27% hike scheduled to be completed by the end of this year.

Sales of germanium substrates, which are used by some LED manufacturers but increasingly for triple-junction solar-cell production, remained flat at \$1.4 million in this quarter.

Despite the leveling-off in demand, Yin says that AXT is now in volume germanium wafer production for two customers, with a third in the final stages of qualification and three more in earlier stages. "Many of our customers with excess epi capacity are not only requesting pricing for germanium substrates but also forward pricing for an expected conversion to 6 inch [germanium] diameters," he revealed.

Demand for germanium used in high-efficiency solar cells recently prompted AXT's key competitor – Umicore – to say that it is setting up a new manufacturing facility in the US.

AXT now expects to post a slight increase in revenue when it delivers its next quarterly report, with anticipated sales of between \$20.1 million and \$20.5 million in the current quarter.



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...AmpTech foundry targets PAs

AmpTech is offering foundry services from its base at the 4 inch Milpitas, CA, fab formerly owned by WJ Communications. The company boasts production-qualified processes for GaAs MESFETs and InGaP HBTs, and it says that it has produced 1.5 million chips in its first nine months of operation.

...GaN radar gets more cash

Nitronex and Raytheon have both gained US government funds to develop GaN radar technology. Raytheon Integrated Defense Systems has signed a \$1 million contract award that could be worth more than \$14 million if all of the options are exercised

for GaN MMICs and RF MEMS. Nitronex began a Phase II Small Business Technology Transfer program for X-band GaN MMICs in the first quarter of 2008 for an unspecified amount.

...GaAs shines through downturn

The handset and GaAs markets will continue to be robust, say reports from market analysts Strategy Analytics and ABI Research. Strategy Analytics sees the GaAs microelectronics industry remaining on track to hit \$5 billion in device sales by 2011. Although GaAs industry growth in 2008 won't match the 17% figure for 2007, it will stay solid at 9%. ABI predicts that this year the mobile device market will expand by 13%.

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INDUSTRY THE MONTH IN HB-LEDs

LITIGATION

Cree fights on against Rothschild

A New York judge has thwarted Cree's bid to restrict the scope of a patent infringement lawsuit brought by retired academic Gertrude Neumark Rothschild. The judge rejected the LED maker's argument that US patent 5,252,499 only applies to substrate doping, but Cree has asked for the judgment to be reconsidered.

In one of the first legal tests of Rothschild's patents, Counsel Albert Jacobs Jr indicated that the professor emerita's team was in the process of opposing that appeal. "Cree clearly doesn't want to pay any significant amount of money for a license so it was hoping to get a favorable judgment on one of the two patents in suit," Jacobs told *Compound Semiconductor* on July 30. "We think that our position in the case has been good from the beginning and we think that it is better since the court denied Cree's bid for a summary judgment."

Rothschild originally also filed suit against Toyota Gosei, Philips Lumileds and Osram in the US District Court for the Southern District of New York. Although these companies chose to accept the licensing settlement on offer, Cree now looks set to proceed to a jury trial.

Another case is due to be heard at the US International Trade Committee, where Rothschild complained against 31 companies that import products containing laser diodes and LEDs. Of these, 13 have already reached licensing deals – which ask for a percentage of the company's revenues –

including Sony and three Samsung subsidiaries. "One would not say that these are companies that don't know how to litigate patents," observed Jacobs. "Substantial companies have decided that business certainty is more important than trying to successfully knock the patents out."

Now, Rothschild is considering extending her action to more companies, and Jacobs says that some who haven't already been named are opening licensing negotiations.

When *Compound Semiconductor* asked Cree why it hadn't also reached a license agreement, it declined to make any comment on the case. In its fiscal 2008 year-end results, Cree recorded \$493 million in sales – its highest ever – of which 84% was derived directly from LEDs. Jacobs says that this level of business gives Cree "significant exposure" to any royalties that might be due to Rothschild. This in turn is likely to be more than enough encouragement to defend the case, he points out.

● A quarterly best \$135.9 million revenue in the period ended June 2008 helped Cree to its 2008 annual sales record, although chip production and annual profits dropped. LED packager COTCO was a key factor in the sales growth, but the deals to buy both it and luminaire developer LED Lighting Fixtures shrunk net income year on year. Fab usage was down as falling sales of bare LED die and efforts to reduce inventory levels outweighed a 140% increase in packaged XLamp sales from fiscal 2007.

SUBSTRATES

LED producers close on 6 inch wafer usage

At least one LED maker is looking to crank up its competitiveness by moving to manufacturing on 6 inch sapphire substrates within 18 months. That's according to sapphire supplier Rubicon Technology, which says that it received development-scale 6 inch wafer orders in the quarter ended June.

"Every time we visit our customers, which is every four to six weeks, we see more advancement in this area," said Raja Parvez, Rubicon's CEO. He anticipates volume production in 12–18 months.

Parvez says that several manufacturers now have MOCVD reactors that are capable of 6 inch wafer growth, and back-end equipment for processing at this diameter is

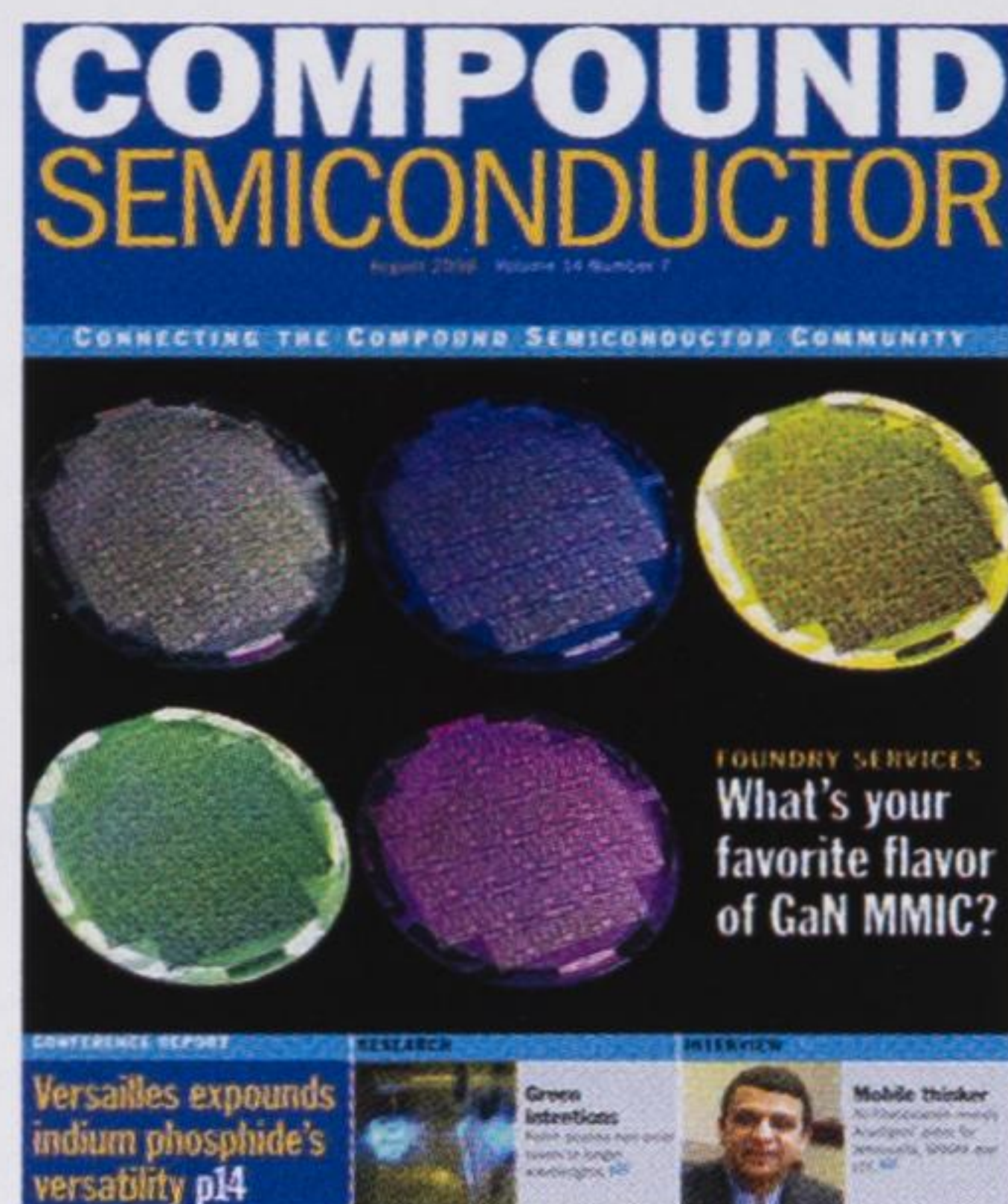
also readily available. He also suggests that larger chip sizes in LEDs, to produce higher total brightness, will help to drive the industry's substrate sizes upwards.

Within Rubicon's LED substrate business, 3 and 4 inch wafer sales grew at 9% over the June quarter, while 2 and 2.5 inch sales grew by just 6%. Overall revenues from LED substrates for the quarter clocked in at approximately \$6.9 million, with 60% earned by 2 and 2.5 inch wafers. LED revenue comprised 60% of Rubicon's overall sales.

Another LED industry trend that is set to benefit Rubicon is the entry of Taiwanese flat-screen display companies AU Optronics and Chi Mei Optoelectronics into chip manufacturing. Rubicon sells blanks to polishing companies that supply high-grade substrates into these new LED players, which Parvez says look set to begin volume manufacturing in early 2009.



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(tick one box only)

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4. What semiconductor materials/processes are used/developed at the place where you work? (tick all that apply)

C1 ☐ III-Vs: arsenides

C2 ☐ III-Vs: phosphides

C3 ☐ III-Vs: nitrides

C4 ☐ III-Vs: antimonides

C5 ☐ II-VIs

C6 ☐ SiC

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D6 ☐ Non-telecom laser diodes

D7 ☐ VCSELs

D8 ☐ LEDs

D9 ☐ Solar cells

D10 ☐ Detectors

D12 ☐ GaN laser diodes

D14 ☐ Power semiconductor devices

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E2 ☐ Semiconductor International

E3 ☐ Solid State Technology

E4 ☐ Laser Focus World

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CSREG08

SOLID-STATE LIGHTING

EPA blasted over LED confusion

The US Department of Energy (DOE) and Environmental Protection Agency (EPA) appear to be at loggerheads over requirements for LED-based lighting products, with the EPA now accused of issuing misleading information.

Senior figures at the DOE rebuked the agency for what it said were a series of errors in a document that the EPA released on July 25. That document was supposed to define the differences between the two bodies' individual criteria for allowing the crucial Energy Star label to appear on LED-based lighting products.

The Energy Star program is run jointly by the two government bodies and its labels are designed to inform consumers that approved products meet strict energy-efficiency guidelines.

However, while the DOE finalized its Energy Star criteria for LED-based lighting nearly a year ago, the EPA unexpectedly issued its own separate guidelines in June. The DOE is now concerned that the obvious confusion will damage the commercialization of solid-state lighting in the US. "EPA's motives and back-handed approach must be questioned," sources close to the contro-

versy said of the latest EPA document.

Ann Bailey, the EPA's director of Energy Star product labelling, did not wish to comment on accusations of spreading disinformation. Her view is that, while the DOE's key role was to fund and nurture the development of LED-lighting technologies, it has no mandate to take the lead on marketing. She also says that the EPA's standards are complementary to the DOE's.

Bailey sees the EPA's standards for solid-state lighting as consistent with its previous approaches to residential lighting, rather than being LED specific, and that this approach is the correct one for consumers: "Consumers aren't interested in which technology is inside the lamp. They don't shop for technology – they shop for efficiency."

In an example that highlights the apparent lack of communication between the two agencies, the EPA appears mistaken about the introduction of these standards. In its latest document, the EPA says that the DOE's Energy Star criteria will come into effect on November 1.

According to the DOE, the EPA is one month out: "The kick-off date is September 30, just like it has always been," it said.

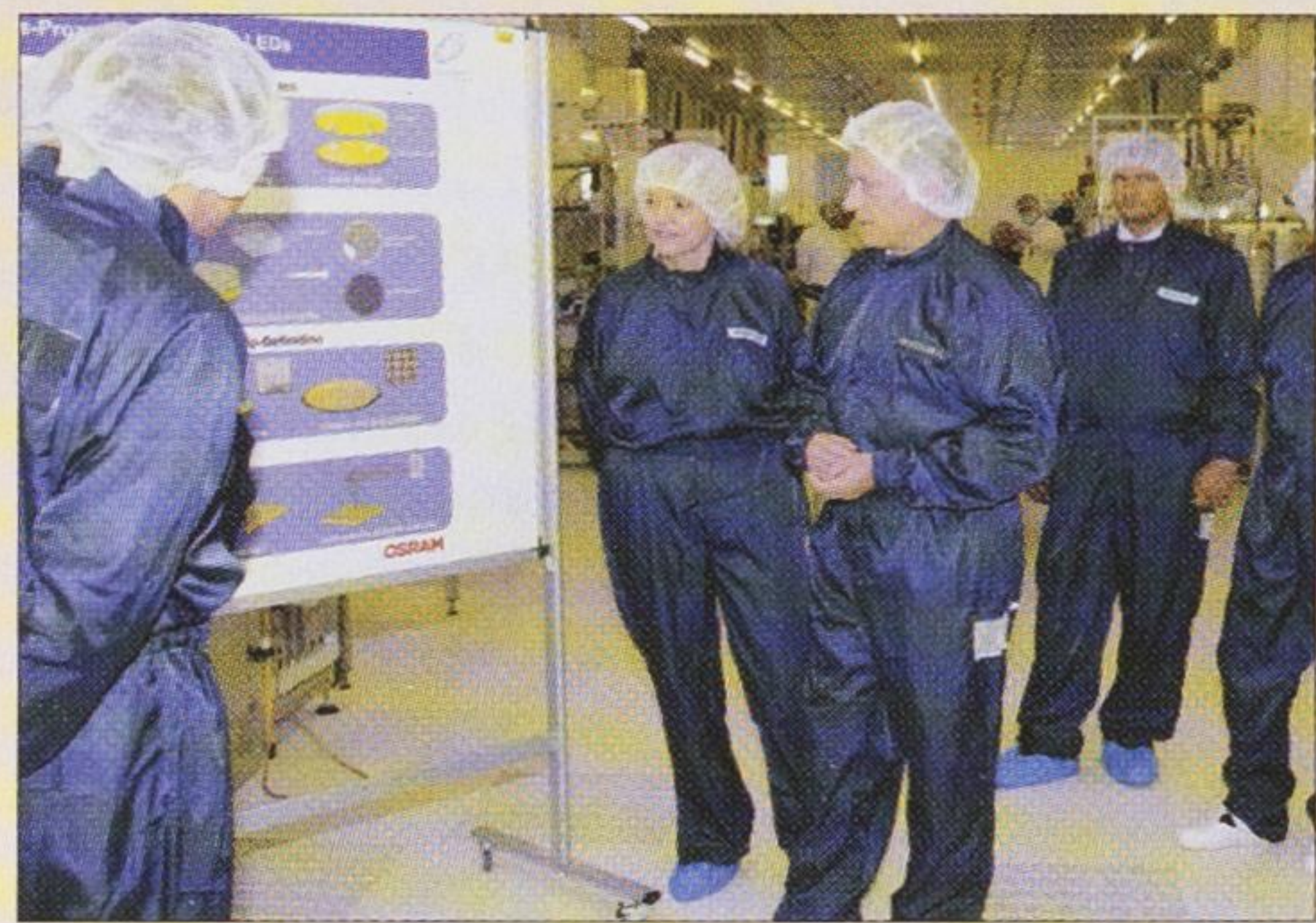
CHIP MANUFACTURING

Showa Denko delays AlGaInP LED expansion

Japanese conglomerate Showa Denko has put the brakes on its plan to double the production of red LEDs to 200 million per month by the end of 2008. After announcing its financial results for the first half of the year, CEO Kyohei Takahashi admitted that the company would have to delay the ramp, a spokesperson told *Compound Semiconductor*.

Slower than expected growth in sales of red LEDs for use in LCD displays contributed to the decision to postpone the ¥1.2 billion (\$10.8 million) expansion. Nevertheless, sales from the compound semiconductor division of Showa Denko's electronics business are up, driven by its latest "ultrabright" 80 lm/W red AlGaInP chips. However, this has been partly offset by a fall in shipment numbers of the company's commodity LEDs.

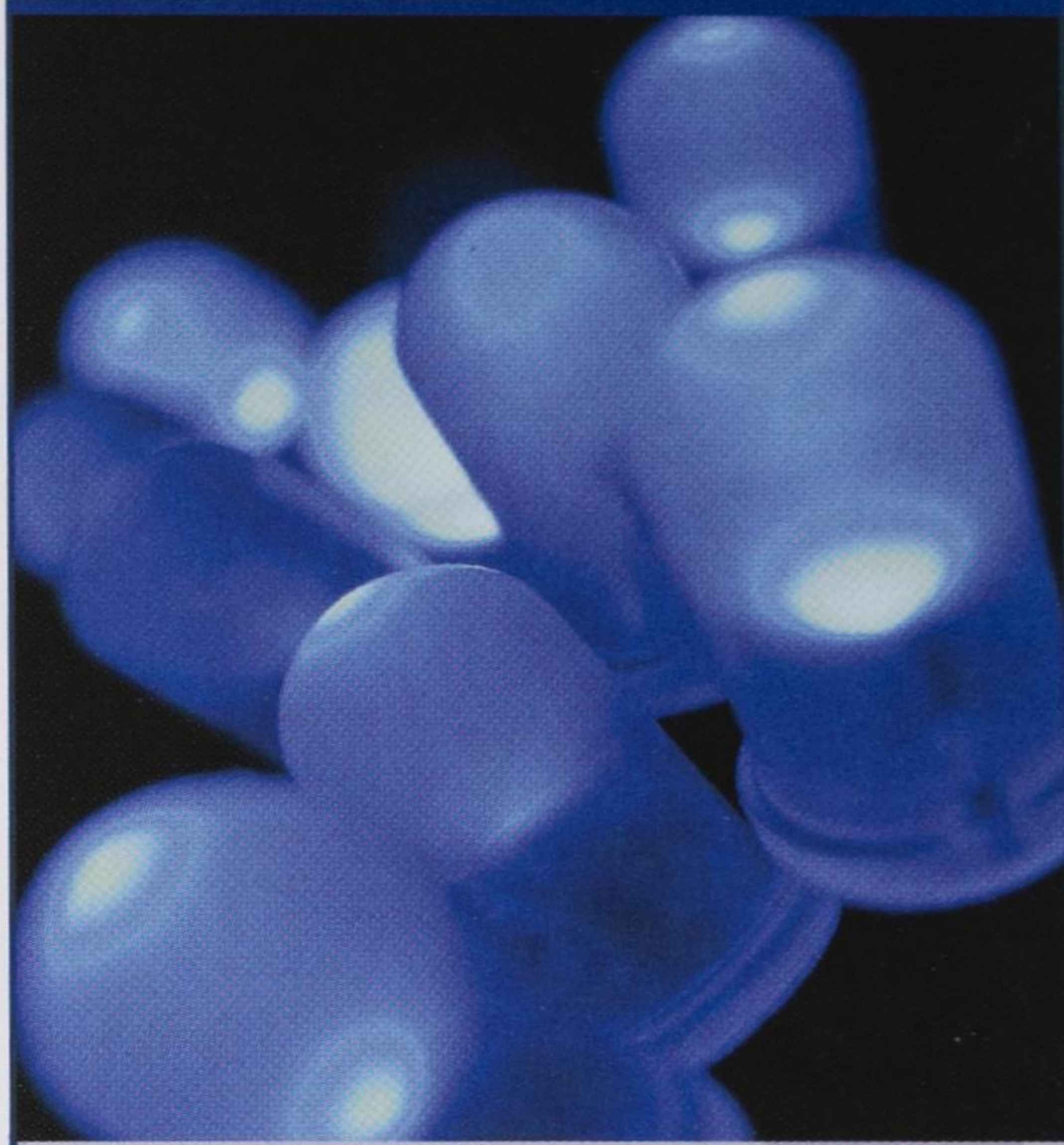
Overall, for the first half of 2008, Showa Denko attained an operating income of ¥9.4 million on sales of ¥510 billion.



German president Horst Köhler visited Osram Opto Semiconductors in August in recognition of its continued LED innovation, only weeks after the company claimed the latest efficiency record for white emitters. Its prototype 1 mm² die operate at 136 lm/W with a total output of 155 lm at 350 mA. "The devices also achieve world-record performance at higher operation currents," Osram told *Compound Semiconductor*. "Actually, the performance increase in the high-current regime is even more pronounced than at 350 mA." The company says that high-quality epitaxial material plus a complete chip redesign provided this answer to the problem of high-power "droop".

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DIODE LASERS

BMW deal underlines IPG's processing power

IPG Photonics is supplying fiber lasers to BMW, breaking the tight hold of its rival, Trumpf, on sales of material-processing lasers to German auto makers. The vertically integrated diode-laser manufacturer is due to deliver ytterbium fiber-laser systems with 63 kW in total output power to BMW in the final quarter of 2008.

"Our main target was to break into German car makers," said Valentin Gapontsev, IPG Photonics' chief executive officer. "For us this has really opened the door for market penetration in cars," he said of the deal, which will supply tools for welding car doors. This adds to a list of existing automobile customers that includes Hyundai, Nissan, Toyota and the PSA group that makes Peugeot and Citroen cars.

In the three months ended June 2008, 84% of IPG Photonics' \$56 million revenues came from material processing applications. Sales into this area grew 6% sequentially and 42% over the same period in 2007.

IPG says that its systems offer much better yields than early experimental laser material-processing tools. Some of these



Fiber lasers from IPG Photonics will soon be welding car doors on BMW assembly lines like this.

performed so badly that they turned automotive manufacturers' senior management against the technology. The Oxford, MA,

company's manufacturing equipment now seems to be changing that perception.

Its MBE-grown GaAs laser diodes, which are available in powers of up to 25 W, are combined in the higher-power systems to operate more efficiently than other laser technologies. Making its own diodes as well as performing subsequent integration gives IPG Photonics another competitive advantage, allowing it to deliver systems comparatively quickly.

On a per-watt basis, IPG says that its systems cost only 15% of the typical price of other systems on the market. Although the automotive industry in particular is conservative, making existing supplier relationships hard to overturn, these numbers are difficult to ignore.

The heavy focus on capital equipment sales continues to serve IPG well. It recorded an \$8.6 million net profit in the quarter, up from \$6.4 million year on year. IPG says that its overall sales in the September quarter will grow further, predicting that it will receive between \$57 million and \$61 million in that period.

SUBSTRATES

€2 m project sets non-polar 2 inch GaN target

A German-Swiss research team has begun work on its effort to match US and Japanese groups developing non-polar GaN material for high-efficiency green laser diodes.

The three-year, seven-university, €2 million (\$3.16 million) PolarCoN collaboration, which started on May 1, has the ambitious aim of developing 2 inch non-polar GaN substrates. Currently non-polar substrates with sizes in the tens of millimeters are typically the largest available, from companies such as Kyma Technologies and Mitsubishi Chemical.

"Non-polar GaN devices use such small substrates," said Ferdinand Scholz, the project's spokesperson. "We'd like to make a difference to that."

Scholz, a professor at the Institute of Optoelectronics at Ulm University, will use his HVPE expertise to grow bulk GaN crystals. This growth relies on the successful deposition of non-polar seeds on m-plane SiC or sapphire by MOCVD elsewhere in the collaboration.

The overall project is being funded by

the German Research Foundation and the Swiss National Science Foundation with the aim of closing the "green gap". Devices in this region are hampered by intrinsic polarization fields in conventional GaN material, which shift the resulting wavelength towards the blue.

PolarCoN's goals therefore include producing an optically pumped laser diode with an output wavelength of more than 500 nm using non-polar or semipolar GaN.

The project's practical goals owe something to the involvement of Osram Opto Semiconductors, which Scholz says had an input into the overall strategy. However, industrial partners will only become involved officially when and if PolarCoN reaches its second stage in 2011.

In the meantime the project will bend all of its academic might, including highly reputed optoelectronics centers like Technical University Berlin and ETH Zürich, to unravelling the poorly known underlying causes of the green gap.

"Our project is very strongly defined as a basic research project," explained Scholz, "not only to reach the goal of a green laser but also to work on the fundamental understanding of all scientific issues related to this problem."



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...Quantum dots get funding

Two optoelectronic companies that are producing devices containing quantum dots have gained investments to move towards volume manufacture. Cyrium Technologies, the Canadian company that adds a quantum-dot layer to compound semiconductor multijunction solar cells, has closed its second funding round, earning it \$15 million. Similarly, Germany-based Innolume, a quantum-dot laser diode and module maker, secured €8.6 million (\$13.3 million) in its third round of investment.

...Pirelli rolls back into compounds

Pirelli's decision to invest \$20 million in InP chip manufacturer CyOptics marks the return of the Italian company to compound semiconductors after an eight-year gap. Back in September 2000, Pirelli's optical components division was a key supplier of the 980 nm GaAs-based pump lasers that power the erbium-doped fiber amplifiers used in submarine networks. Corning bought the Pirelli business for a cool \$3.6 billion.

GaN GROWTH

Zero-indium AlGaIn laser diode hits UV record

Japanese researchers have exploited their high-quality GaN growth technique to produce the first UV laser diode without indium in its active layer.

Using this approach, the team from Hamamatsu Photonics produced the shortest wavelength electrically pumped laser ever. It published details online in *Nature Photonics* on July 27.

The team reduced the wavelength of light that its lasers emit under pulsed operation from its previous best of 355 to 342 nm, but it is mainly pleased with the device design.

"Our achievement is growing an indium-free AlGaIn laser on a sapphire substrate," Harumasa Yoshida, corresponding author on the paper, told *Compound Semiconductor*. "It [enabled the] breakthrough to the deep-UV region."

Laser diodes are particularly sensitive to defects in their epitaxial structure, which can act as centers where electrons and holes combine without emitting light.

In blue-violet lasers' active layers, indium clusters bring together electrons and holes, boosting radiative recombination and the device's emission efficiency. However, Yoshida believes that using indium inhibits the emission of shorter-wavelength light.

In contrast, increasing the proportion of aluminum in lasers grown on sapphire increases the tensile strain in the material, leading to more defects and cracking. Nevertheless, increasing the lasers' aluminum content is what Yoshida wants to do.

"To achieve shorter wavelengths," he said, "the best solution is to fabricate indium-free AlGaIn multiple-quantum-wells in AlGaIn guiding and cladding layers."

What allows Hamamatsu to do this is its novel approach to MOCVD, which is known as heterofacet-controlled epitaxial lateral overgrowth. This produces pyramidal seed crystals by growing GaN over arrays of 2 μ m wide silica stripes. Subsequent growth occurs sideways from these seeds and, although defects are formed, crystal quality improves as deposition goes on.

In this case the lateral growth produced an $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ layer that the team says was "almost equivalent" in quality to the $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$ base material used for its previous 355 nm device. After making AlGaIn cladding, guiding and active layers, etching mirror facets and depositing metal contacts, the device operated with a threshold current of around 390 mA. Yoshida and colleagues measured the pulse output power as 16 mW

near to one side of the laser cavity facets.

"This demonstrates the potential of AlGaIn-based materials operating as lasers over a wide range of UV wavelengths," commented Colin Humphreys, professor of materials science and director of the GaN center at Cambridge University, UK. "It is a significant achievement."

The Hamamatsu team concedes that its device's series resistance – which is around 32Ω at the threshold current – is high for

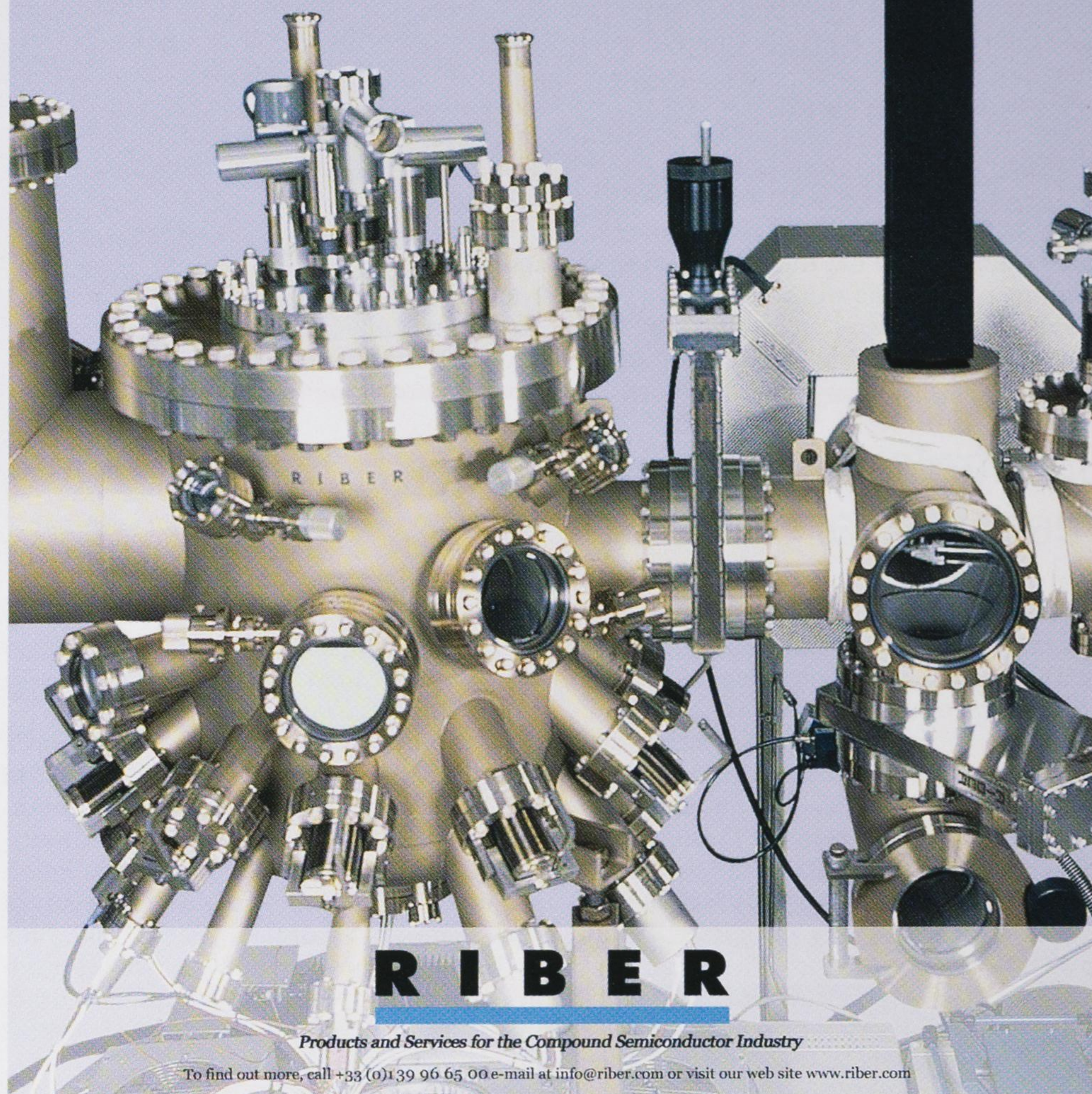
a laser diode. It agrees that this must be improved and that this would help the device to achieve continuous-wave performance. These are goals that Humphreys says that he is in favor of.

"Pulsed-current conditions limit the use of the laser," he explained. "We also know nothing about these lasers' lifetime. For them to be more widely used, these problems need to be overcome, but this is a very promising start."

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PHOTOVOLTAIC SYSTEMS

SolFocus and Everphoton aim for CPV ramps

SolFocus, the Californian company that specializes in concentrator photovoltaic (CPV) systems, will lead the demand for III-V solar cells as it scales up system production over the next three years.

Speaking at the InterSolar US conference and exhibition located with Semicon West in San Francisco, co-founder Ty Jagerson outlined the company's ambitious plans to install systems that are capable of producing up to 100 MW of grid-connected power in 2010. If this is reached it will represent a huge expansion on the expected 2008 deployment of 1 MW, while SolFocus is confident that it will install 20 MW during 2009.

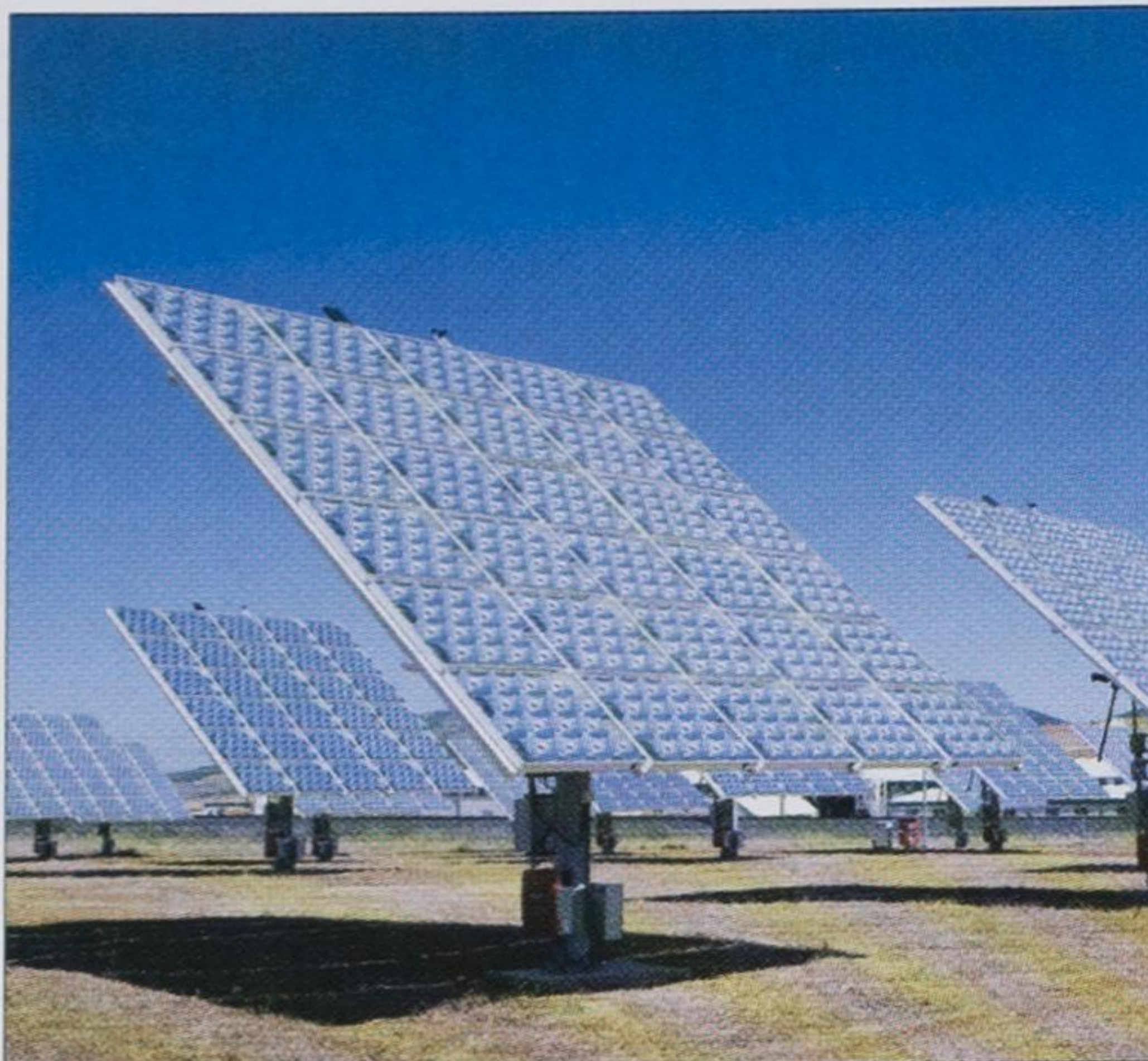
Each of SolFocus' CPV panels includes 16 individual power modules, which in turn focus light onto a single III-V chip at a concentration of 500 times.

These power modules produce a maximum output of 214 W, so SolFocus will require hundreds of thousands of the cells to meet its ramp-up goals.

The company told *Compound Semiconductor* that it is capacity limited this year, although this is not due to any constraints on the supply of III-V cells.

SolFocus has already installed a system at the ISFOC test site in central Spain and it is confident that this installation will help to prove that CPV is a reliable way to produce energy that can be fed into electrical grids in sunny parts of the world.

The company buys its cells from both Emcore and Spectrolab and, contrary to



SolFocus' ISFOC installation, in Castilla-La-Mancha, where the company completed the first 200 kW of its 3 MW commitment at the end of July.

some reports, it says that there is little difference between the two suppliers when it comes to cell cost.

With improvements to both its optical design and the efficiency of the III-V cells, SolFocus says that the conversion efficiency of its panels should rise from 18 to 25% in the next year, with the overall system efficiency pegged at around 2% lower than the figure for panels.

● Meanwhile, Taiwanese start-up Everphoton is also using III-V multijunction cells from Emcore and Spectrolab in its first solar-power plant, but it is looking to nearby suppliers for possible alternatives.

A planned 1 MW plant will demonstrate Everphoton's highly concentrated photovoltaic (HCPV) technology, in what looks set to be a milestone for Taiwan.

"The first 200 kW (peak) will be completed at the beginning of 2009 and will be located in southern Taiwan," a spokesperson from the company told *Compound Semiconductor*.

Once the full 1 MW is deployed, it should rate as the largest HCPV installation by a Taiwanese manufacturer, beating Arima Eco's 300 kW contribution to ISFOC.

Compound semiconductor cells from the world's top-three suppliers will be used in the systems for the pilot plant. "We will also do laboratory tests on solar cells from local and other suppliers," the spokesperson commented.

The firm was founded in 2007 with investments from global top-five LED packaging house Everlight Electronics and electronic material producer Yee Fong Chemical.

Everlight is also a major shareholder in LED manufacturer Epistar, and Everphoton looks set to use its connections with the compound industry to evaluate different sources of cells. Furthermore, Everphoton says that these companies are co-operating to build the HCPV solar-power plant.

Although Everphoton only appears to have been in existence for a year, it claims that its products are based on three years of research and development with experts from Taiwan, Europe and the US.

EPITAXIAL EQUIPMENT

Spectrolab powers up Veeco's solar campaign

As Veeco Instruments' high-volume reactors battle it out with Aixtron products in the LED sector, Spectrolab has boosted the US equipment supplier's solar-cell reputation with a multiple MOCVD system order.

The order for arsenide and phosphide semiconductor systems has helped to drive Veeco's bookings from LED and solar-cell companies up to \$52.1 million in the second quarter of 2008. This figure is up 35% from the previous three months and up 43% year on year.

"Veeco's MOCVD and MBE [reactors] are seeing market pull for III-V concentrator and thin-film solar applications from both research institutes and commercial compan-

ies," said CEO John Peeler. The interest for solar applications came predominantly from Europe and the US, he says, in contrast to the continued dominance of Asia in demand for LED manufacturing equipment.

"In the second quarter we received multi-unit orders from five LED manufacturers in Taiwan and China, several of which were first-time Veeco customers," Peeler said.

Such orders are crucial as the company's latest TurboDisc K465 GaN LED reactor line tries to make up ground lost to high-volume tools launched earlier by Aixtron.

"Aixtron released its newer-generation product a little ahead of us and they received some very strong orders," Peeler said. "It's early to talk about share gain, but our product is getting great feedback and we think that it has compelling advantages in terms of throughput and productivity."

Revenues from the LED/solar part of

Veeco's business grew to \$45.1 million, up from \$28 million received over the same period in 2007. However, these figures were only up by 7% sequentially. Veeco says that shipment delays caused by LED customers who are behind schedule in constructing new manufacturing facilities contributed to a nearly \$10 million build-up in its inventory over the quarter.

Ramping III-V reactor production has further bolstered the Plainview, NY, company's finances because making more tools improves its overall profit margin.

These factors all helped Veeco to a \$4.2 million net profit – its first since quarter one of 2007 – but for the next quarter it is predicting a return to loss. This is thanks to a number of exceptional charges, including a \$3.7 million expense levied against the departure of Ed Braun from his former role as CEO of the company.

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SOLID-STATE LIGHTING

Power struggle threatens LED future

You would think that US government agencies would be working closely to ensure a successful transition to energy-efficient lighting based on LEDs. You'd be wrong, writes **Michael Hatcher.**

Runaway CO₂ emissions are bad. Really bad. But demand for electricity is growing quickly, so we need energy-efficient technologies. This we know.

We also know this: a huge chunk of global electricity demand comes from the US, and one-fifth of that country's electrical energy consumption is used for lighting alone. Solid-state lighting (SSL) based on compound semiconductors offers a potentially massive efficiency improvement and should therefore be deployed widely. So far, so logical.

Where things get complicated, as always, is in the real-world implementation of such logic. And in the case of the US Energy Star program – designed to inform US consumers about energy-efficient technologies – things just got very complicated indeed.

The problem with Energy Star is that it is run by two government agencies: the Department of Energy (DOE) and the Environmental Protection Agency (EPA). Two agencies means problems: "This is our dirty laundry and nobody wants to talk about it," is how one frustrated DOE source describes the situation.

For LED makers the DOE has been key to the development and market introduction of SSL. With dozens of research programs giving it a real insight into technological developments, the DOE is uniquely positioned to manage SSL commercialization.

And the DOE has done a pretty damn good job of that, knowing that, for LED-based lighting to be a success, it is crucial to avoid the mistakes made previously with compact fluorescent lamps (CFLs). Slow start-up times and the harsh, unflattering blue-tinged emission of early CFLs set the energy-efficient technology back years in the US, and a repeat performance with SSL would hurt LED makers.

The DOE believes that it is critical to make sure that Energy Star LED-based lamps really deliver what they promise: bright, attractive illumination and very high energy efficiency. With a clear strategy in place to do that, the DOE's Energy Star criteria come into effect at the end of this month for an initial group of products, including task lights and recessed downlights. By 2011 the criteria will extend to cover all types of SSL application.

So why, in the first week of June, did the EPA surprise everybody (including the DOE) by suddenly bringing out its own separate Energy Star criteria, giving SSL companies a whole different set of standards to meet in order to get the all-important label? Surely the two agencies would have been working closely on something this important, right? Wrong.

In fact, it seems that the whole Energy Star program is affected by a power struggle between the two government institutions. "This is a real mess," said a DOE representative close to the controversy, who believes that the EPA's move jeopardizes the shift to SSL in the US. A carefully staged introduction of the

technology to consumers is crucial, he says, arguing that the broader specification announced without warning by the EPA is "suicidal" and will result in rogue products receiving the Energy Star label.

Naturally the EPA disagrees. Ann Bailey, the agency's director of Energy Star product labelling, said: "We fundamentally disagree that these standards are conflicting and that they will restrict the solid-state lighting market in the future."

So how did it come to this? It certainly never should have. At a White House meeting convened by the US Council on Environmental Quality in October 2007, the DOE received a clear mandate to lead the development, market introduction and wider deployment of LED-based lighting. However, rather than embarking on a "jaw, jaw" response, the EPA appears to have taken the "war, war" option, decamping to cook up some half-baked Energy Star criteria of its own.

According to Bailey, these criteria emerged in response to lighting-fixture manufacturers who contacted the EPA with concerns about the DOE's plans for implantation. But with rogue LED lighting already on the market, the last thing needed is what looks like government-approved fixtures that don't deliver the high-quality light that consumers expect.

In public the EPA says that it is "committed to working closely with the DOE". Speaking to the DOE, you certainly don't get the impression that this is the way the EPA is actually operating. "EPA has bypassed the DOE and created a mess," is how one DOE insider described the non-relationship. And whether it was through deliberate misinterpretation or sheer incompetence, the EPA produced a highly inaccurate representation of DOE criteria for Energy Star lighting products in its recent publications.

According to DOE insiders, there are very few lighting-fixture makers on the EPA's side. More damningly, testing fixtures to meet EPA criteria looks like causing uproar. One independent testing laboratory is angry that the EPA declared it to be supporting the EPA criteria, when in fact it does not even believe that performing the test is possible. Utility companies that support the DOE are said to have complained in writing to the EPA, while the Next-Generation Lighting Alliance is behind the DOE.

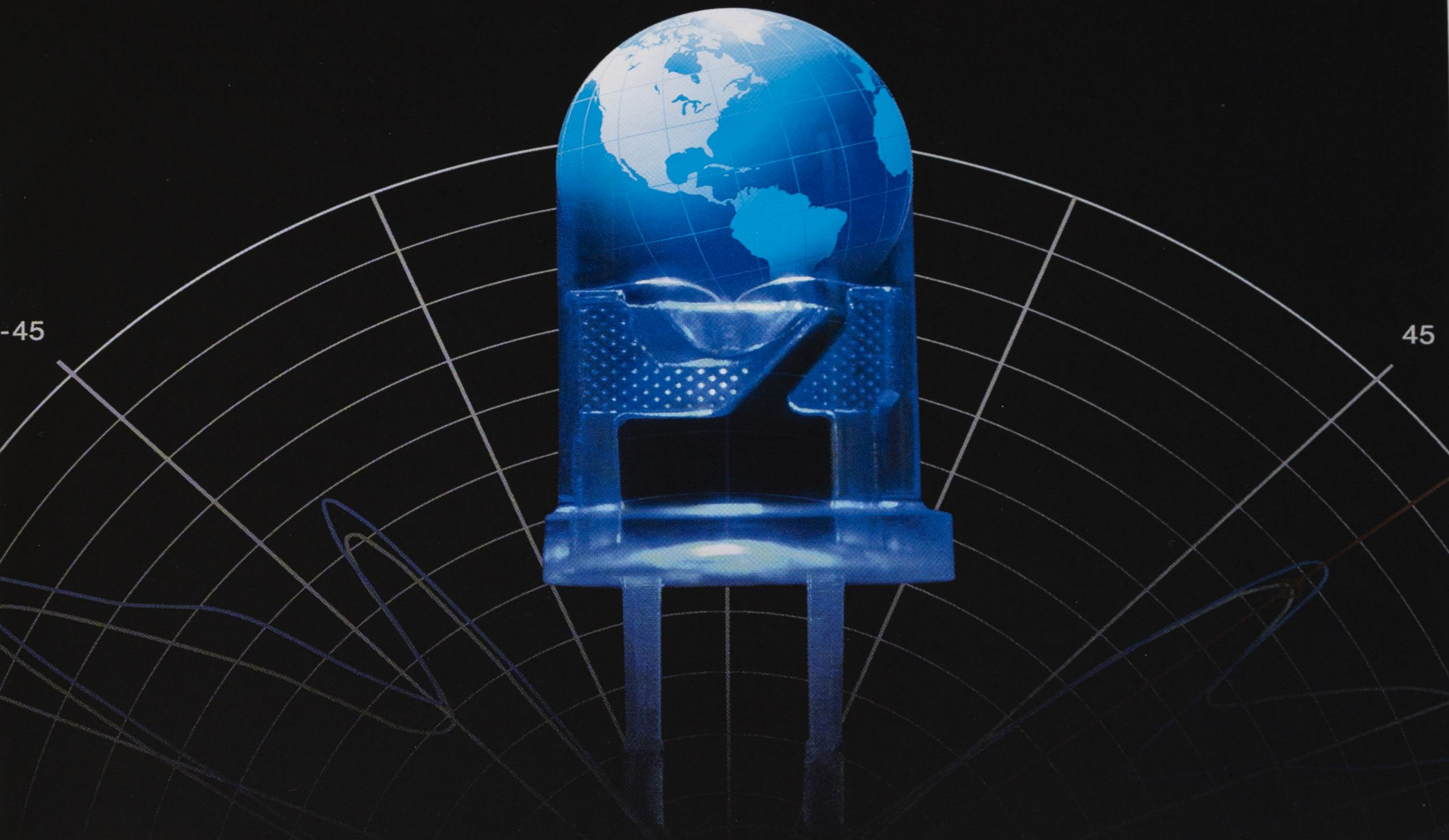
So what happens next? Time is short – the DOE criteria for Energy Star lighting come into force on September 30 and the EPA is showing no sign of backing down. Only the White House can force the EPA's hand – and with a weakened administration on the way out and the presidential election now in full swing, any White House action looks unlikely.

With high-level meetings between the DOE and EPA ongoing, one can only hope that "jaw, jaw" prevails. In our bid to use resources more efficiently, this is one power struggle that we could do without.



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Cadmium-based boules prepared

Security services could get a massive boost from cadmium-based detectors that can identify plastic explosives in a suitcase's contents. Although it's tricky to make these II-VIs, a novel deposition tool and growth on GaAs offer a promising route to making high-quality CdTe and CdZnTe boules, say **Max Robinson** and **Arnab Basu** from Kromek.

Flying offers the promise of holidaying in sunnier climes. However, getting through airports is a pain. Security checks are understandably more thorough than they were before 9/11, and the knock-on effect is far lengthier check-in times.

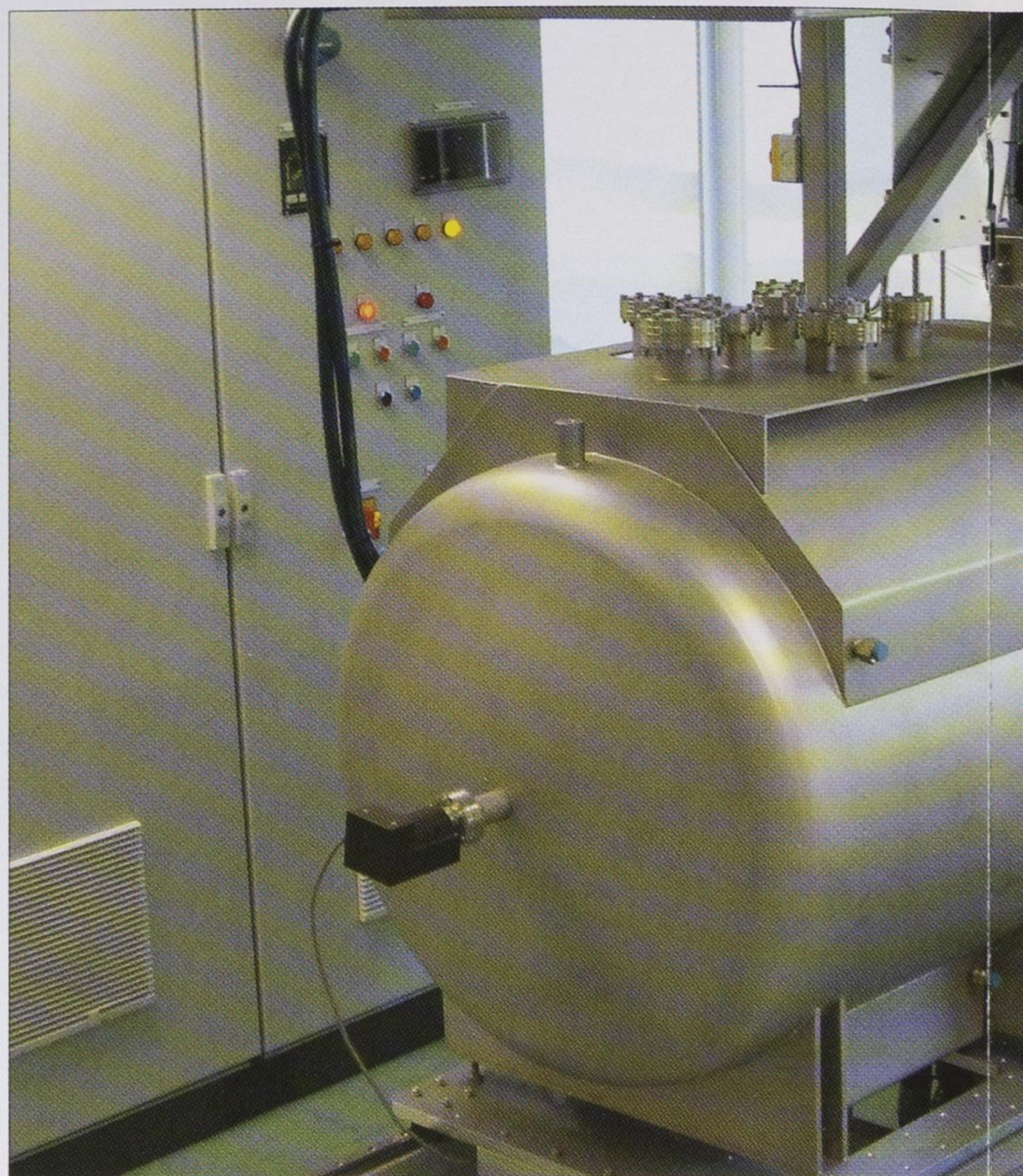
What's needed are better tools for exposing hidden incendiary devices. This would speed up security checks and improve safety. Millimeter-wave systems are an emerging option for detecting concealed weapons under clothing, but X-ray scanners are needed for penetrating the contents of a suitcase.

Existing versions of this technology can locate potentially dangerous packages but cannot always accurately identify the nature of the suspicious materials. Consequently there is a desperate demand for improvement in a technology that has failed to make any significant advances over the last 25 years.

Fortunately, improvements in X-ray detector performance are just around the corner, thanks to an impending switch from silicon-based detectors to those made from CdTe and cadmium zinc telluride (CZT), which can identify plastic explosives in the cluttered environment of a suitcase. These cadmium-based materials are excellent at stopping X-rays and converting the high-energy photons into an electrical signal. Both materials can also be employed in gamma-ray detection cameras for space exploration and medical procedures. The selection of one material over another comes down to personal preference and tends to divide users.

Detection with cadmium-based materials is energy selective and garners information concerning the way in which different materials, individually or in combination, interact with the X-ray tube's energy spectrum. This is a major plus point because it enables accurate identification of materials across numerous market sectors, including medical imaging, security screening and industrial inspection.

So, given CdTe and CZT's strengths, why are so few of these detectors on the commercial market today? Well, the catch is simply this: the materials are very tricky to manufacture. Supply is uncertain, material quality is generally poor and small pieces are the norm. This has meant that many equipment

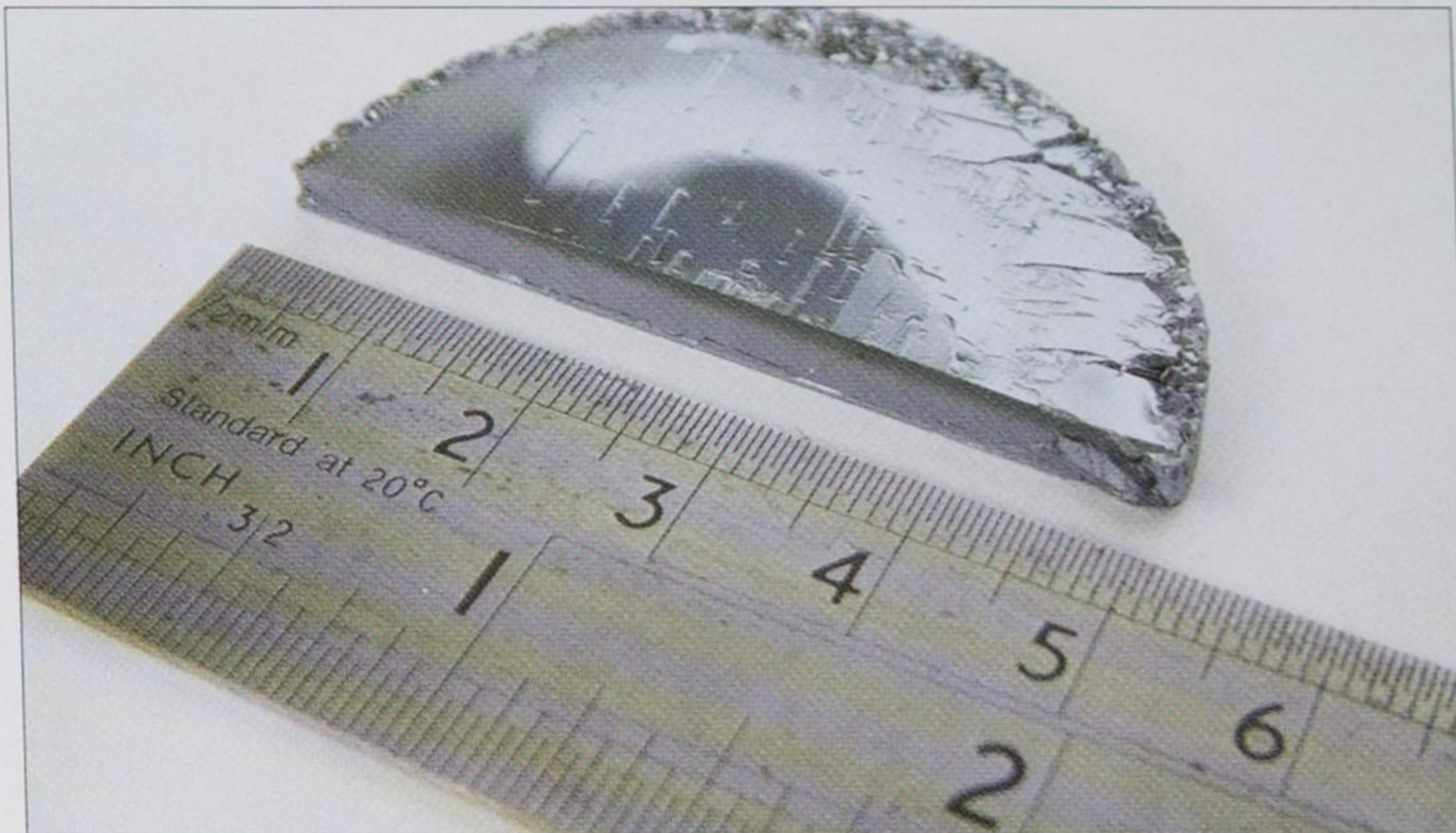


suppliers are wary of turning to CdTe and CZT, and they have backed alternative detector methodologies instead, such as scintillator/silicon arrangements or photomultiplier tubes. However, cadmium-based compounds are routinely employed in some high-value, cost-insensitive applications.

The problems associated with CdTe and CZT stem from the available crystal-growth techniques. Two options exist: growth from the melt and from the vapor. The latter has the edge because both compounds have significant vapor pressures below their melting points. Vapor pressure growth advantages include a far lower growth temperature (CdTe melts at 1050°C), reduced thermal stress and less contamination. Importantly, the crystal grows in a narrow temperature window, which minimizes unwanted tellurium precipitates and inclusions. The vapor process is also self-purifying and prevents the transport of volatile impurities to the growth crystal.

Despite the advantages of vapor-based methods, today's commercially available CdTe is grown by liquid-phase Bridgman techniques. These tend to involve the transfer of an ampoule containing the molten source through a decreasing temperature gradient. At the melting point the source material

e to ignite the detector market



Kromek has developed a multitube reactor (far left) based on PVT that is capable of simultaneously growing several crystals at different growth rates. The growth of CdTe on GaAs substrates offers a route to scaling boules to larger diameters (top left). This has been scaled to a thickness of 12 mm (bottom left).



freezes and ideally forms a crystal.

In its simplest configuration this method involves mechanically pulling an ampoule or crucible through the vertical temperature gradient. The downside is that the crystal is grown in contact with the crucible, which causes stresses due to thermal contraction (this was one of the findings of crystal-growth experiments carried out by NASA on the 1992 United States Microgravity Laboratory space mission).

The seed for CdTe growth via the Bridgman method is a large native polycrystalline ingot. Freezing creates a few large crystals along preferred growth directions, which can be “mined” from the resulting boule, but yield is low – typically less than 15%. In addition, CdTe suffers from extended defects, such as twinning and a subgrain boundary structure (mosaicity), which are associated with the high dislocation densities that are typically in the low 10^5 cm^{-2} . Often CdTe crystals possess twin boundaries that are decorated with tellurium inclusions (1–10 μm in diameter) with dislocation densities in excess of low 10^4 cm^{-2} , which cause subgrain structure. Tellurium inclusions can impact detector-grade material because they distort internal electric fields and cut the detector’s sensitivity and resolution.

The first attempts at vapor growth used closed silica ampoules. Solid-source material was heated to form a gas at one end of the ampoule, before being directed to the cooler side where it crystallized.

Although the method sounds simple, it is virtually impossible to control, due to the link between sublimation, transport and growth rates. These are also incredibly sensitive to the temperature profile, which can cause unwanted fluctuations in stoichiometry and an increase in residual impurity content.

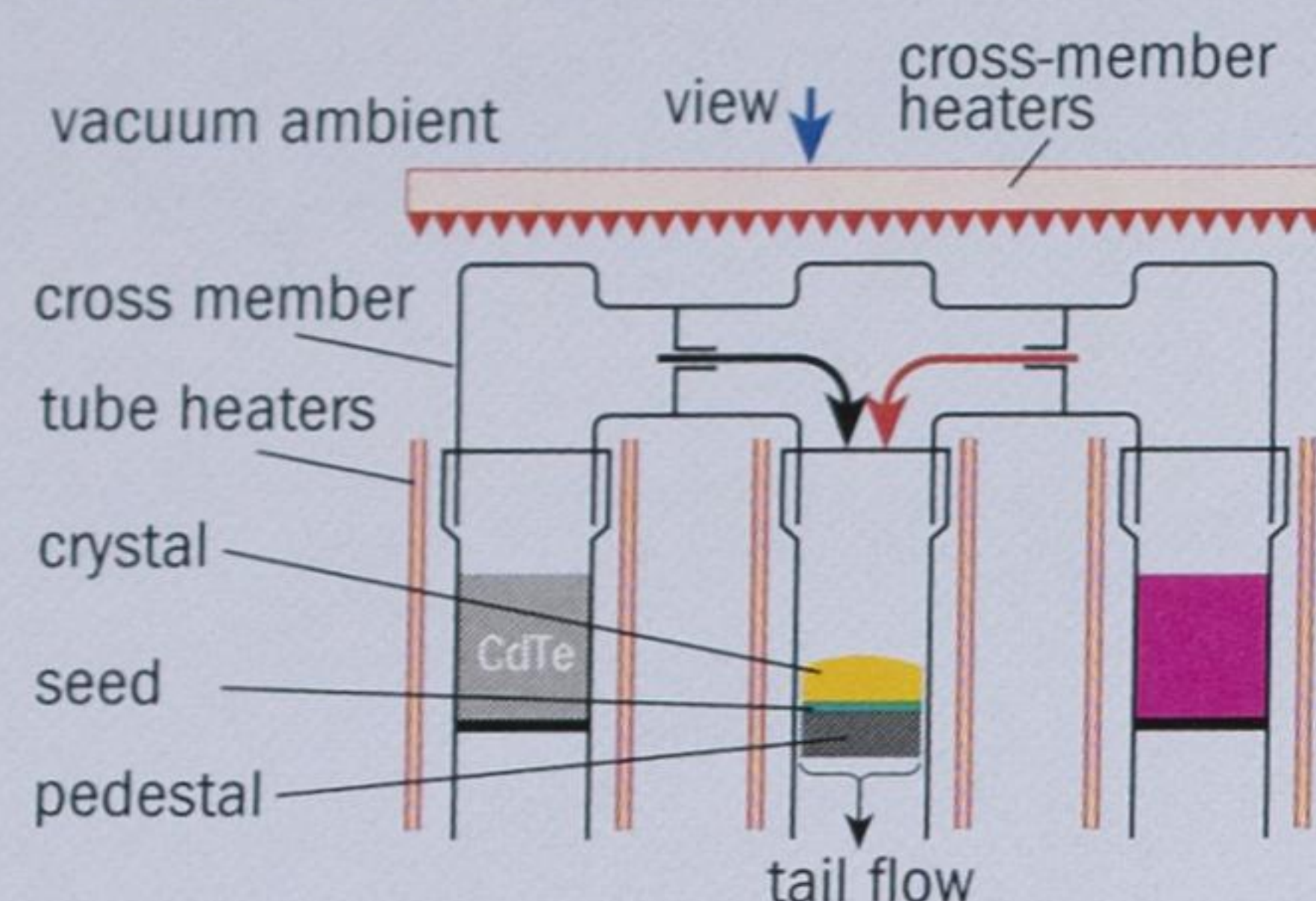
Adding a flow restrictor, such as a capillary, combats some of these weaknesses because mass transport is then governed by the pressure difference across the restrictor, and source and growth sides are thermally decoupled. This technique was first applied to the growth of mercury iodide and has subsequently been used in the NASA-funded CdTe program. The approach promised the independent optimization of the growth and source regimes, but in reality poor thermal decoupling occurred between these two, due to radiative heat transport. To make matters worse, vapor pressures could only be inferred indirectly after the growth was over.

Progress was made with vapor-based processes in the 1970s. The Russian scientists Markov and

Scaling CdTe and CZT growth

Kromek employs a multitube PVT system for CdTe and CZT growth. Quartz tubes are filled with CdTe and ZnTe sources and heated by independent furnaces that are connected to a third, similarly heated, quartz growth tube by demountable quartz cross members. Heating of this cross member prevents the condensation and sublimation of source materials prior to reaching the growth region.

In the growth tube the seed wafer is located on a quartz pedestal that is separated from the inner wall of the tube by an annular gap. This downstream gap allows a proportion of the transported source material to be extracted. This approach also prevents the build up of any source elements or residual gas that could reduce the transport rate. One consequence of all of this is that the vapor pressures of the constituent elements are close to the minimum



equilibrium vapor pressure above the seed crystal, at a growth temperature that is always less than 800 °C.

The tool also features flow restrictors in the horizontal arms of the cross member, which regulate transport and decouple its rate from the source-sink temperature difference. A high vacuum vessel encloses the system, and provides a clean ambient environment, thermal insulation and pumping of the tail flow.

Davydov showed that it is possible to grow a crystal on a seed plate surrounded by a small ring. This avoids contact with the container walls, which leads to a high density of defects. Excess and impurity vapor constituents can be sucked down the annulus and the resulting flow can constrain the crystal geometry to the dimensions of the seed.

Researchers at Durham University, UK, extended this approach with a novel vapor growth process that has been granted a patent in the US, the EU and Japan. The Durham System, a multitube physical vapor transport tool, minimizes axial radiative coupling by physically displacing the source and growth furnace (see box, “Scaling CdTe and CZT growth”). This reactor also allows mass transport rates to be determined directly via optical absorption measurements that reveal *in situ* vapor pressures.

At Kromek, formerly Durham Scientific Crystals, we have acquired the intellectual property for this technique and we are working to commercialize this vapor-phase process. One of our tasks has been to scale the growth tool, and it is now capable of simultaneous growth of several crystals with various diameters at different growth rates.

Sourcing suitably sized seed crystals is a major stumbling block to the growth of cadmium-based crystals. The largest commercially available melt-grown material is just 2 inches in diameter. This has restricted our ingots to that size. But in late 2007 we started to consider a switch to GaAs seed plates. Although this invokes the penalty of heteroepitaxial growth, it is offset by the benefit of employing far larger GaAs substrates of up to 6 inches.

Turning to heteroepitaxy is not as outrageous as it may sound – other researchers have already pro-

duced CdTe-on-GaAs films by MBE, MOCVD and hot-wall epitaxy. These films were up to 10 µm thick and our aim was to scale this to several-millimeter-thick bulk single crystal.

We have already had great success and produced 2 inch diameter single-crystal boules of CdTe and CZT, which are both 12 mm thick. This is the first growth of true bulk material several millimeters in thickness by an epitaxially seeded process.

Both materials compare favorably to material grown by liquid-phase techniques, according to various characterizations. X-ray diffraction measurements show that CdTe forms excellent single-crystal material – the double-axis rocking curve full-width at half maxima is just 25 arc seconds. Resistivity profiles of this compound show good uniformity and a value of $10^9 \Omega \text{ cm}$. Meanwhile, energy-dispersive X-ray analysis on a 5 mm × 5 mm dice cut from single-crystal CZT shows the uniformity of zinc composition in all directions.

Serving the markets

We can produce detectors in house because we have the facilities for slicing, polishing and adding electrodes. However, we don't just want to be a material supplier: we want to move up the chain and offer detector modules, drive electronics and subsystems.

Our current efforts include the development of prototype modules that will enable us to assess the full potential of our material. We are now developing a complete baggage-screening unit employing CdTe detectors for aviation security, thanks to a £350,000 (\$0.7 million) contract from the UK's Home Office, Department for Transport, Metropolitan Police and Centre for the Protection of National Infrastructure. This is due for delivery in early 2009. Trials are likely to follow, before airport deployment.

We have also built a small unit designed to screen for liquid explosives held in containers such as bottles and cartons. This has already received a very encouraging international response, and trials are planned in the UK, the US and the Middle East.

The same CdTe technology could also be used to replace conventional X-ray detectors in industrial inspection tasks, such as checking for flaws or anomalies in assembled products and foodstuffs. Switching to cadmium-based detectors would deliver more information about these products, thanks to the material's energy selectivity. A more thorough form of quality control is also possible.

There are many exciting applications in nuclear medicine and medical imaging. In the same way that silicon advances have fueled the digital photography revolution, the CdTe family of materials should drive a similar revolution in digital radiography.

In all of these cases, cadmium-based detectors are offering one huge improvement over incumbent technologies – energy-selective detection. This is a significant step, because it frees us from the optical equivalent of monochrome images that are harder to interpret, and delivers full-color pictures. ●



About the authors

Max Robinson (left; max.robinson@kromek.com) is the founding director of Durham Scientific Crystals and a consultant to Kromek.

Arnab Basu (right) is Kromek's CEO.



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CRIEPI spearheads Japan's SiC assault

From its unique position linking Japan's power companies, the Central Research Institute of the Electric Power Industry is on a mission to exploit SiC devices' efficiency. **Andy Extance** reports.



In Japan, as well as managing large-scale power networks, electricity companies sponsor research into cutting-edge semiconductor devices, which is largely undertaken at CRIEPI.

Yasuzaemon Matsunaga was an executive in the young Japanese electric power industry where his role in defining the sector's future saw him nicknamed the "demon of electricity". He fought and lost a desperate battle against the state control of power supplies leading up to the Second World War, a battle that ended in his resignation.

However, after the war, Matsunaga returned as chairman of the advisory council for the industry's reorganization. From 1949 to 1951, he oversaw the creation of the present system of nine regional private power companies, which replaced the state-run regime. Also in 1951 he established a non-profit public benefit corporation called the Central Research Institute of the Electric Power Industry (CRIEPI).

Today, as then, CRIEPI's mission is to carry out "research for the benefit of society as a whole". Compound semiconductors have a key part to play in this effort, most particularly SiC power electronics for use as an "optimal energy utilization technology".

"We believe that SiC inverter technology with low-loss power conversion can enhance the use of electric power in households, industry, transportation and power distribution," explained Hidekazu Tsuchida, leader of CRIEPI's SiC research team.

The research model used by CRIEPI allows it to undertake studies either independently or collaboratively. It mainly teams up with Japanese regional power firms, who provided the majority of CRIEPI's ¥33.71 billion (\$311 million) budget for 2008. The institute's intellectual property can then

be transferred for external partners to use in manufacturing or operating electrical power systems.

One such research collaboration saw Tsuchida's team partner with AIST (the Japanese National Institute of Advanced Industrial Science and Technology), and chemical giant and LED maker Showa Denko, to improve SiC wafer growth processes. The lessons learned by this collaboration have since been transferred to SiC epiwafer manufacturing start-up ESiCat. The partners set up ESiCat in 2005, and the company is now selling 2 and 3 inch SiC epiwafers.

Tsuchida's team also collaborates with the Kansai Electric Power Company, investigating SiC defects formed during epitaxial growth and learning how to diminish their effects when fabricating power devices. As is common for CRIEPI's SiC work, this focuses on epilayer growth on 4H-SiC substrates, which it says are particularly suitable for the manufacture of SiC power devices.

The main target is high-voltage bipolar SiC devices, which often suffer from performance degradation when a current is applied. The reason has been narrowed down to imperfections called single Shockley faults that form in the devices. These are nucleated by dislocations on the basal planes of SiC epitaxial layers, known as basal plane dislocations (BPDs).

"Reduction of the dislocation density in SiC substrates and epilayers is crucial to ensure reliability, especially for MOSFETs and bipolar devices," explained Tsuchida. "Understanding the formation of the dislocations can give hints for new methods to control or reduce them."

Defeating defects

The Kansai-CRIEPI collaboration has found success in eliminating certain types of BPD and preventing their propagation from substrate to epilayer, particularly by finely tuning which SiC crystal face the team uses as a substrate. It has also produced devices demonstrating the capability of SiC. These include Zener diodes, which are important in regulating constant-voltage circuits, with a pulse operation capability of 8 kW, compared with an approximate maximum of 3 kW for silicon rivals.

Perhaps CRIEPI's most notable recent achievement is in high-speed SiC epitaxy, leaping to a growth rate of 250 $\mu\text{m}/\text{h}$ – more than 20 times as great as the rate seen in multiwafer reactors. Induction heating warms the sides of the vertical hot-wall reactor that the group uses (figure 1) and the susceptor on which

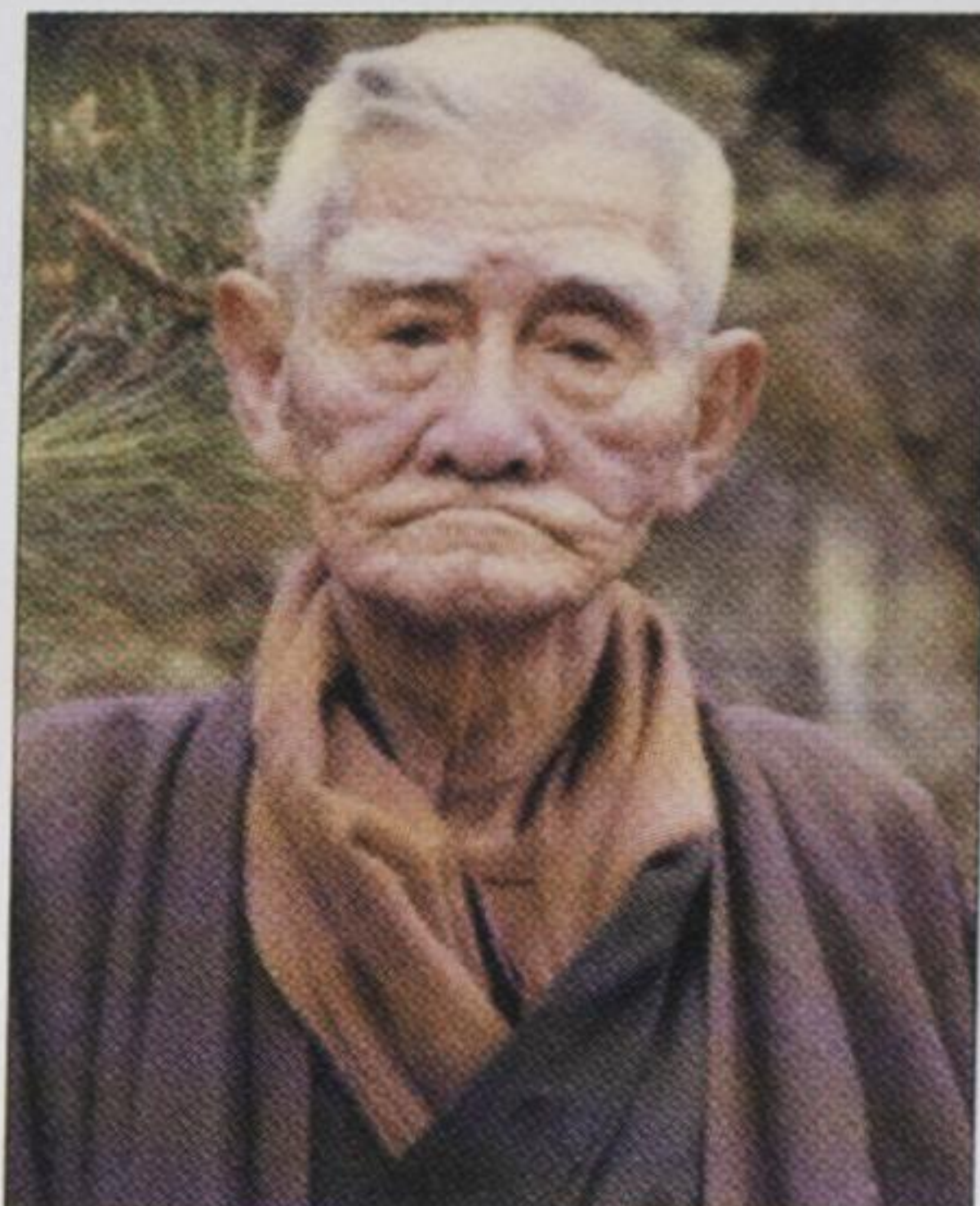
the substrate sits is heated by the resulting thermal radiation. Substrates are loaded from the bottom and the susceptor can be raised close to gas inlets at the reactor top, preventing the unwanted deposition of reagents on the reactor sides.

Rotating the susceptor at 10 rpm during epitaxy ensures even doping levels and SiC thickness across the entire wafer. Low system pressures and high gas flow rates into the reactor lead to rapid film growth and help to suppress the unwanted material nucleation that leads to defects.

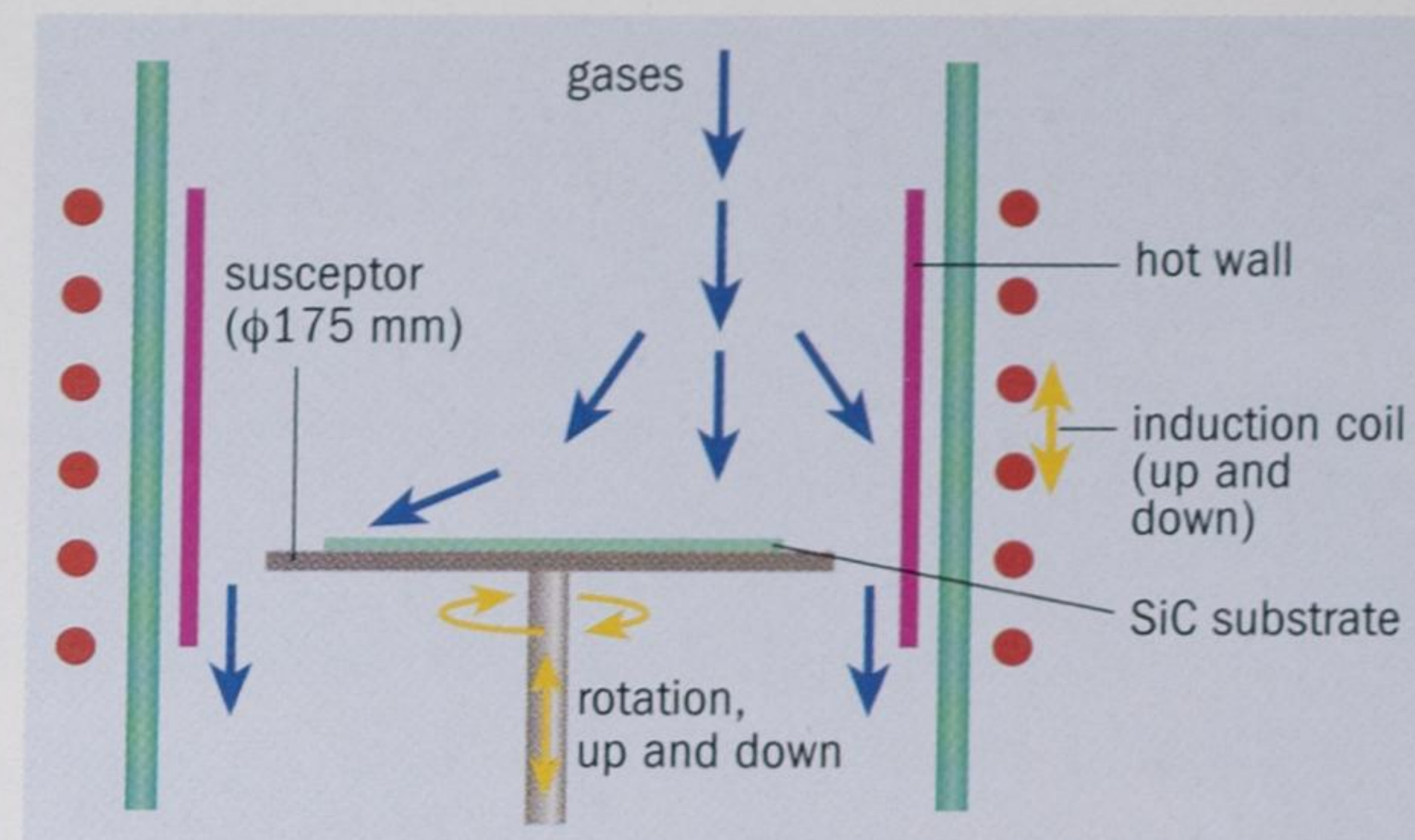
"Our high-speed epitaxy is aimed at making very thick epilayers to produce very-high-voltage devices for electric power conversion in the power transmission/distribution system," Tsuchida explained.

At the October 2007 International Conference on Silicon Carbide and Related Materials in Otsu, Japan, CRIEPI shared the podium with many big-name Japanese companies. With Panasonic, Mitsubishi and Toyota, to name but three, performing their own research independently from CRIEPI, Japan is clearly a major force in SiC. According to Tsuchida, it is the leading force.

"In my opinion, the number of companies in Japan involved in researching SiC materials, processing and devices is now the largest in the world," he said. "Producing low-loss power semiconductor devices is widely accepted as a key issue for energy saving



According to Yasuzaemon Matsunaga, the founder of CRIEPI (left), "Industrial research is the cultivation of wisdom and it should make a contribution to society." **Fig. 1.** (right) Tsuchida's group at CRIEPI used this hot-wall reactor to grow a 280 μm thick epilayer at 250 $\mu\text{m}/\text{h}$.



and CO₂ emission reduction in this country."

With such a well educated outlook, perhaps we will see the fulfillment of SiC's promise in low-loss electrical networks in Japan. What's more, thanks to the intimate relationship with Japanese electricity companies that Matsunaga specified when it was founded, it looks like CRIEPI is destined to be the research institute at the center of the rise of SiC. ●

Further reading

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

L Storasta *et al.* 2008 *J. Appl. Phys.* **103** 013705.



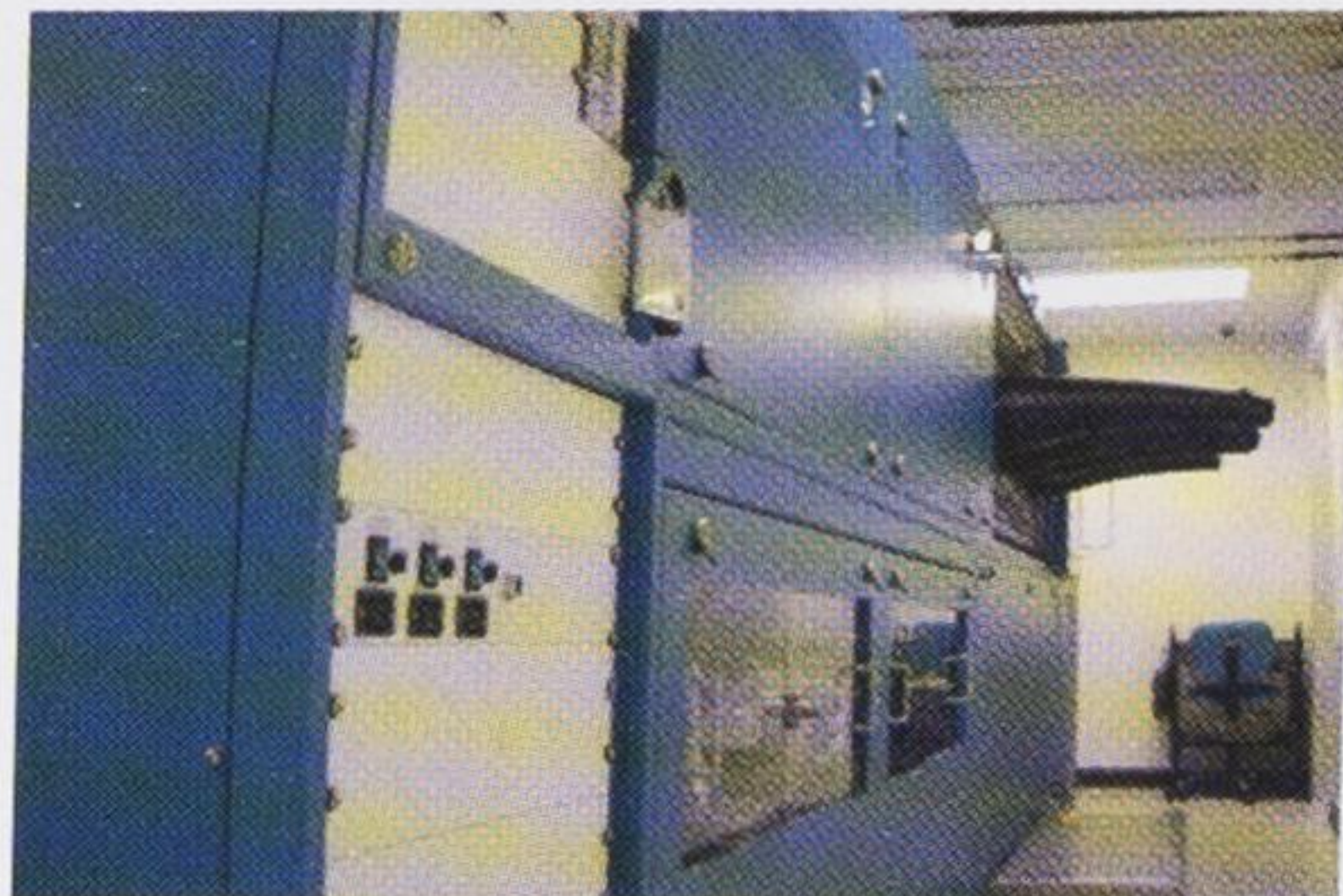
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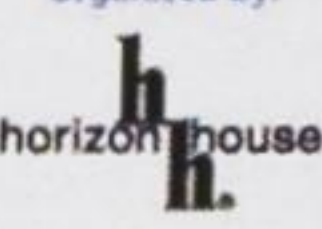
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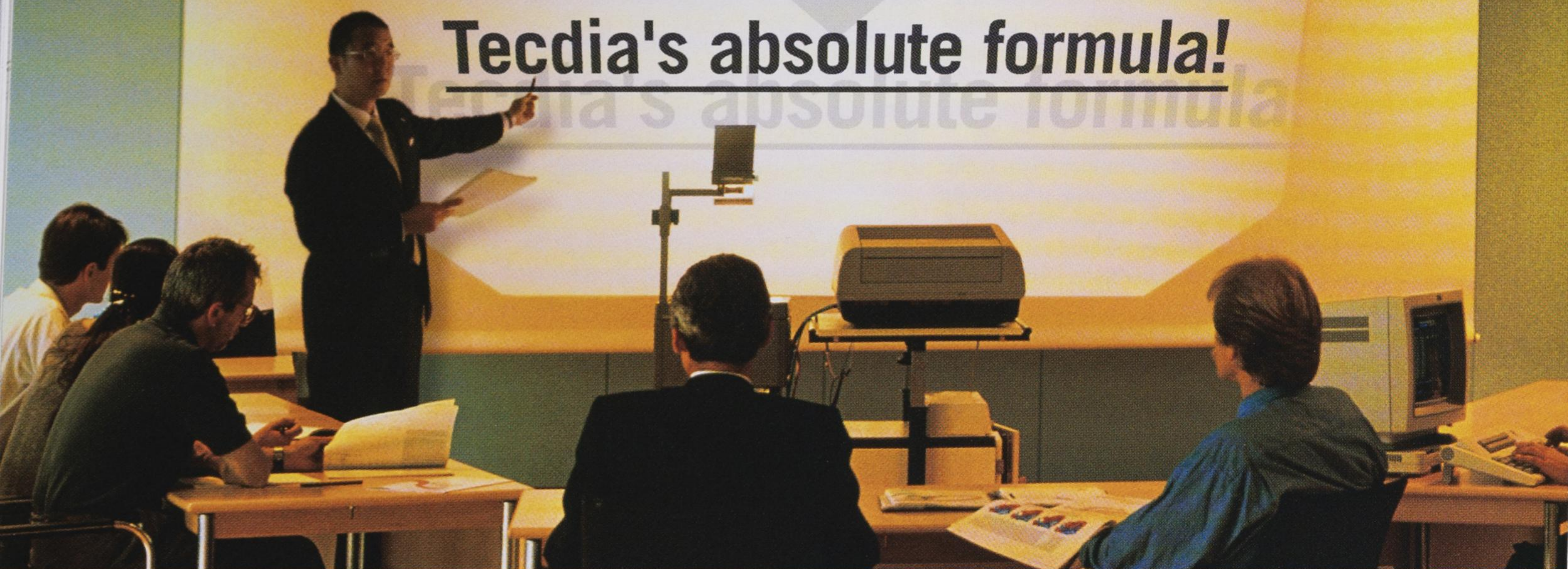
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TD-420
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TD-4L
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W W W . T E C D I A . C O M

Holey LEDs target TV backlights

LCD-based TVs give great pictures if you're willing to invest in a pricey LED backlighting unit. But the cost of this light source could plummet if manufacturers deploy photonic crystal LEDs made with high-volume stamp-based lithography techniques, say Glasgow University's **Faiz Rahman** and **Ali Khokhar**.

Cathode-ray tubes are dead. Walk into any electronics store and you'll see aisles of LCD screens for TVs and computer monitors. Even the competing, and initially superior, plasma display technology is under attack from the latest LCD TVs that are more efficient, lighter and deliver sharper images.

Unlike plasma displays, LCD screens employ a backlight unit (BLU) to project white-light emission through the liquid-crystal panels. Cold-cathode fluorescent lamps (CCFLs) are often used for this task, but LED-based backlighting offers an alternative that is also becoming a popular option in laptop computers, where it can extend battery lifetime, thanks to its higher efficiency.

The advantages of LEDs include a further reduction in the weight, thickness and energy efficiency of BLUs. The solid-state source is also compatible with dynamic contrast control, a technology that produces contrast ratios of up to 10,000:1 by switching off LEDs behind dark areas of displayed pictures.

LED options

BLUs produce white light through the careful mixing of the output of red, green and blue LEDs, or by using blue LEDs coated with a yellow-emitting phosphor. Both options involve GaN-based blue LEDs, which share a weakness found in all forms of this device: the trapping of a high proportion of the light generated by the active region.

This inefficiency means that many LEDs are needed to form a BLU, which adds to the cost. To improve light extraction, researchers have developed several technologies to extract light trapped in the chip by total internal reflection.

Commodity LED manufacturers favor a roughening of the wafer's top surface. Random texturing, which is simple and cost-effective, widens the escape angle and allows a significant fraction of trapped light to escape. However, this is inappropriate for BLUs, owing to the lack of directional control over the light distribution. Roughened LED chips produce an essentially omnidirectional light intensity profile within the emission cone, which is fine for many general illumination requirements but undesirable for LCD backlighting applications, where a more structured beam profile is needed to direct the light to the most appropriate places.

Working out how the light gets trapped, and how



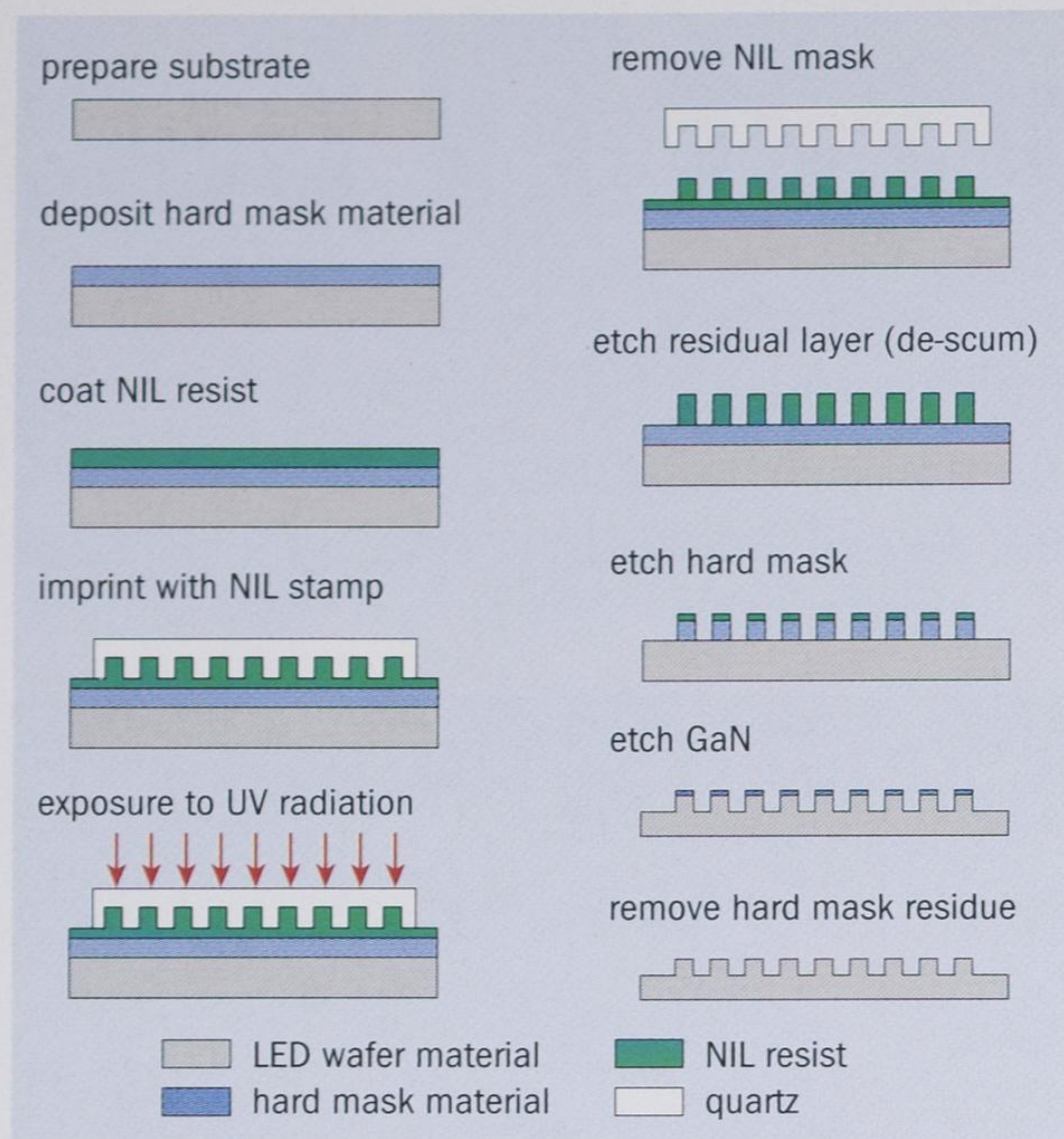
Cold-cathode fluorescents backlight most LCD screens, including models sold by UK electronics chain Currys. LEDs offer an alternative source that can improve contrast through local dimming, but chip prices must fall if this technology is to penetrate mainstream TV sets.

it can be coaxed from the LED, can pay dividends. Calculations and simulations reveal that there are horizontal trapped modes in the GaN overlayers and the sapphire substrate, and the incorporation of an ordered hole-based grating structure on the emitting facet of the LEDs is a practical and effective way to extract them. The most popular choices are periodic and quasiperiodic arrays of shallow blind holes that form a two-dimensional photonic crystal lattice.

Studies show that LEDs incorporating etched photonic crystal lattices can double the surface brightness of unstructured equivalents and influence the device's spatial emission profile. The Lambertian profile produced by planar LEDs is not ideal for BLUs, but optimization of a photonic crystal structure enables tailoring of the radiated intensity distributions to the characteristics of the particular light diffuser and brightness-enhancement films.

US firm Luminus Devices Inc is already enjoying success in this field with its photonic crystal

Fig. 1. (right) Flash nano-imprint lithography involves stamping a resist-coated wafer with a transparent quartz stamp, exposure from an ultraviolet source and etching to create a photonic crystal structure. **Fig. 2.** (far right) The Photonic Quasicrystal LEDs for Display Illumination program employs a conventional LED structure.



PhatLight LEDs. These devices are used in some top-end TVs, such as Samsung's 56 inch rear-projection model, because this manufacturer believes that the higher costs associated with that class of LED can be accommodated into flagship products. However, if photonic crystal LEDs are to make a major impact on the overall market, and the key LCD TV segment, then their manufacturing costs will have to plummet to levels that are comparable to CCFLs.

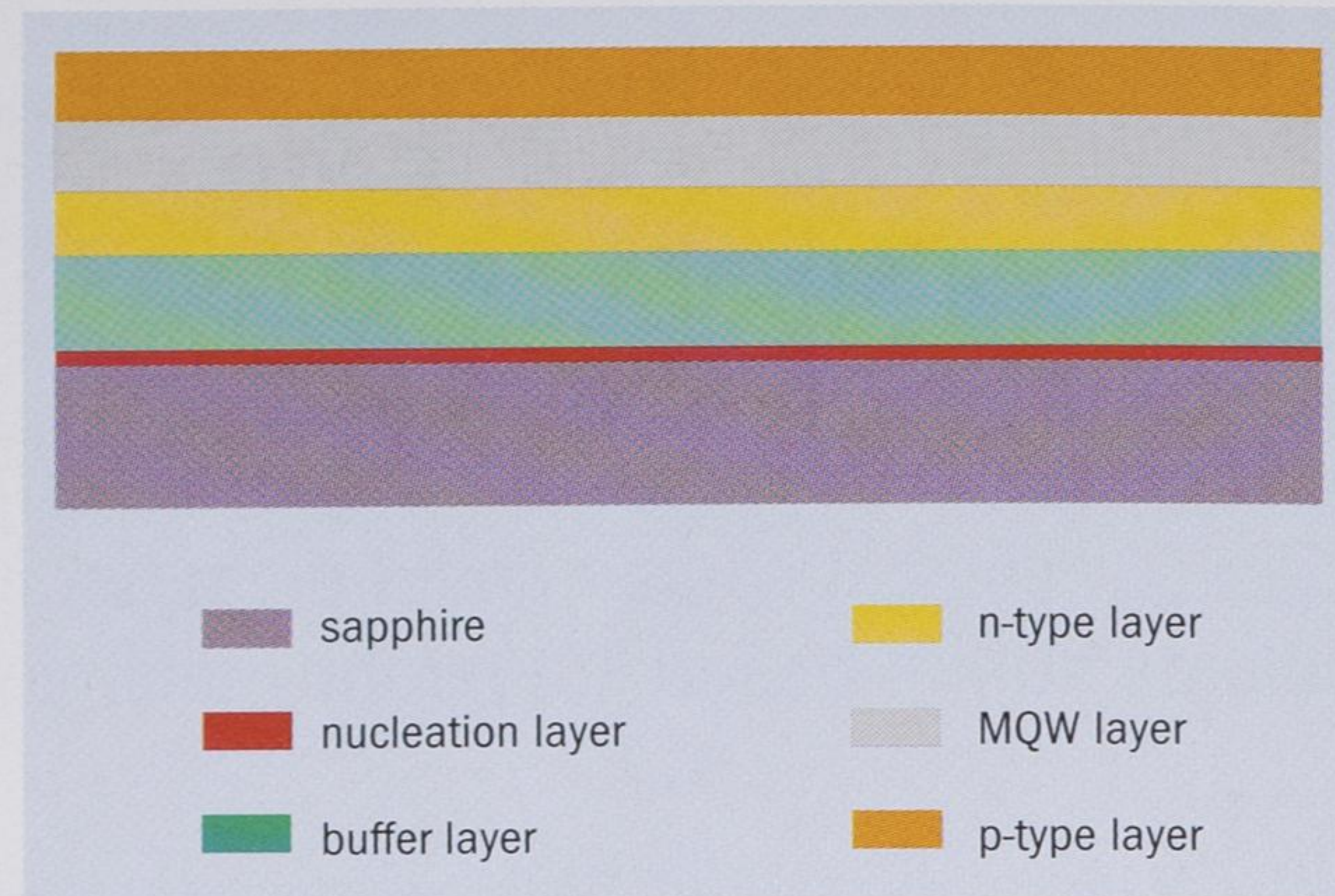
Developing a lower-cost manufacturing technique for photonic crystal LEDs is the primary goal of the Photonic Quasicrystal LEDs for Display Illumination (PQLDI) project, which started in May 2007. This two-year program has £1.2 million (\$2.4 million) of funding from the UK's Technology Strategy Board. It involves our team at Glasgow University's Department of Electronics and Electrical Engineering, the Institute of Photonics at the University of Strathclyde and Sharp Laboratories of Europe.

Quasicrystal benefits

Conventional photonic crystal LEDs, such as those made by Luminus, have attracted a strong patent portfolio, so we have directed our efforts towards quasiperiodic photonic crystal structures. When it comes to display backlighting, this type of photonic crystal has a major advantage over its conventional cousin: the quasiperiodic arrangement of holes delivers freedom for optimizing the output-beam profile, and this in turn simplifies design tweaks.

Creating the photonic crystal structure is a key process step for fabricating this type of device. Modern "deep submicron" optical lithography systems are an obvious choice but not necessarily a good one. Although they can print photonic crystal features with deep submicron-scale patterning, this expensive tool is not found in most LED fabs.

A cheaper alternative is electron-beam litho-



graphy. This is an affordable option that is widely used by researchers investigating photonic crystal devices. However, we have ruled it out. Its incredibly slow writing speed means that pattern-writing costs are prohibitively high. Covering an area of just one square inch takes several tens of hours, which translates into beam-writing costs of thousands of pounds – unacceptably high for volume manufacturing of commodity chips.

Instead we have selected nano-imprint lithography (NIL). This technique involves imprinting patterns on LED epiwafers with a stamp made from a suitable, hard material, such as quartz or silicon. High-resolution techniques, such as direct write electron-beam lithography, can produce the stamp but costs are acceptably low because the stamp can imprint many wafers before it is replaced. In manufacturing environments a master stamp would be made and used to create several working copies.

Our nano-imprinting process employs an Obducat tool and involves pattern transfer from a relief on the stamp to a special NIL resist through the application of pressure and temperature (figure 1). The cross-linking of polymers occurs within seconds to form a hardened resist before the stamp is removed. Dry etching replicates this pattern in the underlying wafer (figure 2).

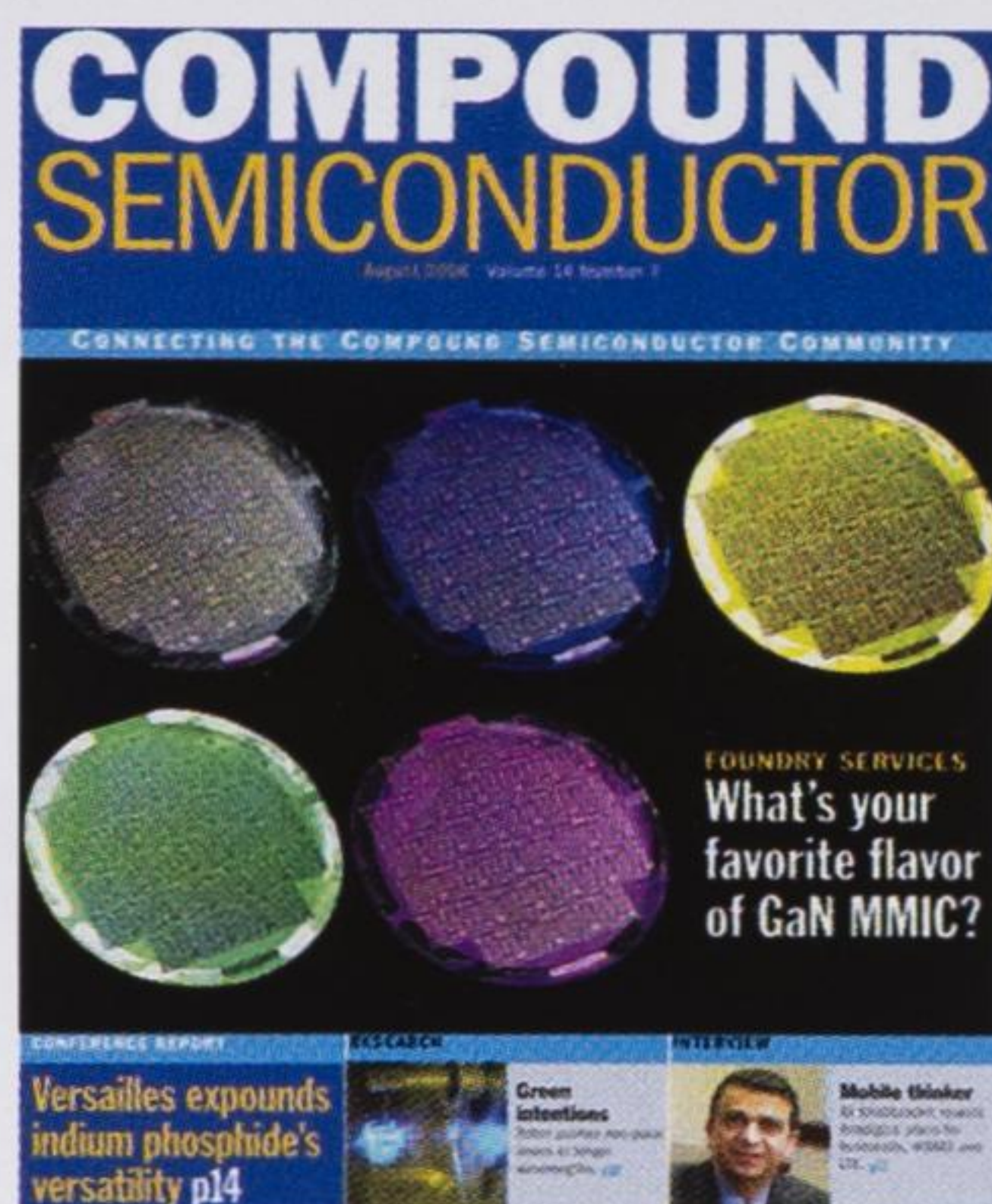
Our efforts began with silicon NIL stamps patterned with electron-beam lithography, which were dry etched to form relief patterns. These stamps work well and our limited number of research and development samples have not suffered from erosion. However, we discovered that silicon stamps cannot handle high process pressures, and in this case it is better to employ stamps made from quartz or SiC.

The transparency of quartz also allows it to be used for "flash NIL". This involves curing the NIL resist through exposure of radiation transmitted through the stamp material, and this eliminates stamp heating. These advantages have encouraged us to adopt an advanced etch process for making high-definition NIL stamps for imprinting on GaN LED wafers with a 360 nm light source.

NIL-based patterning requires a dual etch because imprinting leaves a thin layer of resist, even over "clear" regions. This is caused by material displace-



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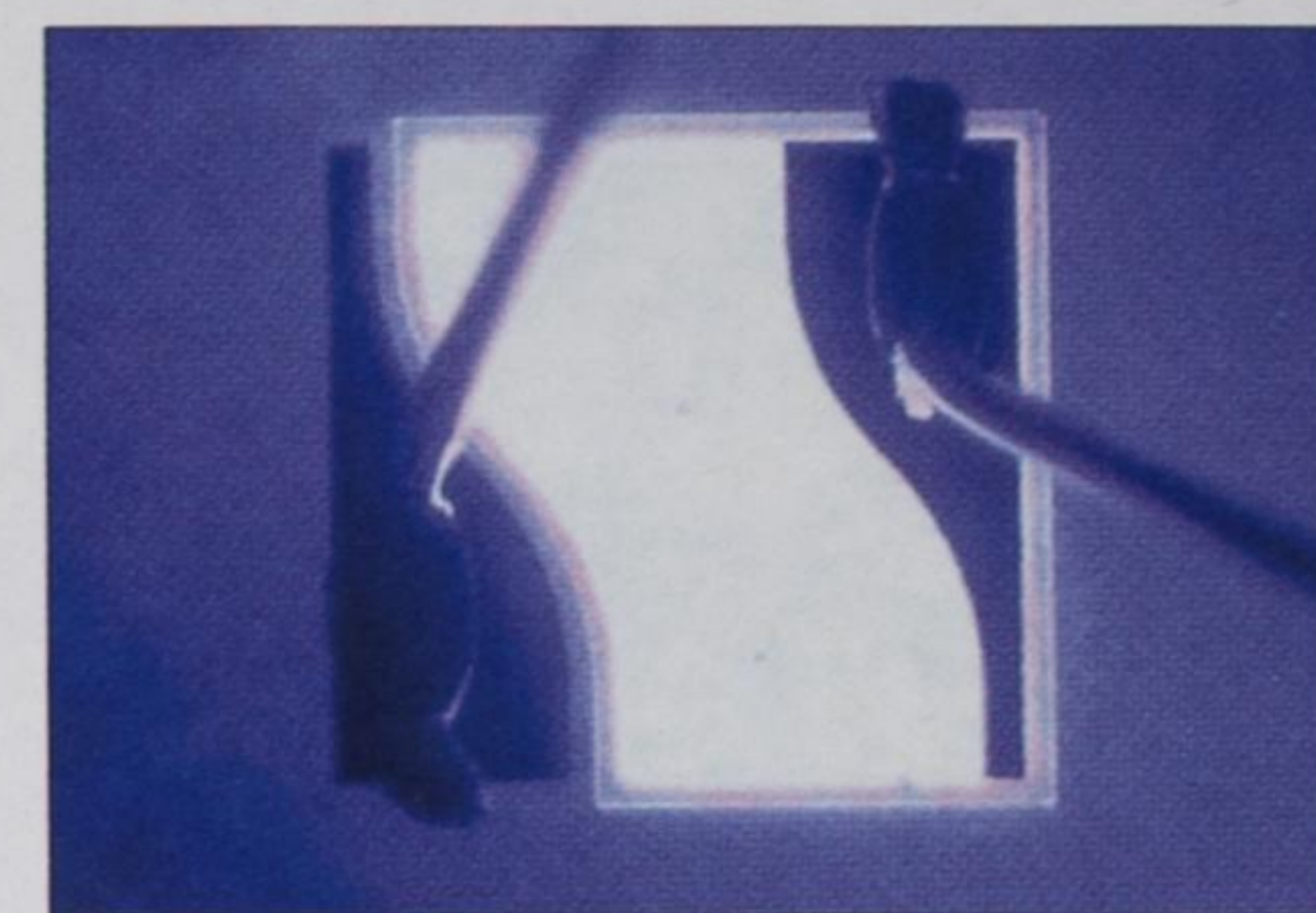
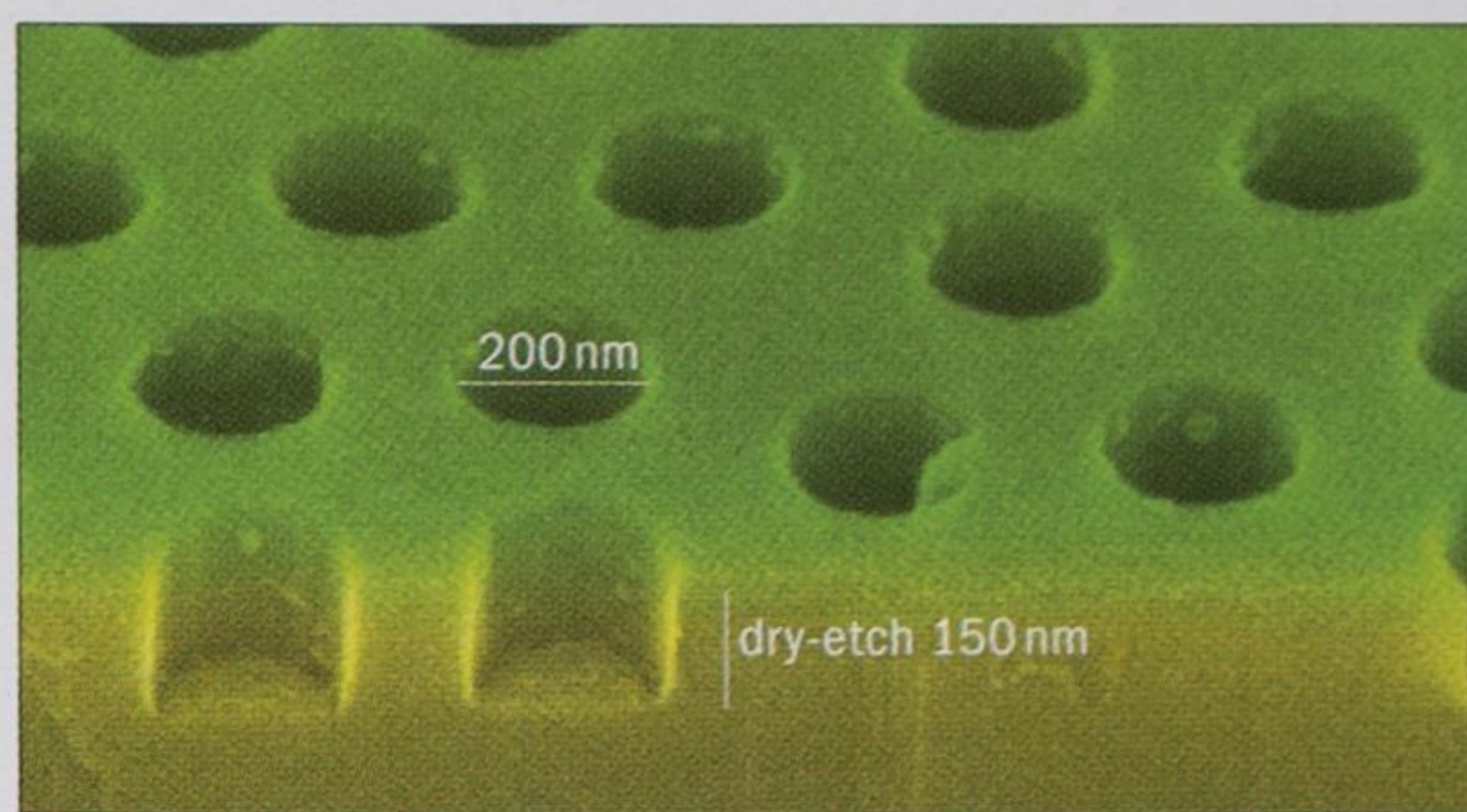
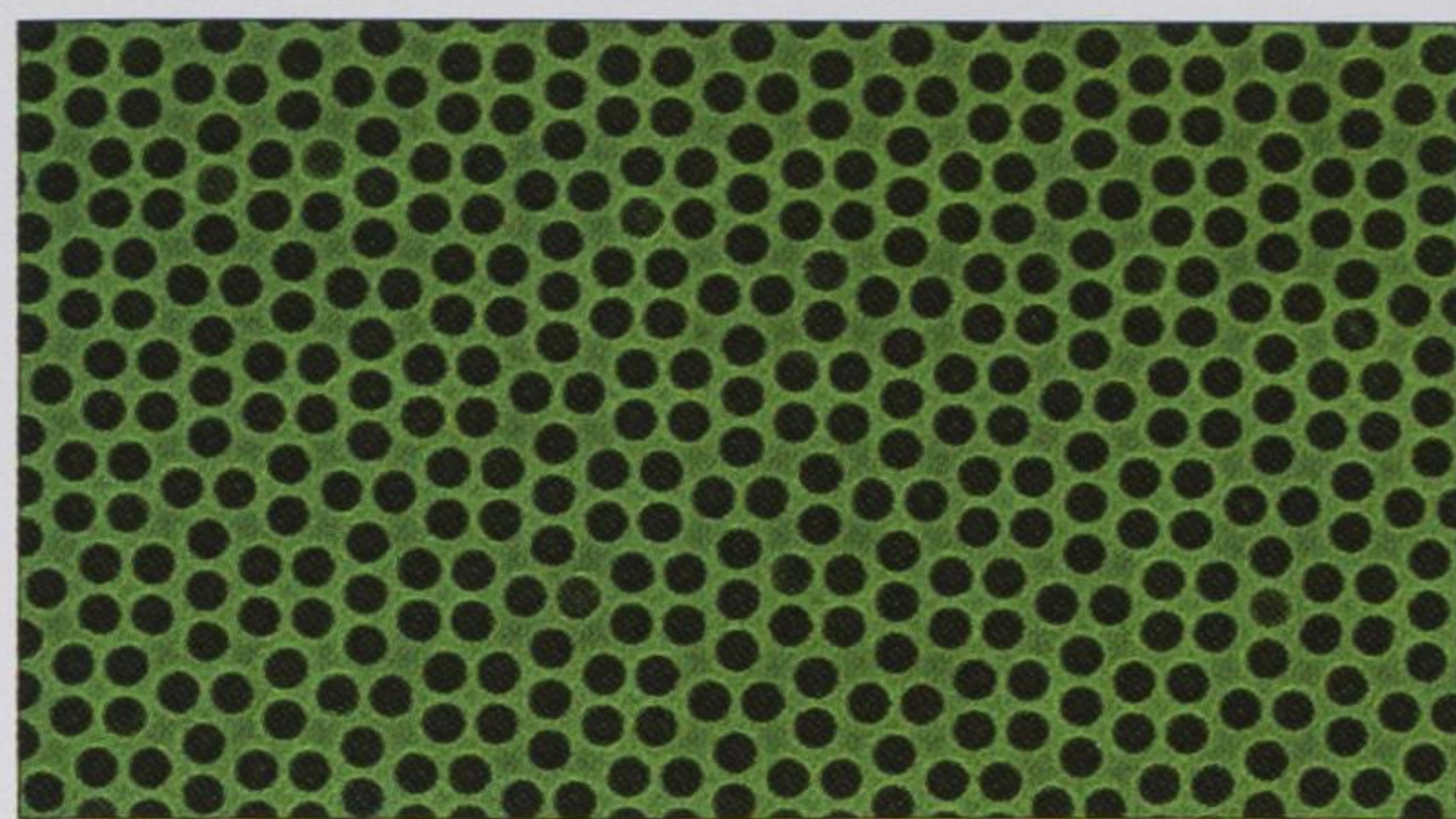
IAN WATSON, ERDAN GU AND MARTIN DAWSON,
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Fig. 3. (left) Quasicrystal patterns avoid patent issues that surround conventional periodic structures, while providing freedom for tailoring the emission profile for a particular application. **Fig. 4.** (center) It takes just five minutes to produce high-fidelity photonic crystal structures with an inductively coupled plasma-etching process that employs chlorine-containing gases. **Fig. 5.** (right) 350 μm square quasiphotonic LED chips have very uniform emission intensity over the top surface.

ment of the resist, which is in a pliable state during the imprinting contact phase. Fortunately, resist-development processes are not required for NIL. Instead the residual layer is removed before the etch proceeds inside the epilayers. This is usually carried out with an oxygen plasma process before the GaN is dry etched. Several gas mixtures can be used. Combinations of methane and hydrogen are one option, but we and others have found that chlorine-containing gases produce better results.

We carry out our dry etching with an inductively coupled plasma etch tool that produces an almost vertical etch profile. This approach also increases etch rates to several hundred nanometers per minute, which means that it takes about five minutes to define a photonic crystal structure across an entire wafer. This short process time makes the technique compatible with high-volume manufacturing.

Developing a process for mass-manufacturing has required us to address a range of challenges. These include fabricating a stamp with sharply defined patterns; ensuring a good contact between all of the stamp's patterned area and the resist-coated substrate; and preventing the stamp from adhering to the NIL resist so that it can be removed easily after imprinting and resist curing. Soft-resist reflow dynamics mean that a thin layer of resist is left at imprinted locations, and photonic LED fabrication processes must also include a step to remove this layer prior to the transfer of the pattern into the substrate material.

We have developed a proprietary process flow that addresses all of these issues and delivers high-quality imprinted features that are subsequently etched into the substrate. The precision of our process is demonstrated by scanning electron microscopy images of our NIL stamp on silicon (figure 3) and a section of one of our imprinted resist-covered wafers (figure 4). These images reveal the sharp definition of the photonic crystal holes. The fidelity of nanoscale pattern replication is an outstanding feature of NIL, which makes it a strong contender for the next-generation lithography of CMOS chips.

To speed up the nanoscale patterning process for high-volume manufacturing environments, NIL stamps must be used in step-and-repeat tools that imprint tens of thousands of dies in a few hours.

This is not as difficult as it may seem, however, because alignment requirements are far more relaxed than those demanded for silicon-chip production.

We, alongside others, are also looking at the possibility of roller imprinting. This has the potential to pattern very large areas at high speeds, and it should be simpler than step-and-repeat imprinting because it only requires a rotary-tool motion. The process is based on imprinting a hard roller with an embossed pattern onto a resist-coated substrate. Pattern transfer can occur by heat-and-pressure or flash-based techniques because GaN epiwafers are deposited on UV-transparent sapphire substrates that allow UV illumination through the wafer's backside.

Work is ongoing in this area and initial results indicate the benefits of a "horses for courses" approach. Smooth wafer surfaces seem to respond better to flash imprinting, but rougher topographies are easier to pattern with the thermal process. Although these techniques still require more development, we believe that they will be taken up by commercial LED manufacturers, probably at the point when GaN LED wafers exceed 6 inch diameters.

After patterning, standard fabrication steps are employed to produce finished LEDs. In our case we make arrays of 350 μm $\times$ 350 μm chips that feature a proprietary p-type current spreading layer that uniformly spreads the current over the entire top face of the device. This is a crucial step because the current spreading layer has to be structurally compatible with the etched photonic crystal pattern.

Our devices (figure 5) can operate at more than 200 mA and feature very uniform emission over the device area. Their angular intensity profile is different from the Lambertian profile of conventional LEDs and we are looking to optimize it under the guidance of our backlight-development team.

The final year of our project will be devoted to optimizing processes, improving device characteristics and exploring new soft-mask approaches for the NIL process. Beyond that we are likely to seek further government and industry support to work on large-chip LEDs for mainstream lighting. Such devices pose their own set of challenges, such as effective thermal management, large-area current spreading and high-efficiency color conversion from blue to a panchromatic spectrum.



About the authors

Faiz Rahman (left; f.rahman@elec.gla.ac.uk) is a lecturer in the electronics and electrical engineering department at the University of Glasgow. His research interests include device-fabrication technologies, quantum-effect devices, radiation detectors and imaging arrays, and computer architecture.

Ali Khokhar (right) is a postdoctoral research fellow in the same department.

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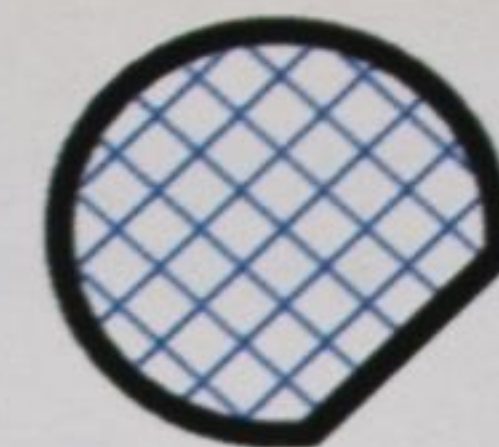
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EPITAXY

Cyclical process improves film quality

If you want to put down robust and highly conformal films for LED and radio-frequency electronic device manufacture, then you ought to consider a novel nanolayer deposition tool that features a plasma film treatment step in each deposition cycle, say **Steve Selbrede**, **Michael Studendorff** and **Paul Werbaneth** from Tegal Corporation.

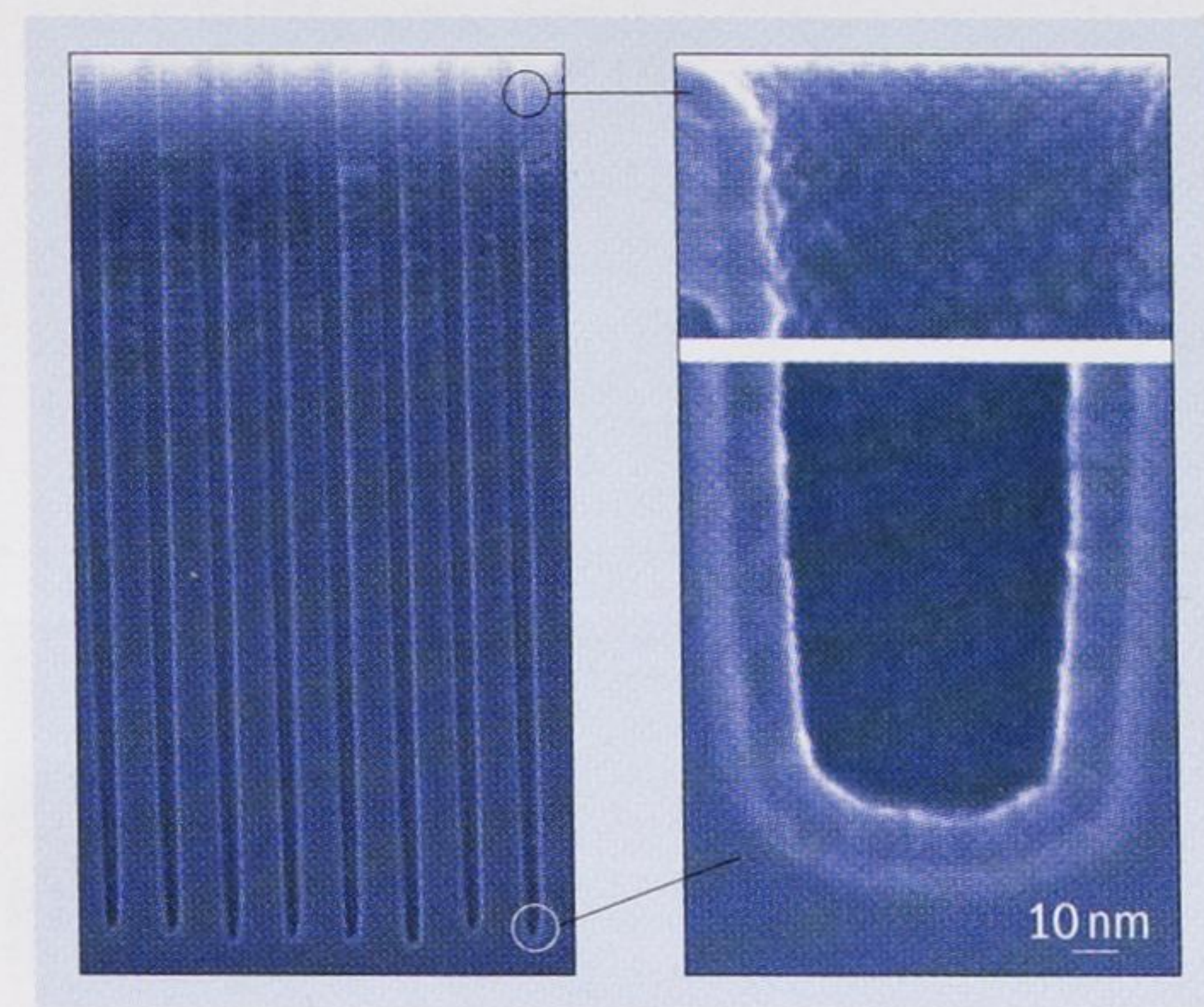
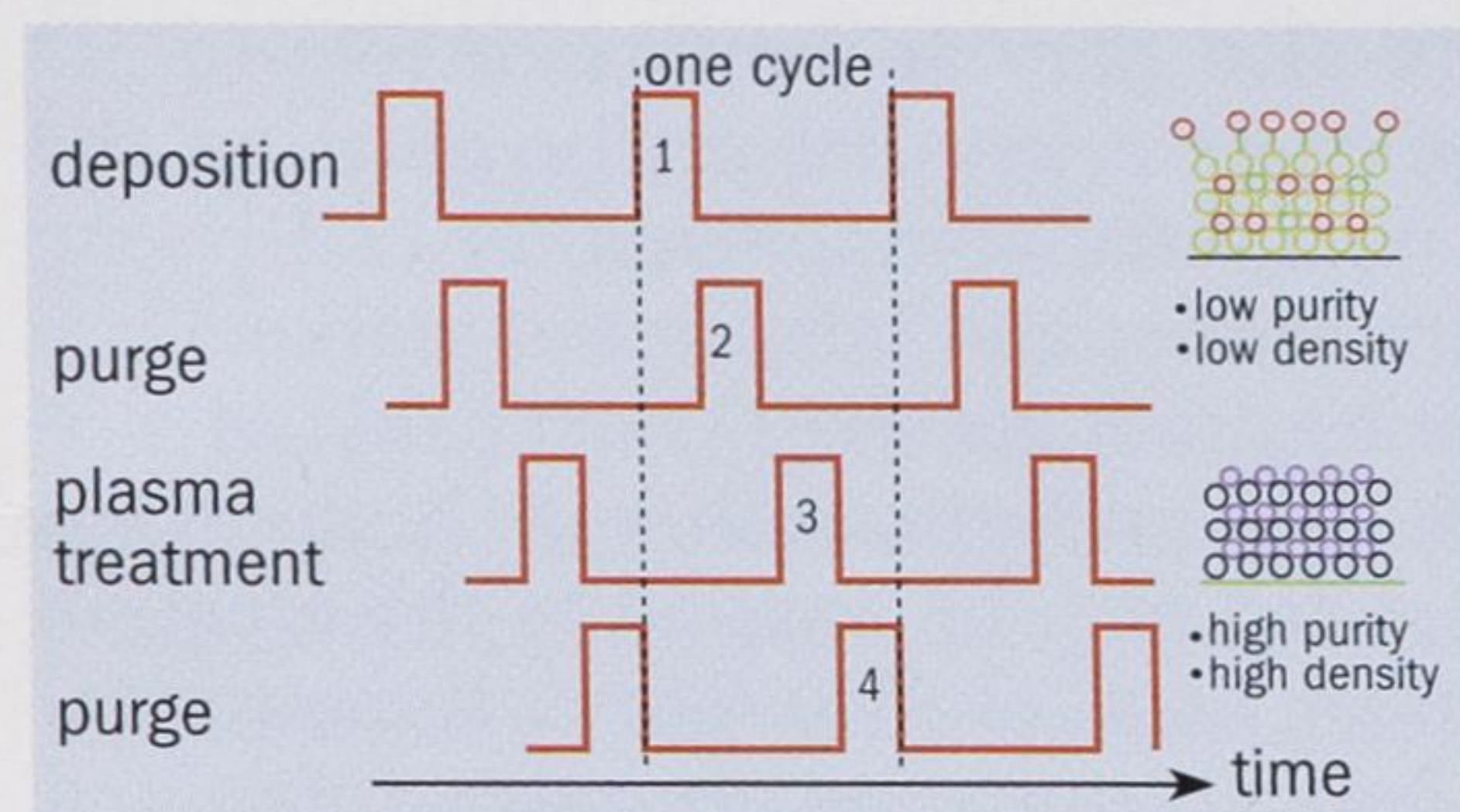
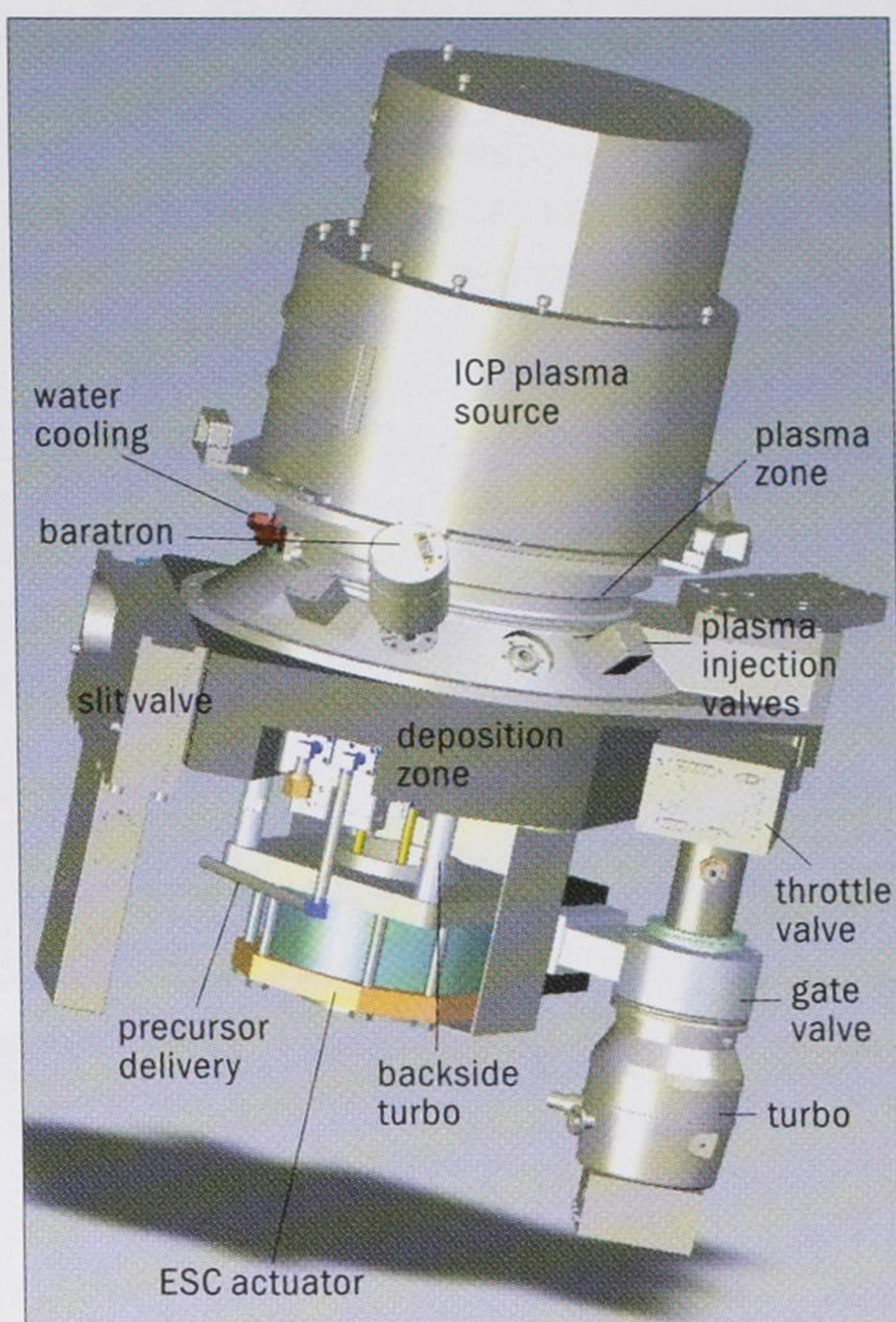


Fig. 1. (top left) Nanolayer deposition (NLD) involves the growth of a film up to 1 nm thick, followed by plasma treatment. Cycling this process produces a film of the desired thickness.

Fig. 2. (right) The Tegal Compact platform accommodates several 50–100 mm diameter wafers, or single 150–300 mm wafers. This can be configured with one, two or three NLD reactors and various front-end/loadlock options. **Fig. 3.** (bottom left) Scanning electron microscopy images reveal the excellent film coverage of the 20 nm thick TiN film in deeply etched structures. The 6.6 μm deep trenches have an upper and lower width of 160 and 90 nm, respectively.



Thin-film deposition and growth processes lie at the heart of compound semiconductor device fabrication. Methods employed include physical vapor deposition (PVD) of metal films for seed layers and interconnects, plasma-enhanced CVD for silicon nitride dielectrics, and MBE and MOCVD growth of epitaxial layers for electronic and photonic structures.

Nanolayer deposition (NLD) can now be added to this list, thanks to the efforts of ourselves and co-workers at Tegal Corporation, which is headquartered in Petaluma, CA. This cyclical deposition technique, which is somewhat akin to atomic layer deposition (ALD) and draws on CVD and MOCVD technologies can produce highly conformal pinhole-free thin films that include metals and metal nitrides. One major plus point is the relatively low growth temperatures. TiN, for example, can be deposited at just 250°C, which is an advantage when processing GaAs wafers because higher temperatures can lead to dopant diffusion in epiwafers and other undesirable effects.

NLD employs MOCVD precursors to deposit a film that is typically 0.2–1.0 nm thick. This is then exposed to a downstream plasma that converts the film into a very pure, high-density nanolayer. Further film growth to reach its target thickness results from cycling the growth and plasma treatment (figure 1). Since the underlying chemistry is based on MOCVD precursors, many materials can be deposited, including nitrides and oxides, such as TiN, TaN, TiON, ZrO₂, and metals such as ruthenium and copper.

There are many applications where NLD offers an alternative to ALD. The latter growth technology is often used for highly conformal metal and metal-nitride film growth and has four major applications, according to IBM's Hyung Giun Kim: the fabrication of diffusion barriers and adhesion-promoting layers; deposition of copper seed or other direct plating layers; growth of low-resistance, chemically and thermally stable liners in contacts and vias; and the creation of forming liners, dielectrics and electrodes in memory-storage cells.

The variety of uses makes ALD a very versatile technique. However, it does have a major, inherent drawback – self-limiting growth. Less than a monolayer is added during each deposition cycle, so many more ALD cycles are required to produce a film of a given thickness than with NLD.

Our NLD process module includes our very own direct vapor draw precursor delivery system that supplies various MOCVD precursors into the reactor. An inductively coupled plasma source is attached to a remote plasma zone, which allows plasma species to be injected into the deposition area. Precise wafer temperature control is ensured by an electrostatic chuck assembly, and turbo pumps provide high vacuum performance. Multicomponent and multilayer films can also be formed through upstream deployment of additional precursor delivery submodules.

The thickness of the monolayer is controlled by the deposition time or the growth temperature, which can be adjusted from less than 100 to more than 500°C. It's critical to get a good balance between system throughput and film quality: too thick and the quality diminishes through incomplete plasma treatment; too thin and throughput suffers because more cycles are needed.

Plasma treatment is the key to the success of NLD. As-deposited film quality strongly depends on the deposition temperature. High-temperature films are generally superior, but conformality – a measure of the thickness uniformity of a film over complex

structures, such as wafers with narrow trenches – tends to suffer. This can be combated with lower growth temperatures that improve conformality through a reduction in the precursor sticking coefficient. However, lower temperatures also increase impurities, predominantly carbon, which in turn impact film quality.

NLD avoids these problems with downstream plasma treatment. This improves as-deposited film quality by removing the impurities through reactions with the plasma species. Volatile compounds are formed instead, which help to “densify” the film. This layer can be treated quickly, which enables high throughput, thanks to the plasma’s high density – it is highly dissociated and vigorously reactive. Since the plasma is generated upstream, and because the wafer is not biased, all of the growth surfaces are treated in the same way, including the sidewalls of high-aspect-ratio features.

Film quality also benefits from our direct vapor draw precursor system. Carrier gases are not used to push the precursor into the reactor, and this reduces the total process gas flow and pressure. The upshot should be fewer particles in the process compared with conventional carrier gas designs.

We have verified our NLD tool’s capability through the growth of a 20 nm thick conformal TiN film in a very deep trench (figure 3, p27). Grown at a temperature of 250 °C, the film was pinhole free and had a

resistivity of 500 $\mu\Omega$ cm.

We believe that our NLD reactor is a very promising tool for high-brightness (HB)-LED production and we have already received an order for our Compact 360 NLD from manufacturers of these devices. Our deposition tool combines low cost of ownership with an ability to produce highly conformal films of excellent quality at low temperatures. This should help to address the grand challenges that are facing HB-LEDs, which include improvements to internal and external quantum efficiency and packaging technology. We are determined to demonstrate how our NLD process can help to overcome these obstacles.

Our tool can also play an important role in 3D packaging, which is a key driver for creating the small, highly integrated components for cell-phone handsets, smart phones and other mass-market consumer electronics products. NLD is capable of fulfilling many of the applications that we highlighted for ALD, and it can also be applied to the creation of “through silicon vias” (TSVs). Three-dimensional TSV ICs have large features and deep structures, and we look forward to the adaptation of NLD processes to the specific requirements of this new and important packaging application.

Further reading

J Crowell 2003 *J. Vac. Sci. Technol. A* **21** S88.

H Kim 2003 *J. Vac. Sci. Technol. B* **21** 2231.



About the authors

Steve Selbrede (left) is Tegal’s chief technology officer, **Michael Studendorff** (center) is the company’s NLD process development manager and **Paul Werbaneth** (right) is the senior director of marketing.



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Speedy InP chips look to boost optical network capacities

The internet is creaking under the strain of rocketing traffic, but help is now on its way in the form of faster transceiver chips that can operate within existing optical networks, reports **Roy Rubenstein**.

The burst of the internet bubble delivered a lasting impact on component suppliers to optical networks. Despite rocketing growth in internet traffic over the last few years, InP chip makers have struggled to make a profit in a market of falling prices. Instead, their focus has been on survival.

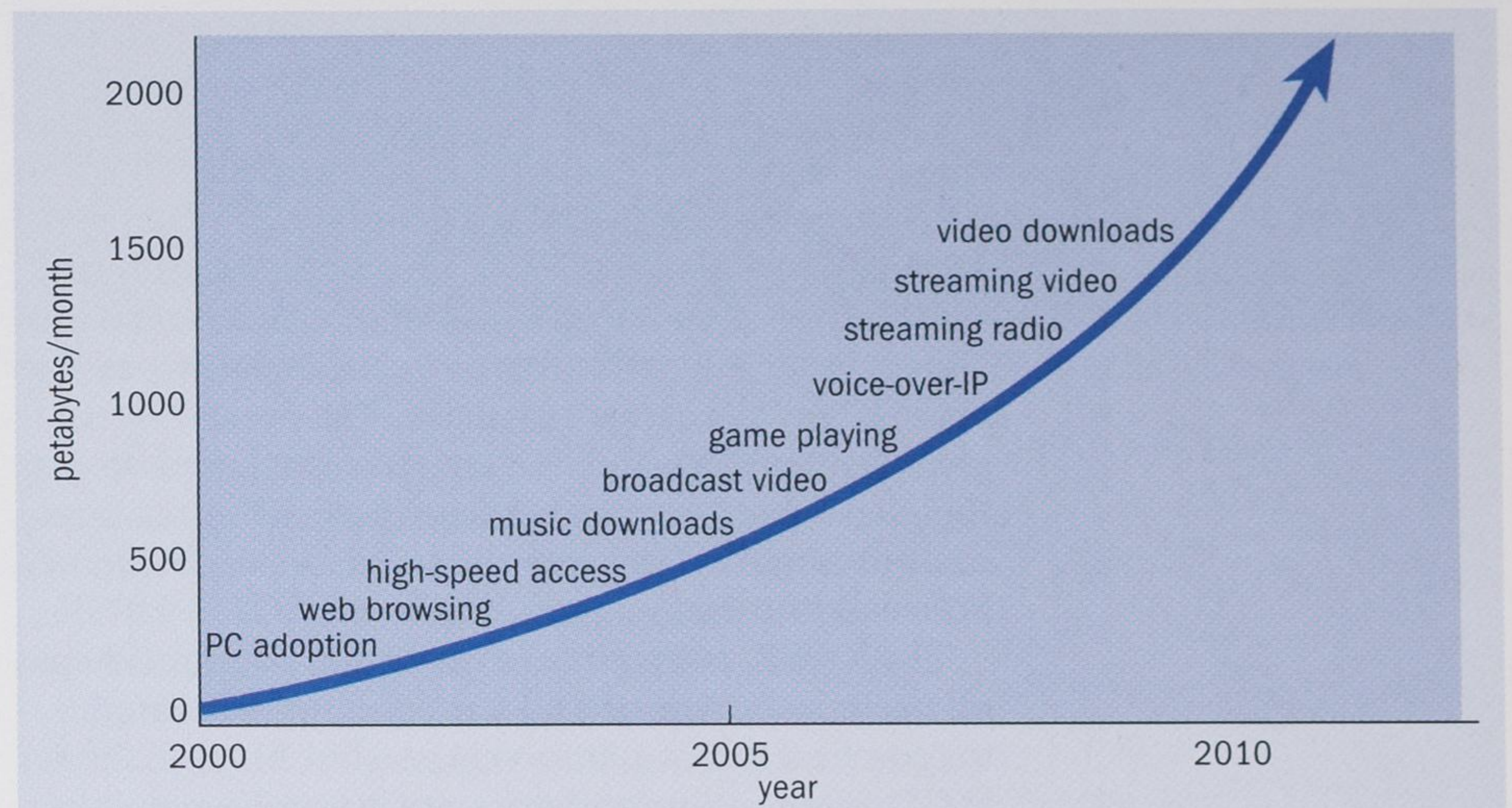
Recently though, things have been getting a little better. Pinch points in operators' networks are prompting a transition from 10 Gbit/s systems to 40 Gbit/s versions. These employ faster components with advanced modulation schemes that should also form the foundations for the emerging 100 Gbit/s transmission market.

Operators are also considering 40 and 100 Gbit/s transmission for their own backbone networks. These firms estimate that core backbone internet protocol (IP) traffic is growing at 45–65% per year. Meanwhile, online video growth is driving data center networking requirements for the emerging 40 and 100 Gigabit Ethernet standards.

Faster transmission speeds can also deliver operational and management efficiencies. Aggregating 10 Gbit/s traffic into fewer, higher-capacity links simplifies an operator's management and equipment inventory. "It results in fewer [networking] boxes and fewer interfaces, and bigger pipes are good for operations," said Glenn Wellbrock, director of backbone network technology at Verizon Business.

The trigger for 40 Gbit/s occurred in 2005, when Cisco Systems and Juniper Networks used this for the interface on core IP routers. However, volume shipments of 40 Gbit/s transponders and systems had to wait until 2007, according to Daryl Inniss, vice-president and practice leader, communications components, at market research firm Ovum.

Inniss says that the 40 Gbit/s market can be divided into two. One sector is very-short-reach (2 km) client-side transponders that link core routers to dense wavelength division multiplexing (DWDM) equipment. The other is 40 Gbit/s line-side interfaces for long-haul transmission. Last year these sectors were worth \$75 million, and they will generate \$900 million by 2012. By then, line-side interfaces will have shifted from line cards based on discrete components to transponders.



Changes in the way that the internet is used are driving the ramp in traffic, according to Ovum.

Existing 40 Gbit/s interfaces are based on the SONET OC-768 data-rate standard. However, interface options will expand, thanks to the addition of 40 and 100 Gigabit Ethernet standards that should be completed in 2010.

High-speed designs

Implementing advanced modulation schemes delivering faster speeds is challenging because there are inherently fewer photons in the optical signal. On top of this, dispersion increases with speed.

However, three advanced modulation schemes capable of handling the extra speed have emerged: duobinary modulation; and the phased-based schemes of differential phased-shift keying (DPSK) and differential quadrature phased-shift keying (DQPSK) (table 1, p30). These exist alongside the existing intensity-based non-return-to-zero (NRZ) modulation scheme used for very-short-reach 40 Gbit/s transponders.

Duobinary, the simplest of the three, involves the interference of data signals – “0s and 1s” are replaced with a three-level signal. Circuitry is relatively simple, but the technology is unsuitable for long-haul transmission, and operators such as Verizon Business favor phase-based modulation. DPSK

Table 1. Modulation schemes

Modulation scheme	Pros	Cons
Duobinary	lowest cost; best tolerance to chromatic dispersion	limited reach ~600 km
DPSK	supply chain exists; best reach performance: 1500–2000 km; 300-pin MSA transponders available	does not fit 50 GHz channels without adaptation; worst for second-order polarization-mode dispersion and poor CD tolerance
DQPSK	fits 50 GHz spaced channels; best tolerance to PMD; building block for 100 Gbit/s transmission	not the reach of DPSK: 1000 km+; supply chain limitation; more challenging to fit within a 300 pin MSA transponder

components already exist, while DPSK transponders are appearing from JDSU, Opnext and Finisar. There is growing interest in the more advanced DQPSK. This is more tolerant to dispersion, which makes it a promising building block for 100 Gbit/s systems.

DPSK encodes data using the relative phase of consecutive bits, with zeros and ones coded as “no change” or “ π -change” in phase. The optical signal is always on, unlike an NRZ-coded signal, and it’s just the phase that changes between bits. Absolute phase doesn’t need to be controlled – it is the difference between bits that matters, hence the “D” in DPSK.

The DPSK transmitters that have been produced all use a laser source and a modulator. The modulator can be a direct-phase version, but Mach Zehnder (MZ) intensity modulators are becoming popular. These are driven from the on state, through off and back to the next on state. Operated in this way, the MZ modulator becomes a very precise digital phase modulator, giving direct coding of PSK information onto the optical signal.

Recovery of the bit stream requires phase sensitivity from the receiver. The simplest way to implement this is with a delay line interferometer and balanced photodetectors. An incoming bit is delayed and interferes with the subsequent bit, which converts the phase information to intensity after the interferometer.

DQPSK extends the technique and four phases are used to represent the binary data. This halves the signalling rate compared with intensity-based, duobinary and DPSK modulations, which use 40 Gbit/s electronics. This means that DQPSK works with less demanding 20 Gbit/s electronics and the slower signalling suffers fewer dispersion impairments. It also works with 50 GHz DWDM channels, while DPSK needs to be adapted to meet such spacing.

However, these benefits come at the expense of the greater complexity of DQPSK’s transmitter and receiver. A single MZ modulator arm is used to encode the DPSK signal, but two arms are needed for DQPSK. In effect, two parallel 20 Gbit/s systems decode DPSK streams.

Bookham is developing DQPSK modulators



Engineers at Bookham’s Caswell, UK, facility have developed a 40 Gbit/s differential quadrature phased-shifted keying modulator designed to complement its tunable laser chip.

that are designed to be used with its tunable laser chips. “For 40 and 100 Gbit/s we wouldn’t say we will never [monolithically] integrate [the two], but every decibel is important,” explained Andy Carter, Bookham’s vice-president of technology. He believes that a hybrid approach also speeds time to market. The 40 Gbit/s DQPSK encoder is targeting the cost-conscious metro/regional network (100–800 km), but it can also serve the long-haul sector.

One design challenge is the radio frequency – getting 26 GHz electrical signals in and out of the device. The modulator employs on-chip detectors. “The device needs a sophisticated set-up process, such as balancing the phase in the two [MZ] arms,” said Carter. “The detectors enable this to be automated.”

US system vendor and InP integration specialist Infinera is also backing DQPSK. This February it demonstrated an InP-based 10 × 40 Gbit/s DQPSK transmitter photonic integrated circuit (PIC) in the lab. This extends the capacity of its existing PIC from 100 to 400 Gbit/s, which it claimed is the most efficient way to reduce transport costs. Infinera is backing faster rates by halving the channel spacing and switching to DQPSK, which extends the capacity of each channel.

The DQPSK PIC swaps Infinera’s existing electroabsorption (EA) modulator with a MZ in each of the array’s 10 lanes. “The structure is the same as discrete implementations of a 40 Gbit/s DQPSK modulator,” explained David Welch, Infinera’s chief strategy officer. The number of components per channel is significant with DQPSK. This drives up the optical losses, but they are compensated by the introduction of distributed-feedback (DFB) lasers.

Infinera's latest system, the ILS2, uses its existing 10×10 Gbit/s PIC and has a passive PIC that enables 25 GHz channel spacing. "It will also use in future the DQPSK modulation PICs," said Welch.

The company is now working to improve its demonstrator PIC's performance, its sensing and control, and particular DQPSK receiver PIC challenges. "There is also the 400G electronics in and out, the packaging and the silicon ASIC (application specific IC) to feed the 400 Gbit/s phase-modulated signal," said Welch.

System and component vendors are also eyeing the emerging 100G Ethernet market. At the Optical Fiber Conference, Opnext presented a paper on an integrated InP 25 Gbit/s DFB and EA modulator.

Opnext's device is part of a coarse WDM (CWDM) 100 Gigabit Ethernet transceiver design to meet the IEEE's single-mode fiber 10 km reach specification. A CWDM design was selected because the wide wavelength spacing between the four channels provides a sufficient margin for the lasers to drift with temperature without needing a cooler. Avoiding using a thermoelectric cooler reduces transceiver power consumption by up to 3.5 W.

Getting the directly modulated DFB to work at 25 Gbit/s demands a reduction of the device's overall capacitance. "For a directly modulated laser, you want as short a [laser] cavity length as possible because it acts as a capacitor, reducing the overall frequency response," said Matt Traverso, senior manager of technical marketing at Opnext.

In a DFB/EA, the laser and modulator are isolated, which improves modulation at 25 Gbit/s. Although the 100 Gbit/s standard is not completed, Opnext believes that the DFB/EA can meet the final specification while delivering a high yield.

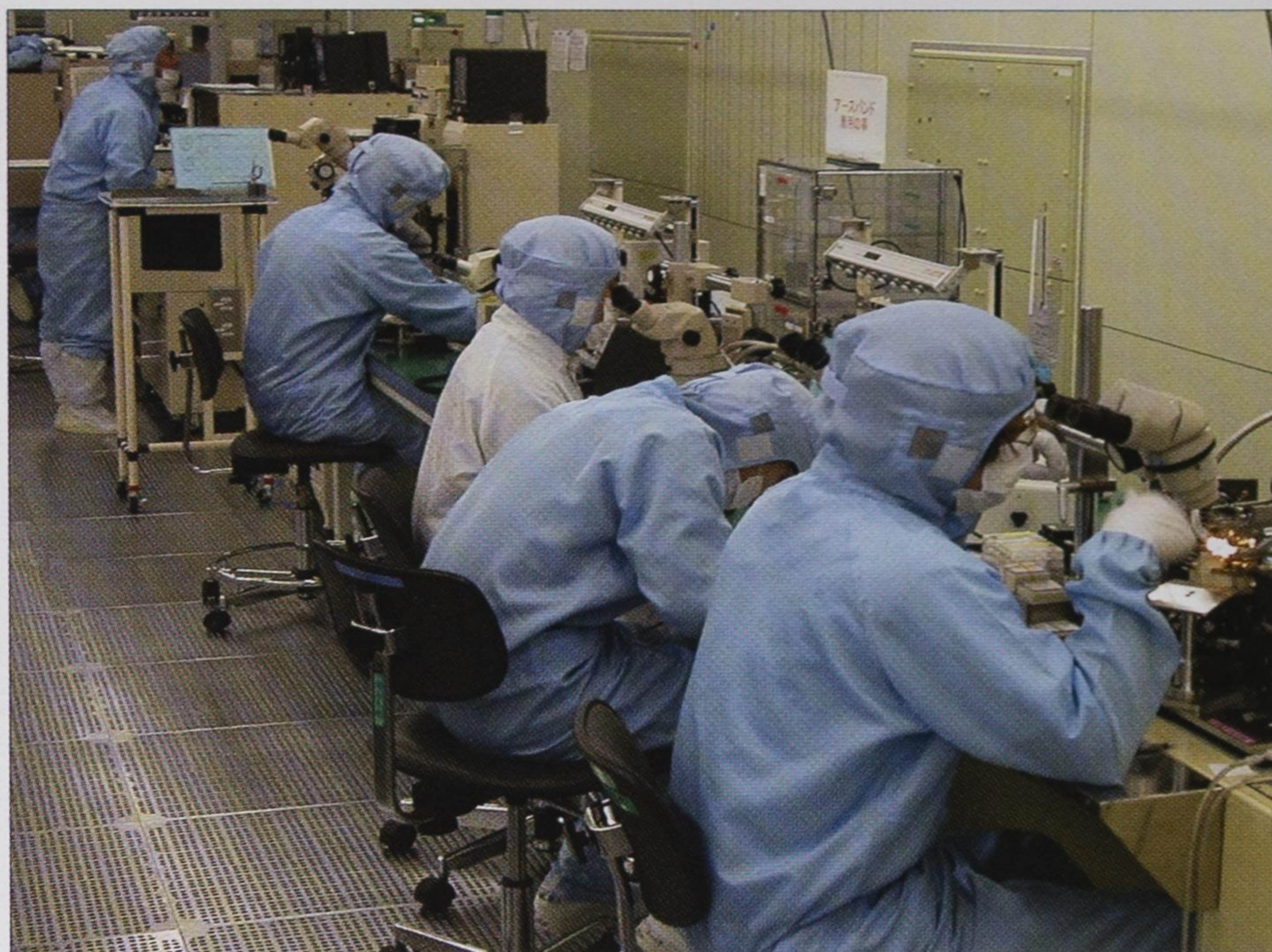
Any resulting Opnext transceiver product for 100 Gbit/s would use discrete packaging or hybrid integration – the firm has not disclosed its preferred approach. A discrete design would employ existing manufacturing techniques, but a hybrid design would have manufacturing benefits at high volumes.

In May the IEEE Task Force adopted closer spacing between channels – dubbed LAN-WDM – for the 4×25 Gbit/s specification. Some standard group members believe that the design will be easier to produce monolithically even though a thermoelectric cooler will be required. Opnext's CWDM DFB/EA does not meet the requirements, but it is now adapting its device for a LAN-WDM implementation.

Balancing detectors

U²t Photonics is one of several firms offering balanced detectors for DPSK and DQPSK. It is also working with partners to develop a balanced receiver that integrates the delay line interferometer with balanced detectors. This will simplify 40 Gbit/s transponder and line-card design.

Detectors for 10 Gbit/s requirements are surface illuminated. However, with this configuration the responsivity – the efficiency of converting the optical



Opnext is developing a coarse WDM 100 Gigabit Ethernet transceiver at its fab in Japan.

signal to an electric current – is traded with device bandwidth. This means that at 40 Gbit/s the surface-illuminated detector's bandwidth is limited unless responsivity is sacrificed. To overcome this, U²t's photodiode is edge-illuminated by a waveguide.

The detector's power linearity is also important, especially for long-haul applications that employ a preamplifier at the receiver. "Power linearity [of edge detection] is much improved," said Jens Fiedler, U²t's vice-president of sales and marketing, who revealed that absorption is well distributed across the volume of the detector.

Great care is needed to control the amplitude of the output in a balanced receiver so that it is equal in both detectors. Phase must also be balanced, so that the pair of detectors have the same phase dependencies and transit times.

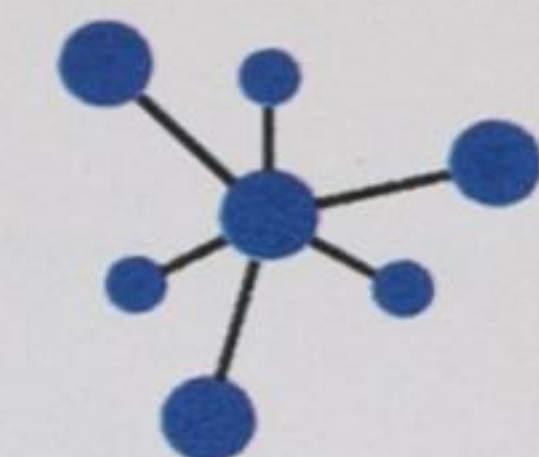
The company also offers 100 Gbit/s detectors, which are initially for use in the lab and for test equipment. "Optimizing the design for 100 Gbit/s requires slight changes," said Fiedler, such as the detector's layer structure and the electrical circuits. U²t is also sampling its 100G Ethernet detectors. "We are awaiting the market pull and the final adjustments to meet customer needs," said Fiedler.

"The client side and the line side are challenging at 40 and 100 Gbit/s," commented Ovum's Inniss. "There are so many different solutions – serial and [wavelength] multiplexed."

As a result, optical component makers are facing hard decisions, but operators are providing an incentive. Verizon Business intends to adopt 100 Gbit/s transmission as early as 2009. "The target is 2009. Will we get it? That's debatable," said Wellbrock. "We certainly want 100G as soon as possible and we're pushing the industry in that direction."

About the author

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DETECTORS

GaN shapes up for multispectral imaging

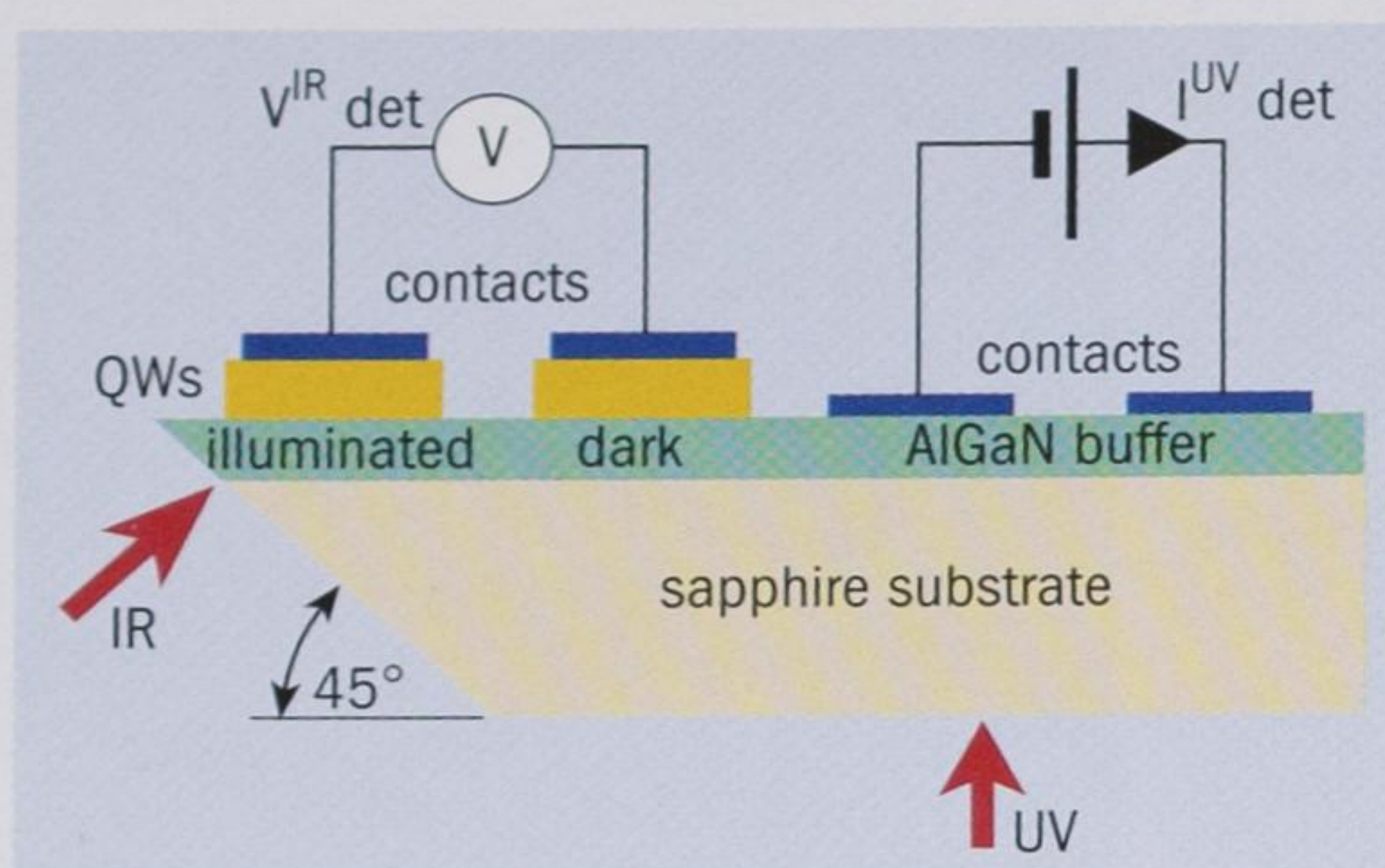
A European partnership, which involves researchers from Switzerland, Austria and France, has developed a monolithically integrated photodetector of deep ultraviolet (UV) and near-infrared (IR) light.

The device, which features an AlN/GaN superlattice for 1.4 μm detection and an AlGaIn buffer layer for sensing at 250 nm, is a step towards the development of single sensor arrays for multispectral imaging.

Using more than one sensor array for multicolor imaging has several drawbacks – bulkiness, higher costs that result from additional optical components, and a reduced robustness to mechanical shocks.

Multispectral cameras are attracting interest in various applications, according to Daniel Hofstetter from the University of Neuchâtel, Switzerland, who is a member of the research team.

UV imagers can identify a missile's exhaust plume and be overlapped with visible images to identify the weapon's location. Also, a defective high-voltage insulator in



Quantum wells provide infrared detection and the AlGaIn buffer layer detects in the ultraviolet. The ultraviolet detector employs two 50 $\times$ 100 μm Ti/Al/Ti/Au ohmic metal contacts. The infrared detector has two Ti/Au Schottky contacts of the same size.

a power station can be identified by its UV emission and picked out with an overlapping visible image that locates the position of the failed component in a circuit.

The team's detector was fabricated from a plasma-assisted MBE-grown epiwafer that featured a 250 nm thick silicon-doped

Al_{0.65}Ga_{0.35}N layer and a 40 period superlattice comprising 1 nm thick silicon-doped GaN quantum wells and 2 nm thick AlN barriers. Reactive ion etching and the addition of metal contacts completed the fabrication.

The device's UV response spans the 200–250 nm range, and current responsivity peaks at 10 mA/W. IR responsivity hits 10 V/W at 1.37 μm .

Hofstetter is confident that the team can improve detector sensitivity. "For the UV, a sensitivity of several hundred milliamps per watt is expected."

Improvements in this area will be followed by the fabrication of two-dimensional arrays for multicolor cameras. "In a later stage, a three-color detection device sensitive in the solar-blind UV, the near-visible UV and the near IR will be integrated on the same chip," said Hofstetter.

Journal reference

D Hofstetter et al. 2008 *Electron. Lett.* **44** 986.

EDGE-EMITTING LASERS

New barriers enable longer wavelengths

GaSb-based continuous-wave laser diode emission has been extended from 3.1 to 3.36 μm , thanks to the efforts of Gregory Belenky's team at the State University of New York at Stony Brook.

The increase in this type of laser's spectral coverage could enable the detection of more hazardous materials by *in situ* spectral monitoring. These gases are identified by absorption bands spanning the 3–5 μm region.

Stretching the GaSb-based emitters to longer wavelengths required a radically dif-

ferent design. It wasn't possible simply to extend the emission of existing 3.1 μm lasers because adjustments in quantum-well composition would eliminate the valence-band offset with the barrier, and ultimately hamper radiative recombination.

The team therefore turned to compressively strained InGaAsSb quantum wells and quaternary AlInGaAsSb barriers. Two variants of the new laser design were grown in a Veeco GEN-930 MBE reactor.

Edge emitters were fabricated with two and four quantum wells. The latter produced a superior performance at 12 °C and delivered a 3.36 μm output of 15 mW at 3 A.

Belenky says that the laser's characteristics could be improved through standard

optimization of the design, which would reduce charge carrier and optical losses.

The new design is capable of operating at longer wavelengths, "but we cannot see any reason to go beyond 3.5 μm ", explained Belenky. "Cascade devices work satisfactorily in this spectral region."

He revealed that the researchers are now working with Power Photonic, a small firm at Stony Brook. "We are planning to fabricate devices with improved beam quality for free-space applications, and to design and fabricate DFB lasers for infrared spectroscopy."

Journal reference

L Shterengas et al. 2008 *Appl. Phys. Lett.* **93** 011103.

EPITAXY

Hybrid growth improves gate-oxide quality

MIT's Cheng-Wei Cheng and Eugene Fitzgerald have carried out the first *in situ* atomic layer deposition (ALD) of a III-V oxide in an MOCVD reactor.

The new approach could aid development of III-V MOSFETs, which have been held back by the lack of a high-quality oxide. Over the last few years *ex situ* ALD has cut the mid-

gap interfacial defect density of GaAs oxides to 10¹² eV⁻¹ cm⁻², and this switch to an *in situ* process has delivered an additional four-fold reduction in this key figure of merit.

The researchers discarded the common oxygen source – water – in favor of isopropanol. This prevents water from degrading III-V film quality during MOCVD growth.

Using an Aixtron close-coupled shower-head cold-wall reactor, a zinc-doped GaAs layer was deposited by MOCVD at 650 °C. Isopropanol and trimethylaluminum sources were then employed to add an

11.5 nm thick Al₂O₃ film at 500 °C.

X-ray photoelectron spectroscopy revealed an absence of the unwanted oxides As₂O₃ and As₂O₅, which lead to Fermi-level pinning. However, the Al₂O₃ layer was oxygen deficient and contained an aluminum cluster.

Measurements of interfacial mid-gap by the conductance-frequency method showed a defect density of 2.5 $\times$ 10¹¹ eV⁻¹ cm⁻².

Journal reference

C-W Cheng et al. 2008 *Appl. Phys. Lett.* **93** 031902.

enabling wafer processing technology



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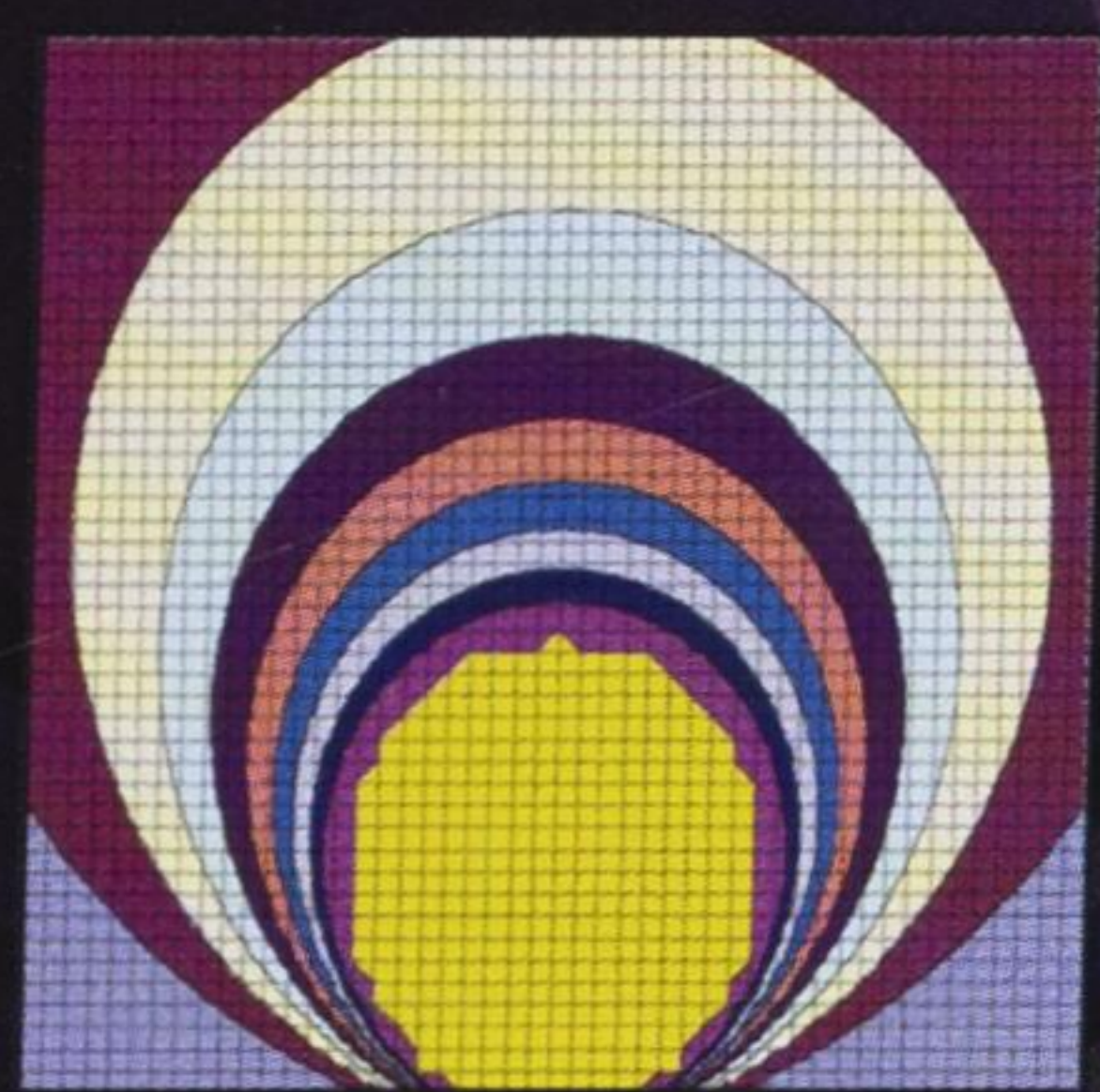
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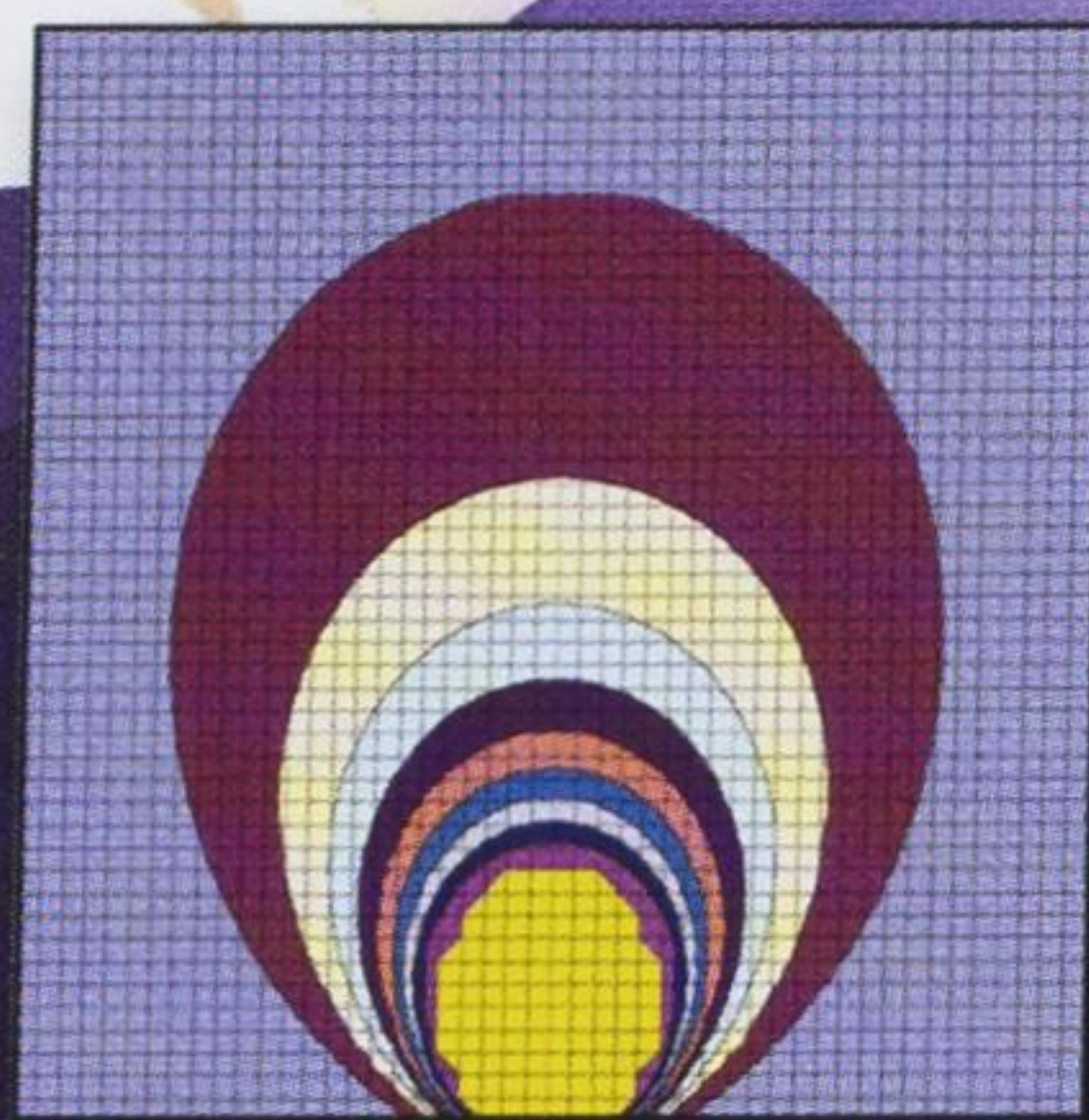
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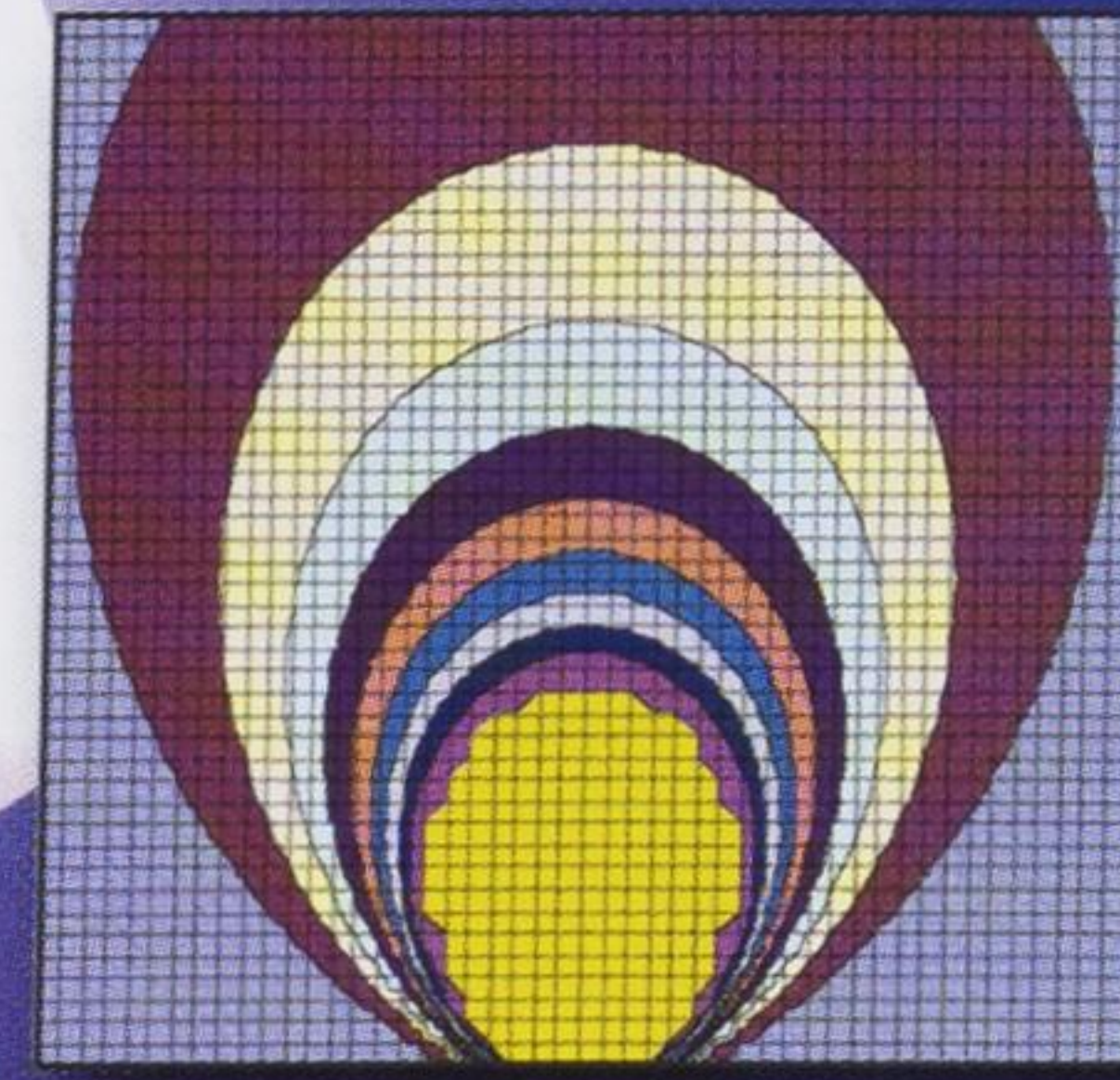
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