

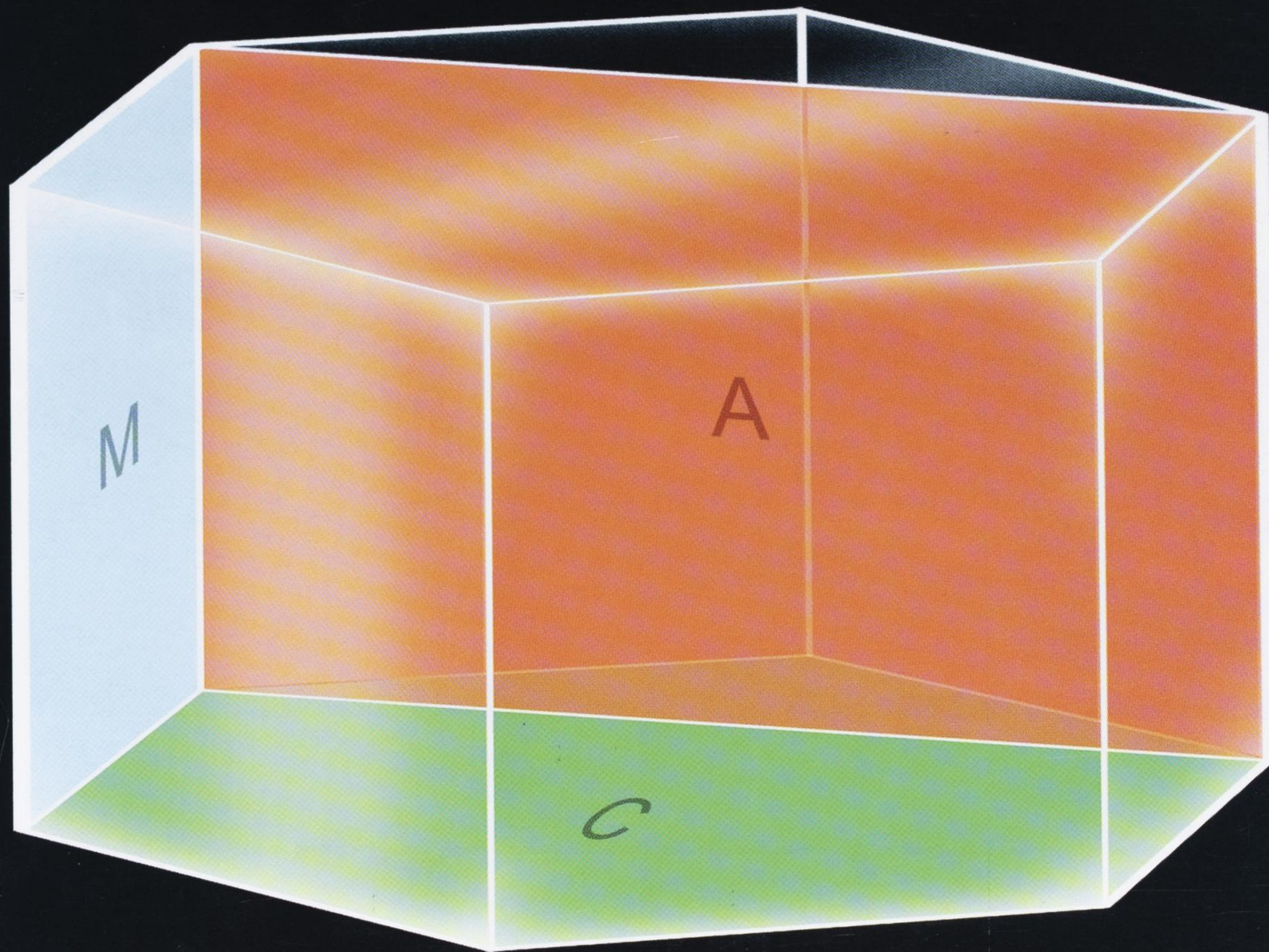
# COMPOUND SEMICONDUCTOR

December 2008 Volume 14 Number 11

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

## GALLIUM NITRIDE

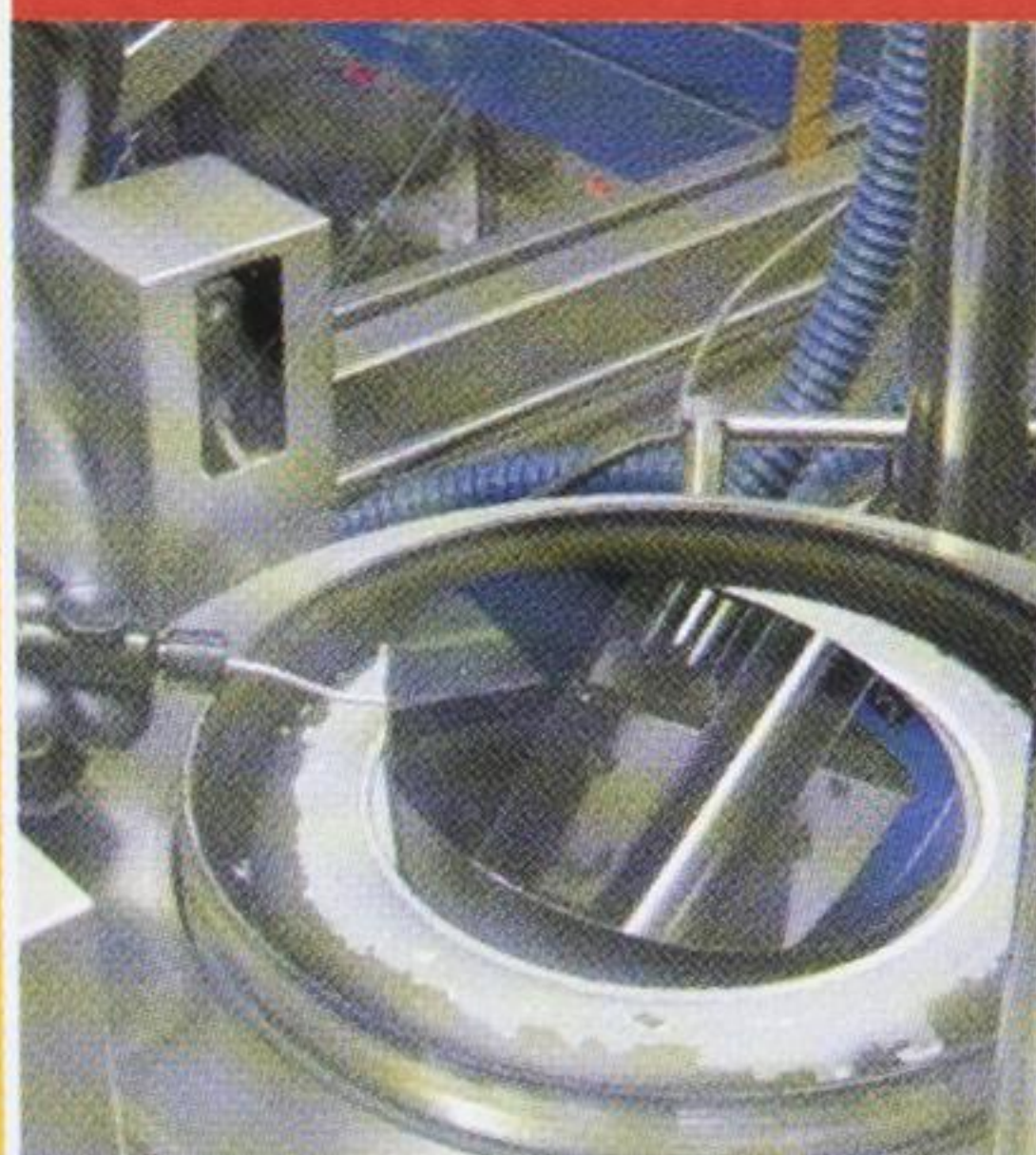
# Which plane do you want to grow on?



### PORTFOLIO

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on the cards in  
2009 p13**

### POWER ELECTRONICS



**Sizing up**  
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IMEC's high-voltage  
GaN HEMT production  
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deployment in Australia  
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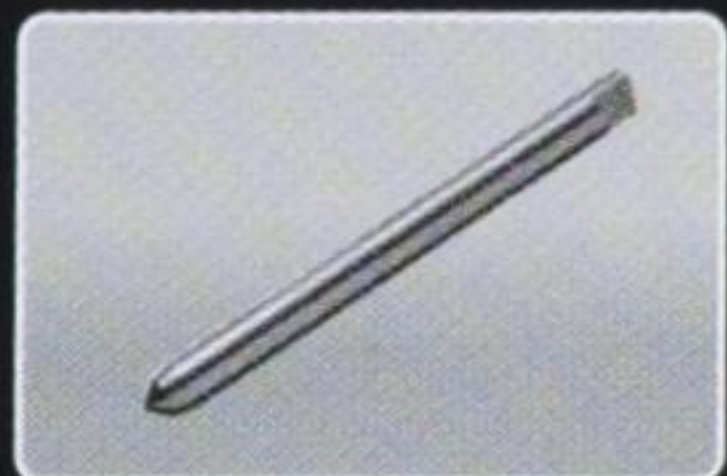


# Flawless, The Ultimate Sharpness, Tecdia Scribers

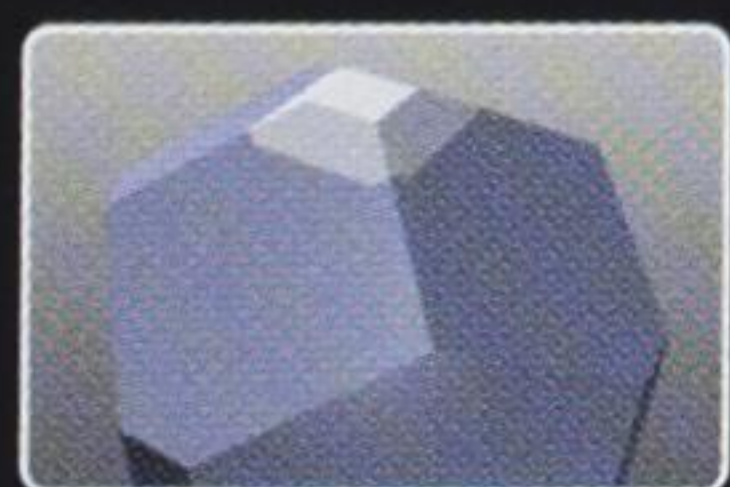
## TECDIA's Scribing Tool Selection



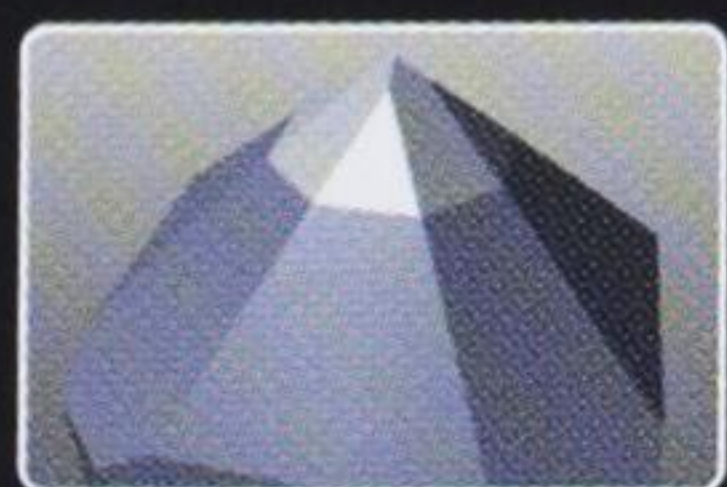
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wafer use



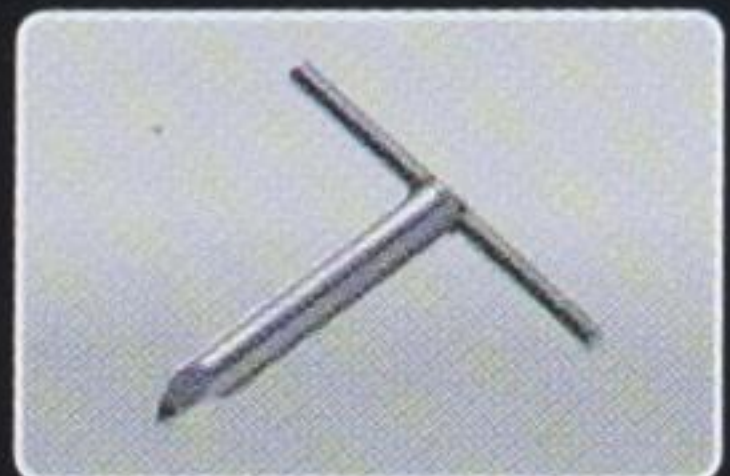
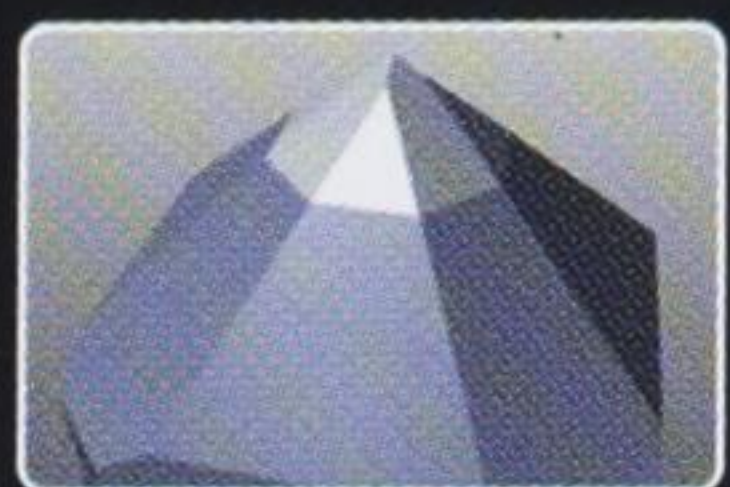
**TD-3P**  
For mostly Inp wafer use



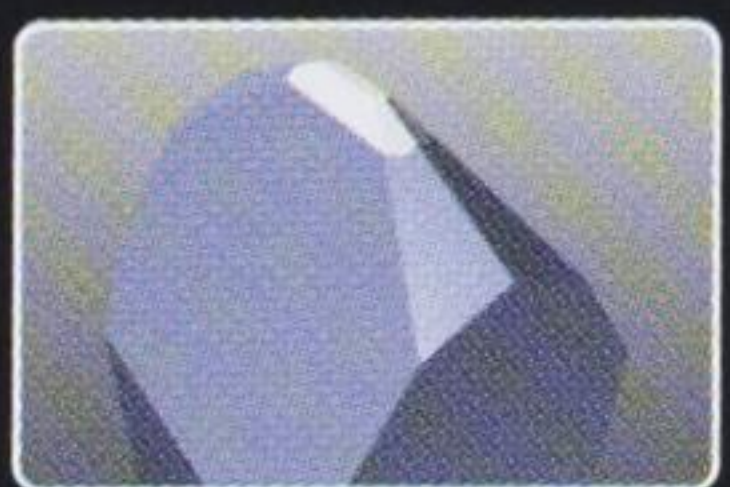
**TD-4PB**  
For mostly silicon wafer  
use, toe-cut type



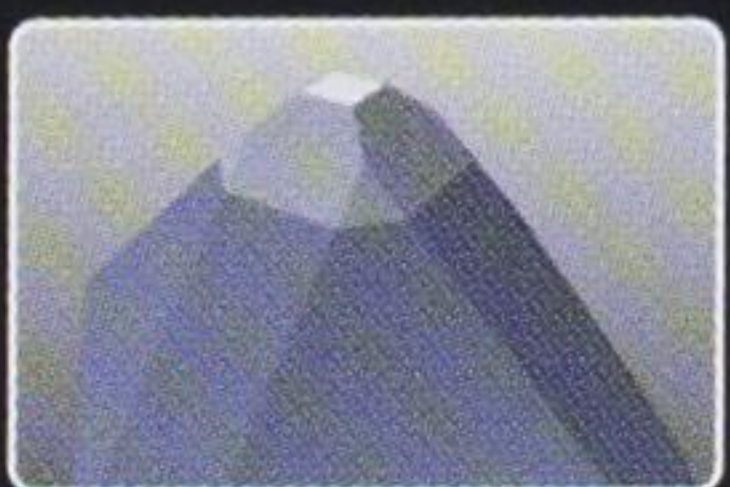
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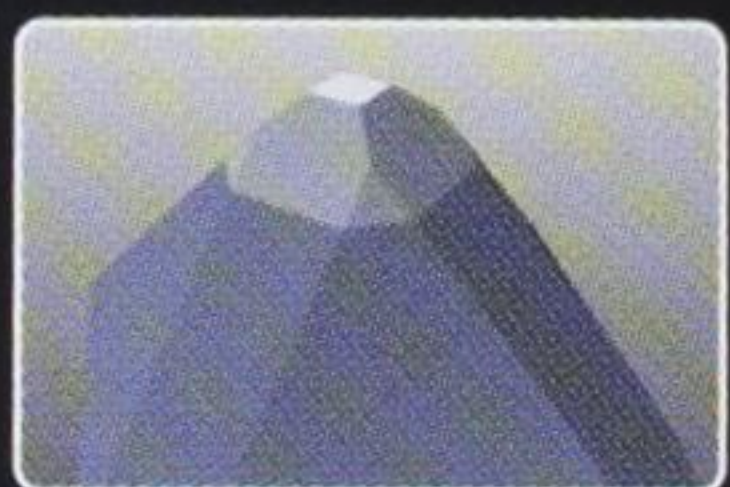
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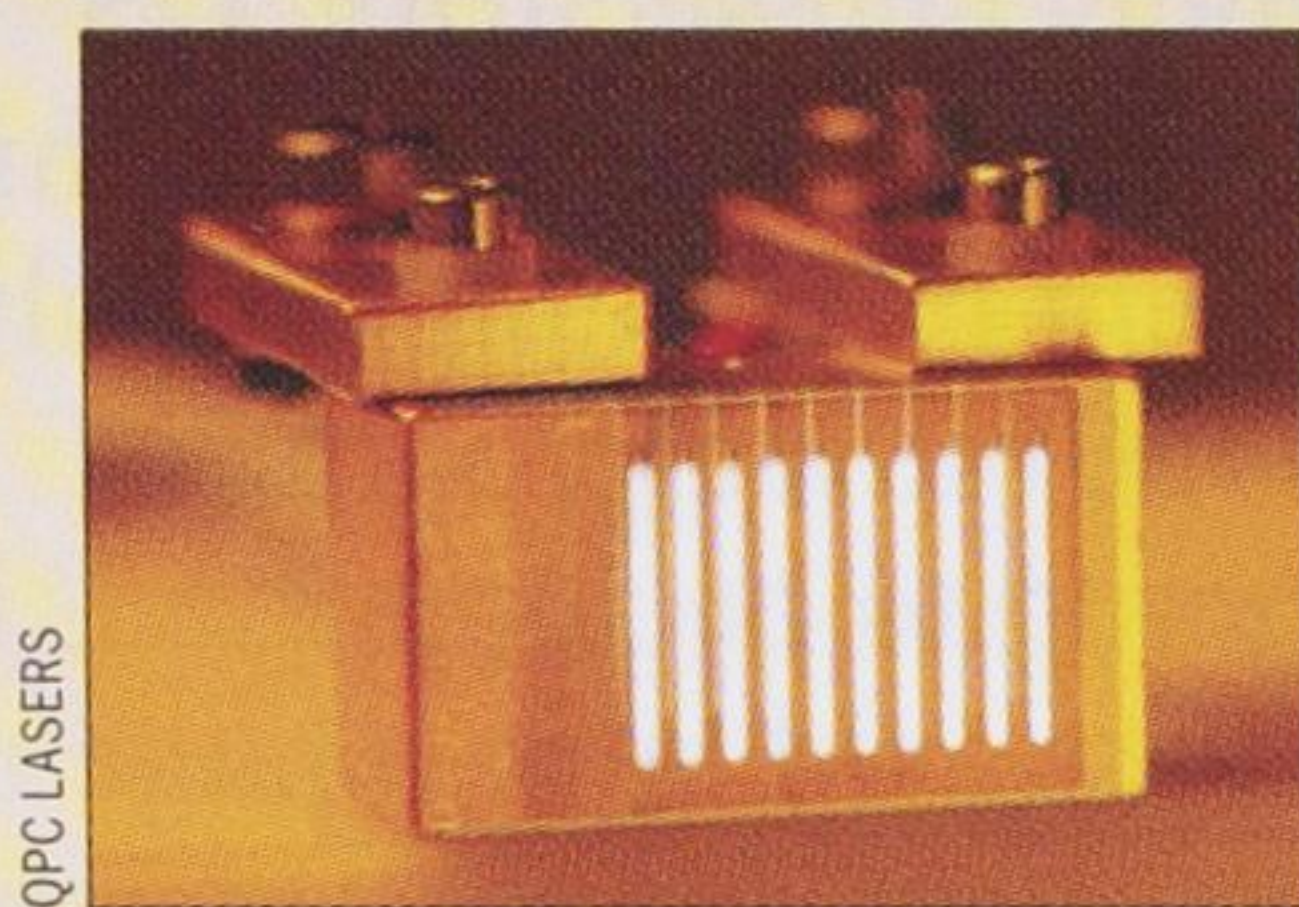
## INDUSTRY

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**6** **The Month in RFICs:** Sanken claims first GaN-on-Si inverter...Sumitomo improves bulk SiC growth rate...Nitronex teardown shows thermal impact...Anadigics sheds 100 jobs and gifts market share.

**10** **The Month in HB-LEDs:** MOCVD suppliers see order push-outs...LED backlights to grab TV share in 2009...HVPE promises high-indium LEDs.

**12** **The Month in Optoelectronics:** Finisar readies bailiffs as QPC defaults...Falling sales trigger upheaval at JDSU...Quantum-dot VCSELs further chip comms.



### **Sending in the bailiffs**

QPC Lasers' efforts to gain funding based on its surface-emitting diode lasers have failed. **p12**

**13** **Portfolio: QPC's demise heralds consolidation** In early November, QPC Lasers filed for bankruptcy and became the first direct compound semiconductor casualty of the 2008 global financial crisis. Is this a sign of things to come, or an isolated incident, wonders Michael Hatcher.

**14** **Interview: We ate with scalpels and tweezers, says Aixtron founder** Twenty-five years ago, two scientists at Aachen University in Germany joined forces with a local businessman to launch an equipment company. The result: the world's leading MOCVD tool supplier. Richard Stevenson talks to Aixtron co-founder Holger Juergensen about the early days.

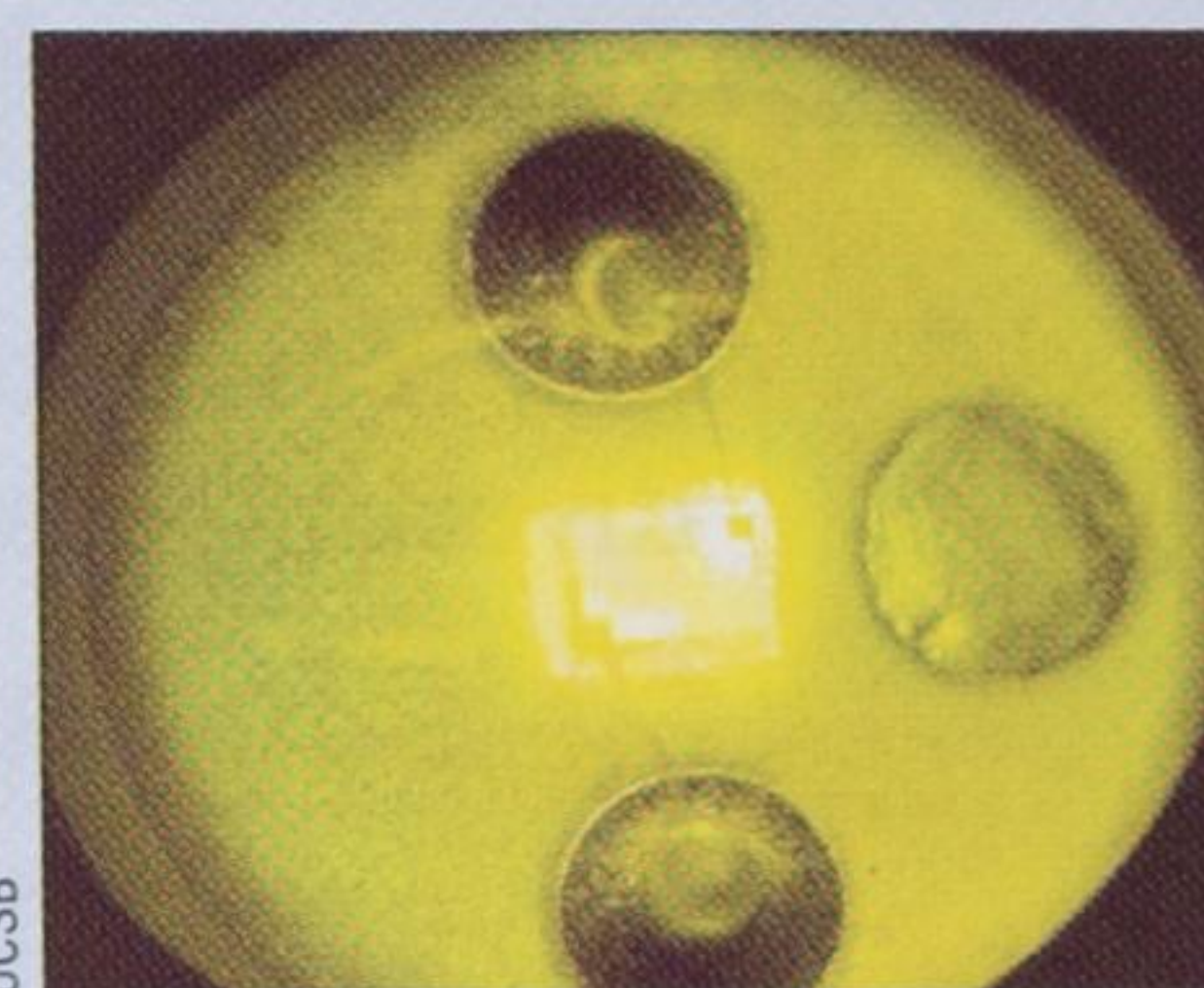


### **Looking back**

Aixtron's first location was the Aachen University technology center in Germany. **p14**

## TECHNOLOGY

**17** **Different faces fit for GaN researchers:** Researchers can choose between non-polar, semi-polar and polar substrates for nitride growth. But what are the benefits of one of these faces over another? Richard Stevenson reports from IWNS.



### **Yellow brights**

Efforts at the University of California, Santa Barbara, have extended nitride LEDs into the yellow. **p18**

**21** **Avago shrinks its chip footprint:** Surface mount processes that populate printed circuit boards with passives can now add active die too, thanks to Avago's WaferCap technology. This ultimately opens up a path to low-cost amplification for cable TV, base stations and instrumentation, says the company's Jim Roland.

**23** **IMEC enlarges nitride epiwafers:** GaN FETs grown on large silicon wafers should make a big impact in the multi-billion dollar power electronics market. They can operate at breakdown voltages of up to 800 V, offer superior switching efficiencies to silicon incumbents and give little away in terms of cost, says IMEC's Marianne Germain.

**26** **Product Showcase/Suppliers Guide Solar**

**27** **Materials Update: MBE unmask the real indium oxide** Indium oxide was thought to be a very wide-bandgap material with no carriers close to its surface. But recent results suggest otherwise and indicate that this material could be used for terahertz generation, says a team of researchers from the UK.

**28** **Research Review:** Luminescence interrogates interfaces...Nitrides deliver high ultraviolet efficiencies...Single-frequency laser hits 12 W power record.

**Main cover image:** GaN has a hexagonal crystal structure. All of today's devices are grown on the c-plane and are subjected to strong internal electric fields that hamper light emitters by pulling electrons and holes apart. However, researchers are learning how to avoid these problems by turning to growth on non-polar planes, such as the m-plane. See p17.



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# Times like these



“Interesting times”, as the Chinese curse would have it. Well, these times are looking pretty interesting at the moment – we seem to be living through what will one day be looked back upon as a period of massive global upheaval. In keeping with the sentiment of the original Chinese meaning then, at the moment many things do look worryingly “interesting”.

But, according to scholars, that infamous phrase also carries a more upbeat interpretation. They believe that it is derived from another Chinese saying, which translates as: “Heroes are made over turbulent times”.

My knowledge of Chinese proverbs is as sketchy as the next person’s, but in my book it is indeed in times of adversity that true leaders emerge – which applies in any sphere, whether it is business, family life or sport.

Out of great adversity, some huge achievements have arisen. Plans for the Hoover Dam were well under way when the US was hit by the Great Depression of the 1930s, but its construction was accelerated rapidly by diverting cash into the project to provide employment. You could even

“It is in times of adversity that true leaders emerge”.

argue that economic and political shocks are necessary to bring about sweeping change.

As an energy project first and foremost, the Hoover Dam resonates with one of today’s big questions – energy supply and security. US president-elect Barack Obama has clearly signalled his intentions in this area, to follow the lead of the \$2.6 billion investment of venture capitalists in the “clean-energy economy” with a 10-year, \$150 billion program.

Leaving aside how that level of investment is going to be supported, it is clear that advanced semiconductor technologies should have a huge role to play. In Obama’s New Energy for America document, improvements to energy efficiency feature heavily. With an aim to increase the energy efficiency of all federal buildings by 40% within five years, expect to see the US government buying lots of LED-based lamps shortly.

With other plans for investment including a digitized electricity grid and widespread use of hybrid electric vehicles, the high efficiencies of our community’s wide-bandgap semiconductors are sure to come to the fore. Commercial-scale renewable energy is certain to feature some CPV, at least in the sunniest of the US states.

It isn’t just the great leaders who emerge in times like these. Great fortunes are also won, often through the success of new technologies. “Interesting” just got interesting.

**Michael Hatcher** *Editor*

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C4 ☐ III-Vs: antimonides

C5 ☐ II-VIs

C6 ☐ SiC

C7 ☐ SiGe, SOI, epitaxial oxides, other silicon heterostructures

C8 ☐ Other (please specify) \_\_\_\_\_

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D2 ☐ InP ICs or discretes

D3 ☐ Wide bandgap ICs or discretes

D4 ☐ Devices employing SiGe, SOI or other silicon heterostructures

D5 ☐ Telecom laser diodes

D6 ☐ Non-telecom laser diodes

D7 ☐ VCSELs

D8 ☐ LEDs

D9 ☐ Solar cells

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D12 ☐ GaN laser diodes

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## LEGISLATION

# EU seeks 2010 incandescent bulb ban

Government ministers from all of the European Union (EU) member states have come together to call for the rapid completion of a plan to ban incandescent light bulbs.

Politicians from 27 member countries emerged from a Transport, Telecommunications and Energy meeting asking for a ban on the least efficient bulbs from 2010. In a statement they ask the European Commission "to submit a draft regulation in 2008 that will launch a gradual process of phasing out, until incandescent lamps and all of the worst-performing lights are banned."

The EU's current draft proposals give two timescales for adoption, with the more aggressive of these phasing out incandescent

lighting in four years. The more cautious framework suggests a nine-year phase-out, with 100 W-plus output incandescents being banned by 2009 and bulbs below 25 W output ultimately being banned in 2017.

When *Compound Semiconductor* asked number-one European LED manufacturer Osram its response to the politicians' statement, it re-emphasized its commitment to the proposal of the European Lamp Companies' Federation, ELCFED. Claiming other multinationals with strong interests in LED production as members, including GE and Philips, ELCFED is squarely behind the slower phase-out plan.

As well as banning incandescents, the EU

proposal advocates the removal of halogen lamps from the market. The scenario with the highest potential level of energy savings – 78 TWh/year, estimated as equivalent to 34 Mt of CO<sub>2</sub> emissions annually – suggests banning all halogens, as well as the least efficient compact fluorescent lamps.

At the other end of the spectrum, LED-based luminaires are highlighted in the EU's most efficient category, which demands 111 lm/W efficiency from a 700 lm lamp. This is perhaps optimistic, however, as even the winners of the US Department of Energy's 2008 Lighting for Tomorrow solid-state lighting prize achieved just 72 lm/W efficiency at best.

## PHOTOVOLTAICS

## III-V solar deals ready for 2009 build-out

Solar Systems has opened the test plant for the world's largest planned concentrator photovoltaic (CPV) installation in Australia, days before being challenged for that crown by the sector's biggest European deal.

The AUD10 million (\$6.8 million), 140 kW CPV research site in Bridgewater is the first step in the AUD420 million, 154 MW large-scale site due for commissioning in 2013.

Meanwhile, SolFocus has secured an €80 million (\$103 million) deal to provide more than 10 MW of systems in Spain.

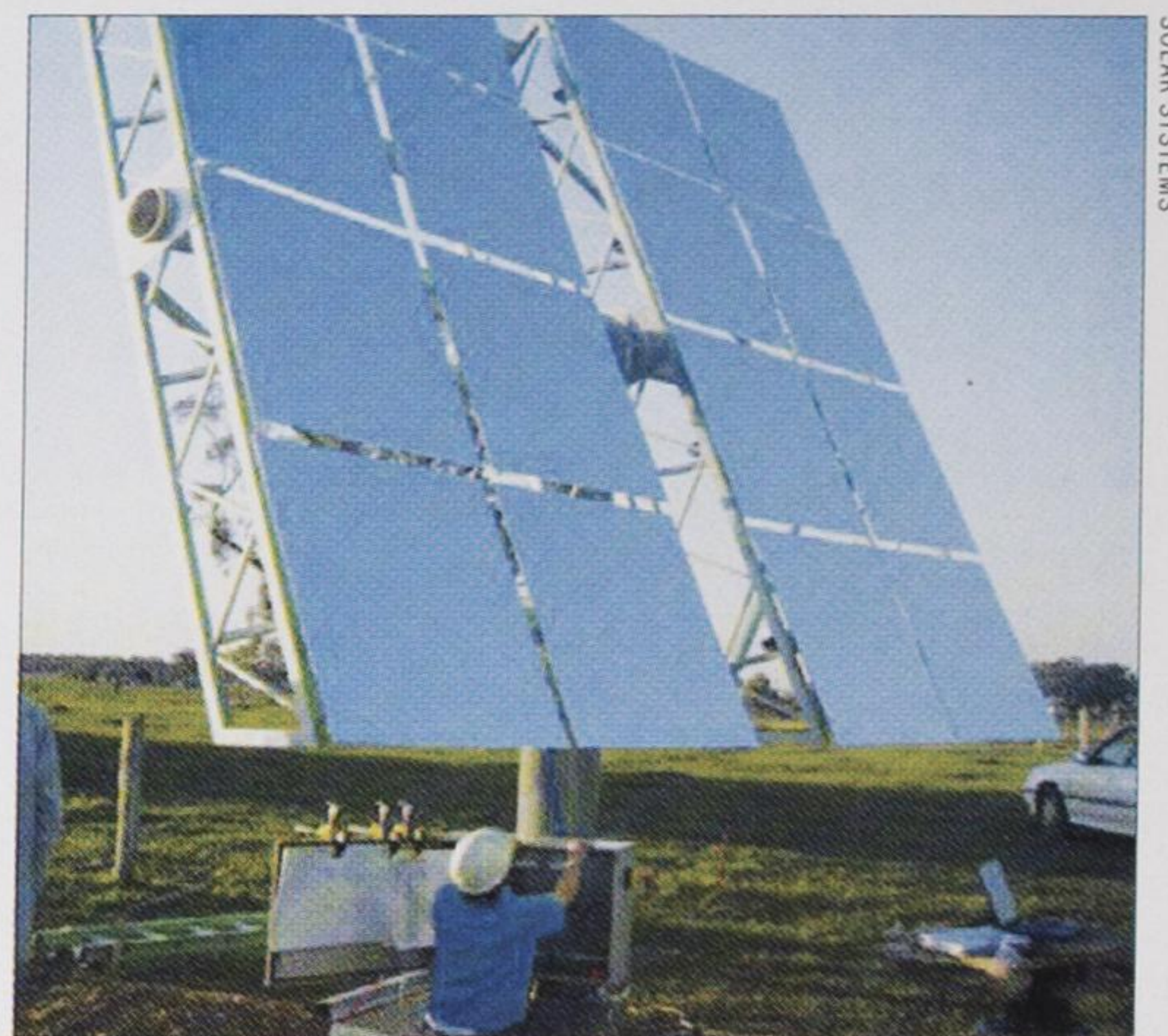
The Californian system maker points out that this will be the largest CPV deployment

in Europe and intends to complete installation by the end of 2010. In contrast, Solar Systems' planned ramp sees only 2 MW built at the 154 MW site in 2010, making SolFocus likely to overtake it as the provider of the world's largest CPV project.

Construction on Solar Systems' landmark station will begin in 2009, with the support of its power company backer TruEnergy and the Victoria state government.

SolFocus is also now primed to undertake its European deal with the little-known company EMPE Solar through 2009, after completing its 0.5 MW allocation at the experimental ISFOC CPV installation.

This momentum is good for GaAs-based cell producers like Emcore and Spectrolab, who supply SolFocus, while Solar Systems has an exclusive agreement with Spectrolab.



**Solar Systems has opened its heliostat system test facility,** paving the way for construction to commence on its large-scale 154 MW plant in 2009.

## CELLPHONES

## Nokia forecast rattles GaAs chip stocks

Nokia, the world's leading maker of cell-phone handsets, and therefore one of the world's largest consumers of GaAs chips, has shaken the industry with its downbeat forecast for 2009.

The Finnish company, which accounts for around 40% of all handsets sold, is now expecting total industry volumes to peak in 2008 and decline next year. Although Nokia's is only a preliminary estimate, and the company did not detail how much of a slump it anticipated, the impact on GaAs manufacturers was immediate.

Shares in Skyworks Solutions, RF Micro Devices and TriQuint Semiconductor, whose fortunes are strongly linked to Nokia and the other leading cell-phone makers, fell by between 10 and 20% as investors digested the news.

If Nokia's prediction is accurate, 2009 would see the first annual decline in handset sales since 2001 – when there was a 3% drop. Because GaAs-based power amplifiers and light-emitting diodes now feature in virtually all cell-phone handsets, the market for compound semiconductor devices is strongly linked to Nokia's forecast. And, since 2001, when around 400 million handsets were shipped, the market has trebled in size to a remarkable 1.2 billion units – with GaAs companies reaping the benefits.

In the current quarter, usually the strongest of the year, Nokia expects 330 million unit shipments. Although this is below expectations, it will still represent a sequential increase from the figure of 310 million recorded in the third quarter. Nokia reckons that 1.24 billion handsets will sell in 2008 altogether, up nearly 9% from the 1.14 billion registered in 2007.

Prior to this announcement from the company, GaAs manufacturers had said that it was too early to tell what impact the global financial crisis would have on the compound semiconductor industry. Nokia's forecast is one of the first pieces of concrete evidence for makers of GaAs components, and will no doubt have a ripple effect throughout the rest of the industry supply chain.



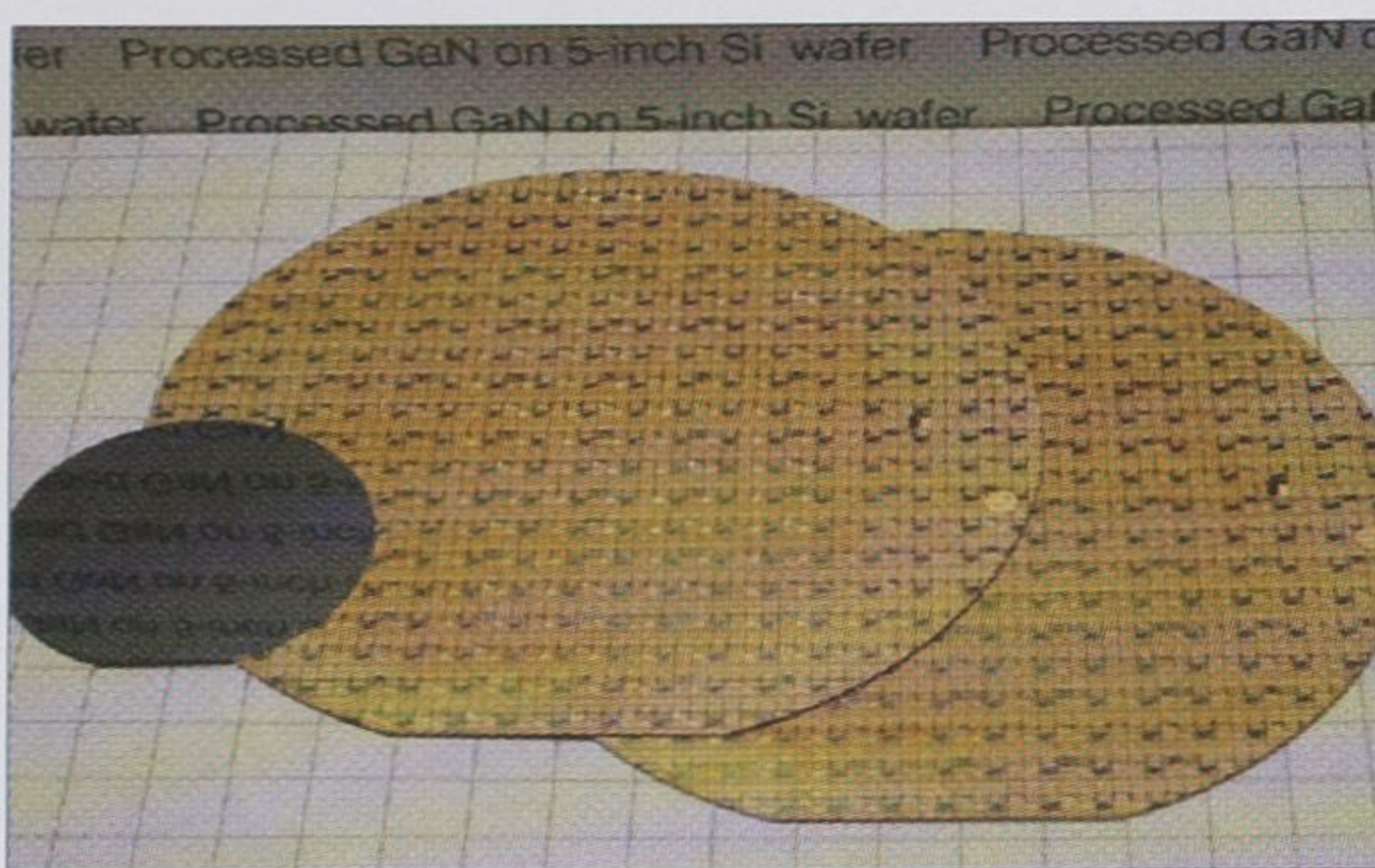
## POWER ELECTRONICS

# Sanken claims first GaN-on-Si inverter

Sanken Electric has produced what it says is the first power supply circuit to use GaN-on-silicon transistors, which were produced using its own epitaxial expertise.

The Japanese company has produced normally off field effect transistors (FETs) with a 157 mm gate width, a 1 V threshold voltage and on-resistance of 72 mΩ. "Gate leakage current is about four orders of magnitude smaller than conventional normally on type FETs," said Hirokazu Goto, manager of Sanken's GaN development group.

The company has exploited its GaN FET's 800 V breakdown voltage in a demonstration inverter circuit, proving its effectiveness for power applications. Goto says that these devices are in development, with the aim of reducing the chip size to one-seventh that of silicon MOSFETs, but are targeted for commercialization in the near future.



**Sanken's 5 inch processed GaN-on-silicon FET wafers** should offer more-economical power electronics than competing GaN devices made on 2 inch sapphire substrates (shown alongside).

Sanken deposits material on the 5 inch silicon wafers by MOCVD, with multiple GaN/AlN buffer layers easing tensile stress on the final GaN film. "We produced non-

pitted and crack-free epilayers," Goto said. "The thickness of the total epitaxial layers could be increased to more than 5 μm."

The team's GaN-on-silicon epitaxial expertise comes from an LED manufacturing approach that Sanken developed in 1995. It is using GaN's high breakdown field to make chips smaller and more efficient than silicon competitors.

Most other firms working on exploiting the advantages of GaN for power devices are using SiC or sapphire substrates, which are more expensive than silicon. However, recently a number of groups have announced progress in GaN-on-silicon technologies and may be able to challenge Sanken's inverter claim. These include US power electronics giant International Rectifier, European research center IMEC (see feature, p23) and GaN start-up Velox Semiconductor.

## WIDE-BANDGAP MATERIAL

## Sumitomo improves bulk SiC growth rate

Sumitomo Metal Industries has unveiled a new solution-growth method that it claims produces bulk SiC twice as quickly, and with fewer defects, as conventional sublimation methods.

The Japanese steel-making specialist has extended its high-temperature material production expertise to make 6 inch diameter SiC wafers and reached growth rates of more than 200 μm/h. Sumitomo has successfully produced 5 mm thick, 2 inch diameter single crystals and is aiming for 10 mm thickness by March 2009 to allow wafer slicing.

The method involves dipping a seed crystal into a melt that it reticently describes as "a high-temperature solution of metals such as silicon and titanium". The seed is then rotated when pulled out of the solution, in a similar manner to the Czochralski process used for making bulk silicon.

"We can improve the crystalline quality of SiC even using a low-quality seed," Kazuhito Kamei, who is responsible for Sumitomo's SiC development, told *Compound Semiconductor*. "We feel that our process could be an alternative to physical vapor transport and chemical vapor deposition processes, which seem to have some problems in controlling quality," he said.

Kamei says that Sumitomo is targeting the 6H, 4H and 3C crystal polytypes of SiC,

with typical dislocation densities below  $10^4 \text{ cm}^{-2}$  and getting ever lower. Sumitomo has been working on a SiC solution-based crystal growth method with Japan's New Energy and Industrial Technology Development Organization since 2000. It first produced 2 inch diameter material in 2004 and 6 inch in 2006.

The two are working to help to reduce SiC costs for the power semiconductor market, and say that the method is compatible with epitaxial layer growth. Kamei points out Sumitomo's involvement in the power electronics market through its subsidiary SUMCO, which was formed by the merger of its silicon wafer business with Mitsubishi's. SUMCO is now the second biggest silicon wafer supplier in the world.

## CHIP DESIGN

## Nitronex teardown shows thermal impact

Those looking to exploit the availability and comparatively low cost of Nitronex's GaN transistors should pay attention to the chips' thermal management measures.

That's the upshot of the teardown of two Nitronex GaN-on-silicon HEMTs by Canadian laboratory MuAnalysis. "It's easy to break these transistors, not with high currents, but by affecting their heat management," Martine Simard-Normandin,

president and CEO of MuAnalysis, told *Compound Semiconductor*.

The Ottawa company has performed teardowns on plastic-packaged 5 W, 3 GHz and 18 W, 3.5 GHz HEMTs, which were purchased for \$10 and \$40, respectively. It discovered that the comparatively low thermal conductivity silicon substrate features through-silicon-vias covered with silver-filled epoxy adhesive on the transistor backside. Such thermally conductive metal-filled epoxies are used to help transport heat away from temperature-sensitive components.

MuAnalysis also performed emission microscopy on the GaN HEMTs under

normal operation and observed photoluminescent spots coming from the device. The emission was often brightest from the source side of the device, which Simard-Normandin suggests is simply due to higher current levels passing through this region. Light emission is a clear indication of energy being lost from the RF signal ultimately produced from the transistor.

MuAnalysis' primary occupation is performing reliability testing and failure analysis under contract to chip manufacturers. Simard-Normandin sees teardowns as a way of increasing MuAnalysis' knowledge of GaN technology to serve developers.



## MANUFACTURING

# Anadigics sheds 100 jobs and gifts market share

GaAs chip maker Anadigics has laid off 15% of its workforce, as its competitors snatch market share away from the company on the back of its manufacturing misfire.

On November 5, 100 employees learned that they would be leaving the Warren, NJ, based company's global operations within days. The head-count reduction will focus on areas previously expanded to meet anticipated levels of output, a spokesperson for Anadigics told *Compound Semiconductor*.

The company emphasized that no product lines or ongoing research efforts were being lost along with the redundancies. The move will cost Anadigics up to \$2.4 million in severance payments, but will contribute up to \$20 million in annual cost savings.

"This was a difficult decision because of the impact that it has on people," said Gilles Delfassy, chairman and interim CEO, "but was necessary to return to profitability."

"In our efforts to accommodate the unprecedented demand for products, we created increasing inefficiencies in our manufacturing operations, which have further limited our output," Delfassy said, commenting on expansion plans put in place under his predecessor, Bami Bastani. "We are going for a complete overhaul of our operations to improve our execution and productivity."

The move comes as the company slid backward from peak sales of \$80.5 million in the three months to June, to \$58.1 million in the quarter ended September. This figure is \$4 million below its previous guidance, thanks to problems in Anadigics' broadband business piling up on top of lost revenues from handset producers.

The company's high-profile wireless LAN products previously earned it sole supplier status with Intel, but this is where the latest problems are focused. Intel has delayed some orders from Anadigics and has added a second source of power amplifiers for its latest Centrino 2 platform.

Despite recording a \$15.5 million loss for the quarter, the chip maker remains confident that next year it will return to the profitability it lost this quarter. It is now targeting handsets due for production ramps in 2009.

Meanwhile, Skyworks Solutions has stormed to a near-doubling of annual profit as it reaps the benefit of Anadigics' difficulties. "We're ramping production with customers who experienced some supply chain disruptions a year ago," said CEO David Aldrich. "We are in fact being awarded that business because we are able to deliver."

Through 2007 and 2008 Skyworks has underlined this ability by improving profit margins six quarters in succession to return \$111 million net profit for its fiscal 2008. The annual total revenue of \$860 million that produced this profit has also jumped 16% from \$742 million in 2007, which itself produced a \$56 million net profit.

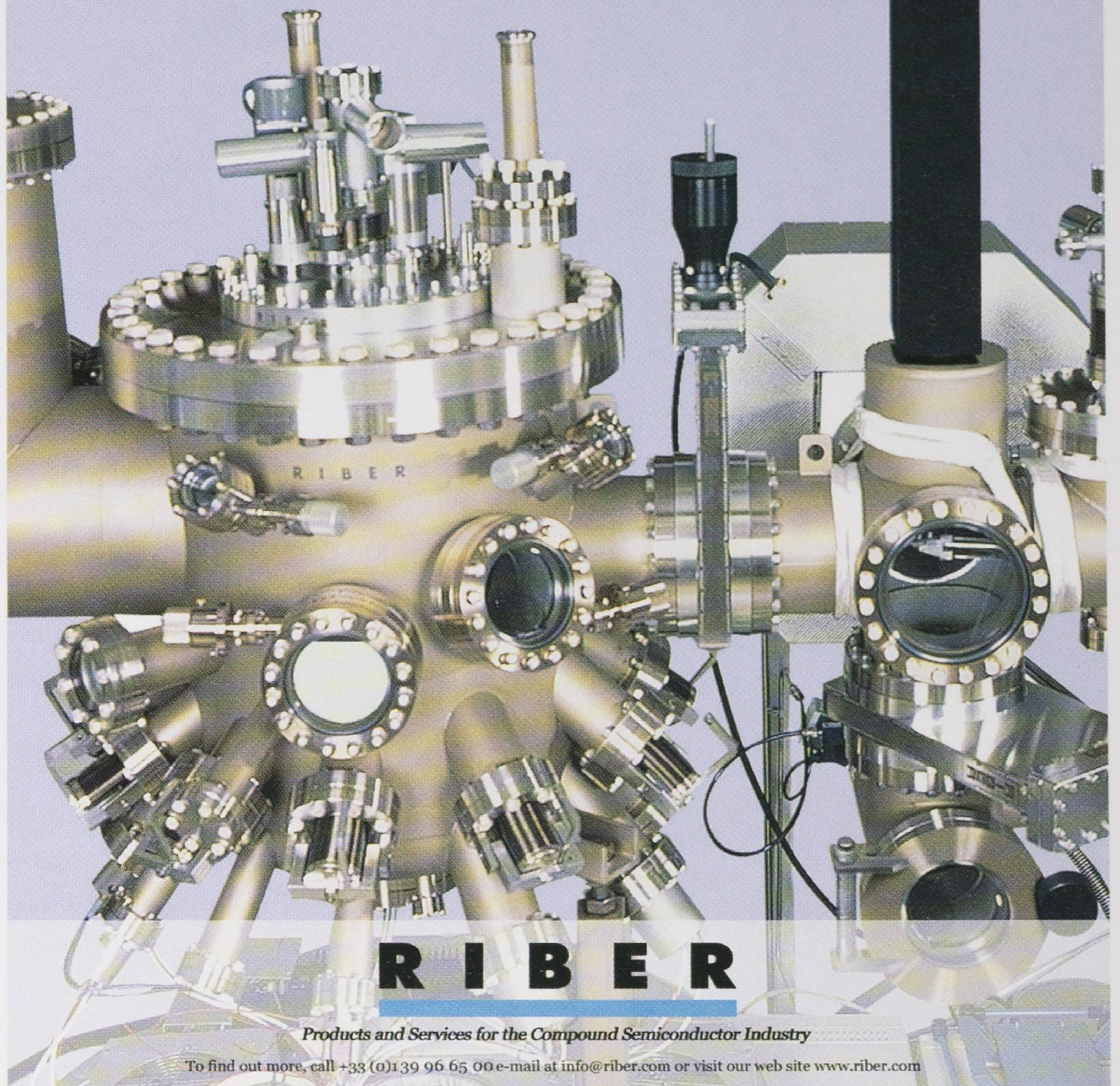
RF Micro Devices also improved its profitability in the September quarter, after growing its market share – including at

Samsung, the principal handset maker that shifted its business away from Anadigics – and having a leaner cost profile. In the three months that ended on September 27, the Greensboro-based firm posted total sales of \$271.7 million, up 13% sequentially. And although RFMD posted an official operating loss of \$19 million in the latest quarter, a large portion of that was attributed to the cost of implementing its own restructuring, which is now complete.

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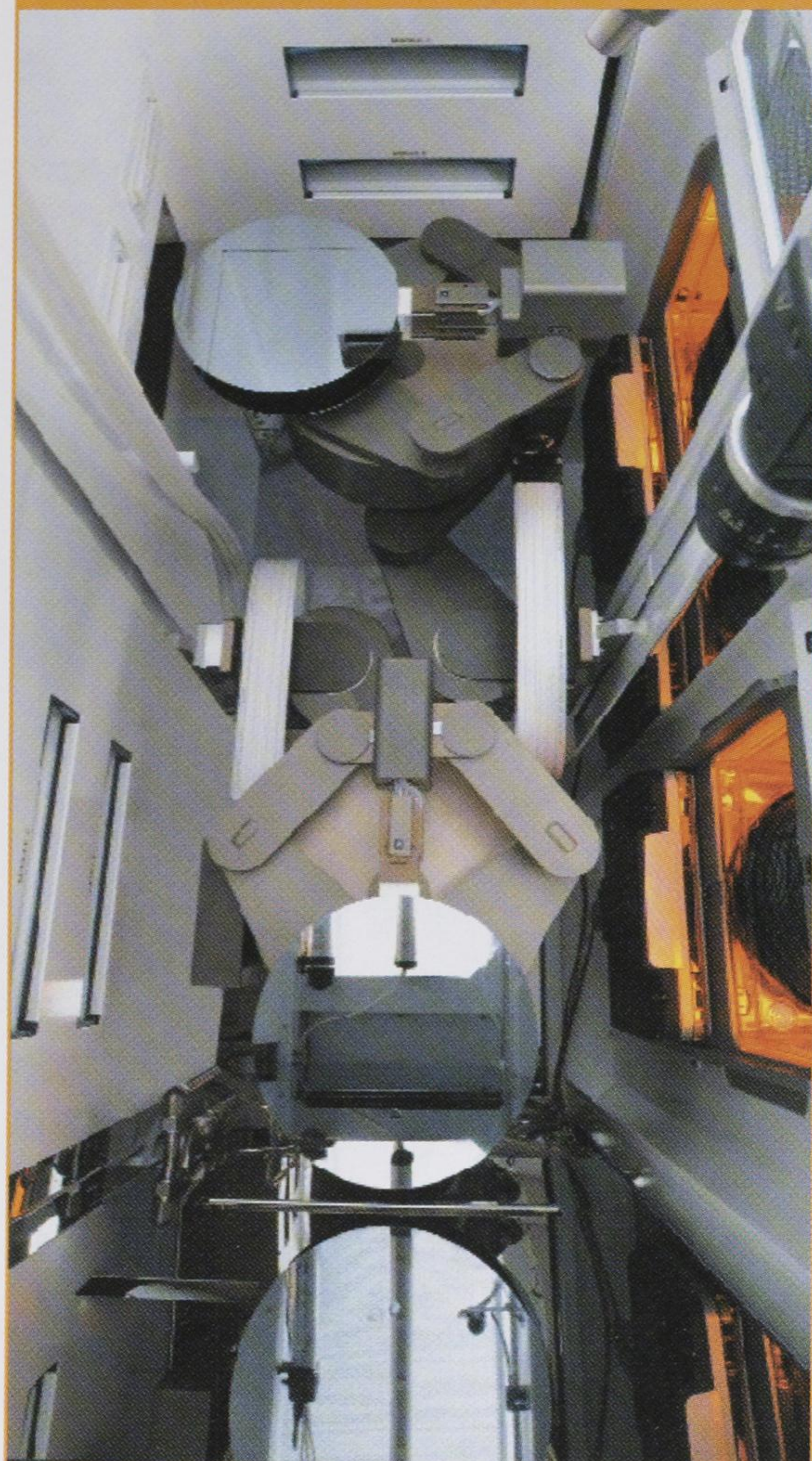
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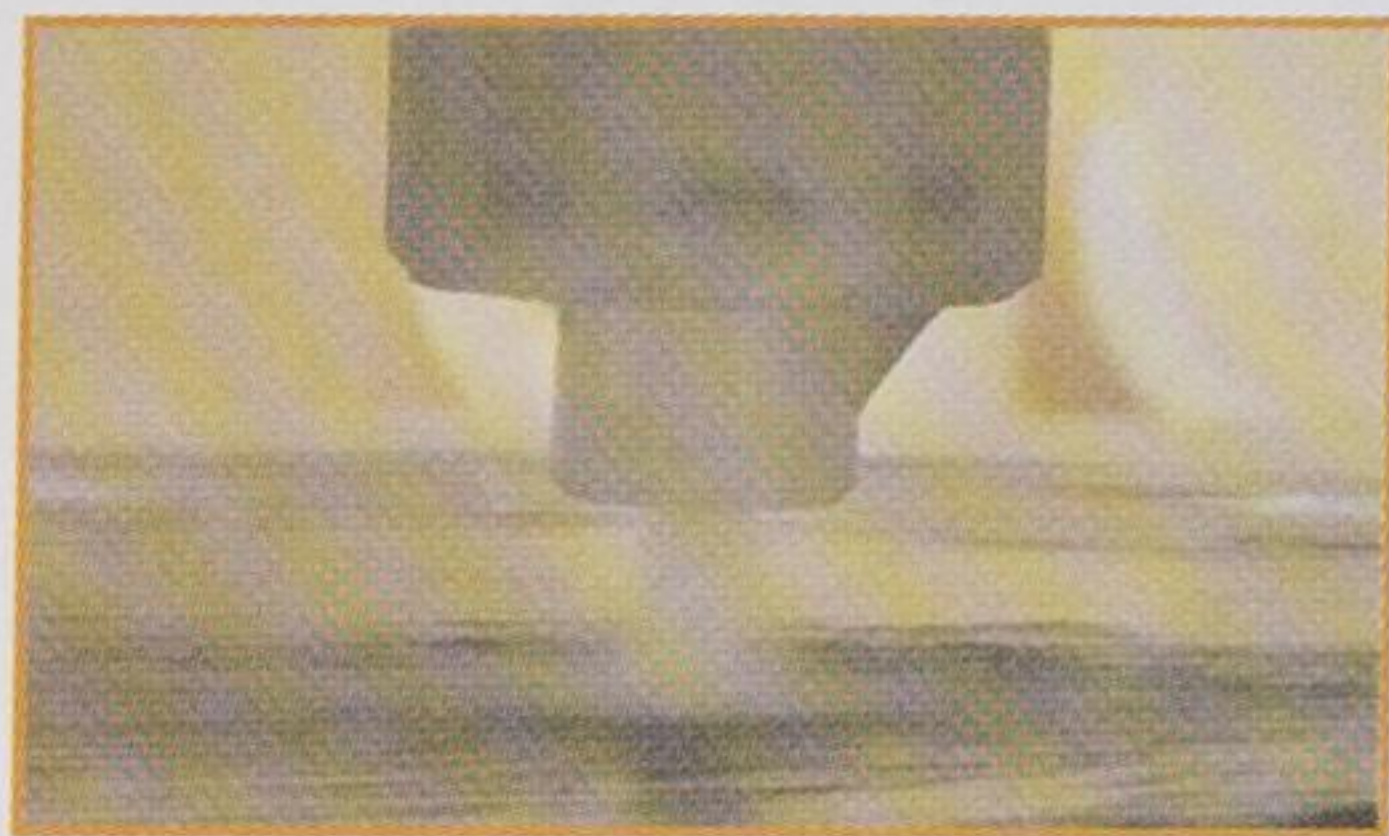
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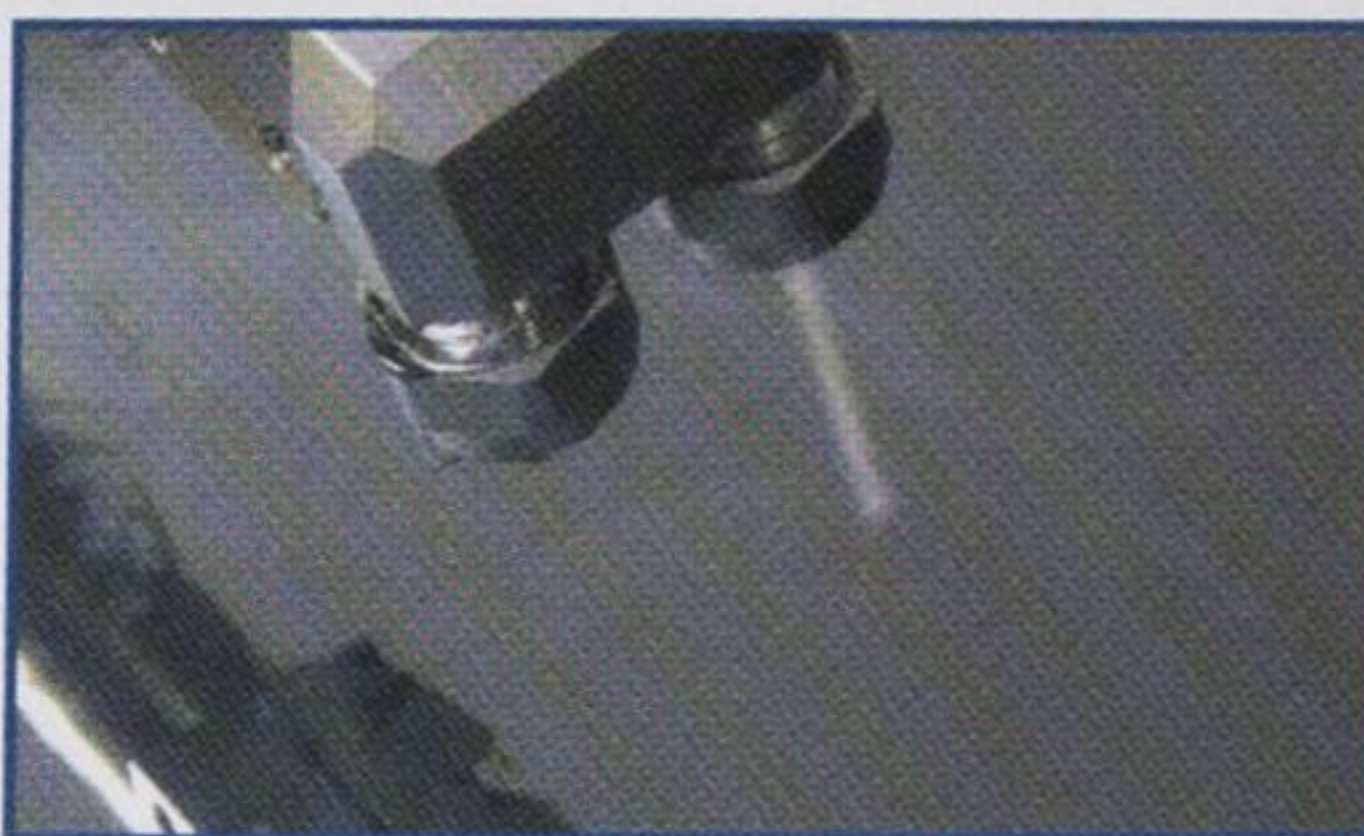
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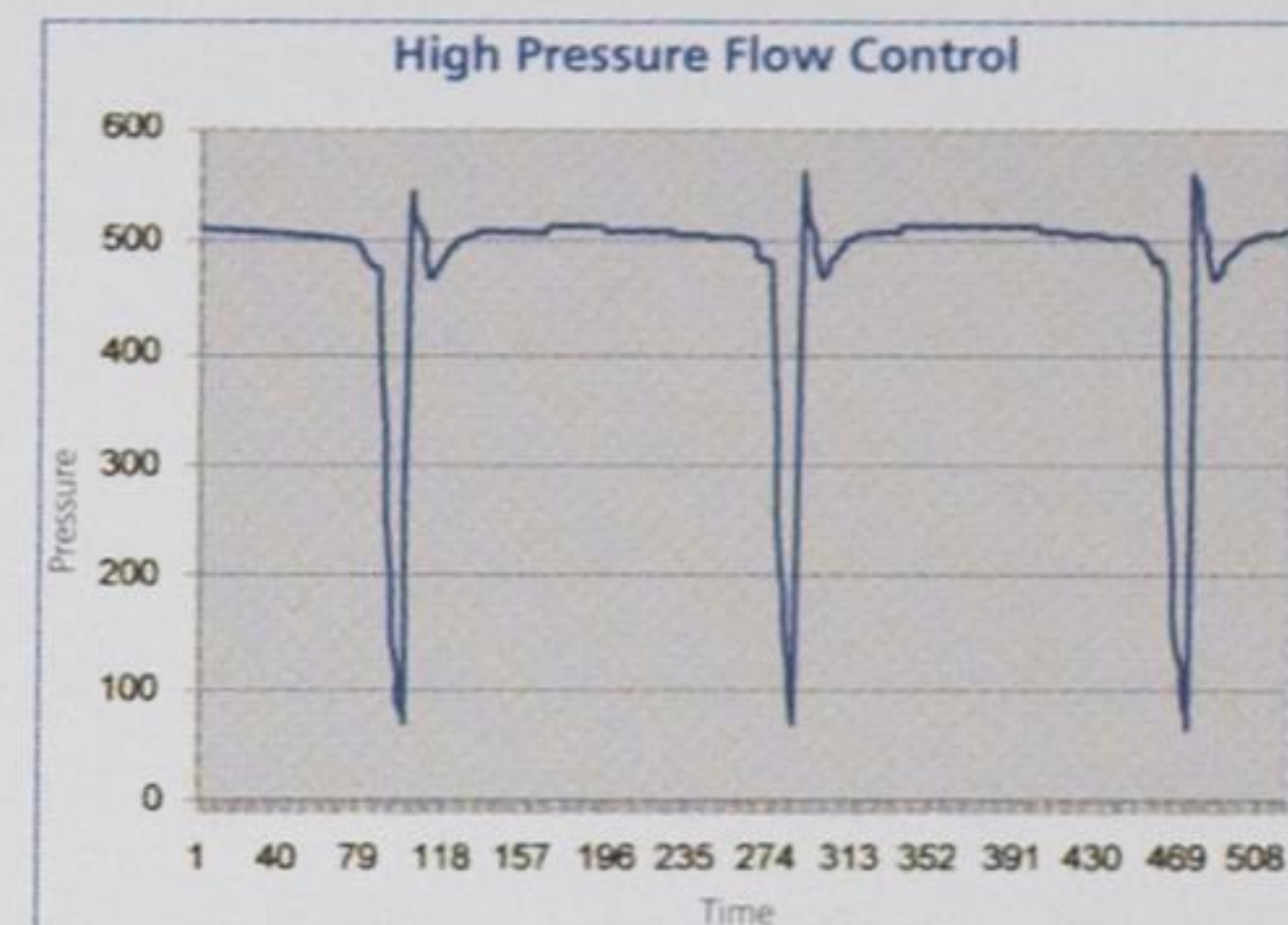
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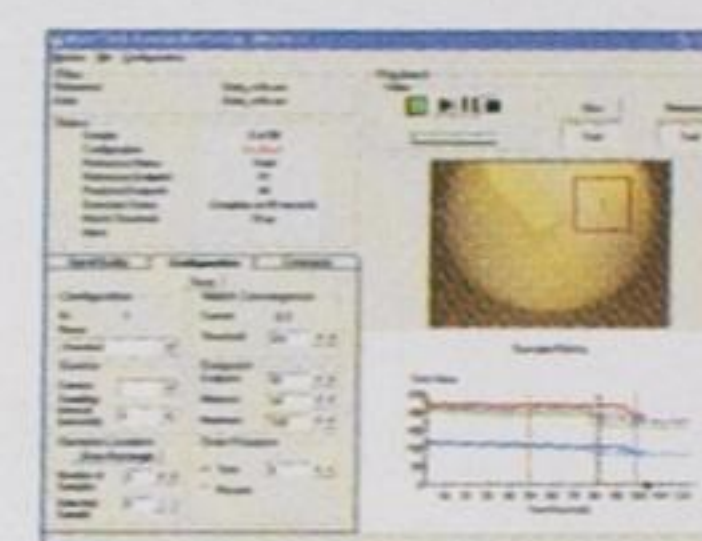
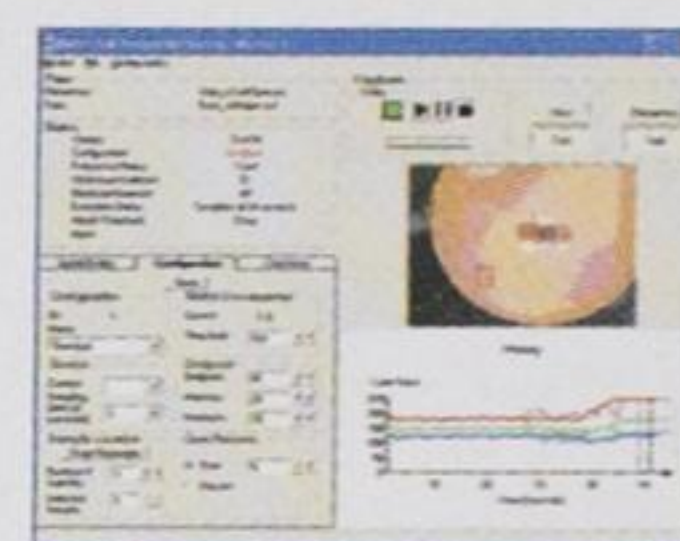
Backside/Bevel Cleaning



Stream Flow Etch



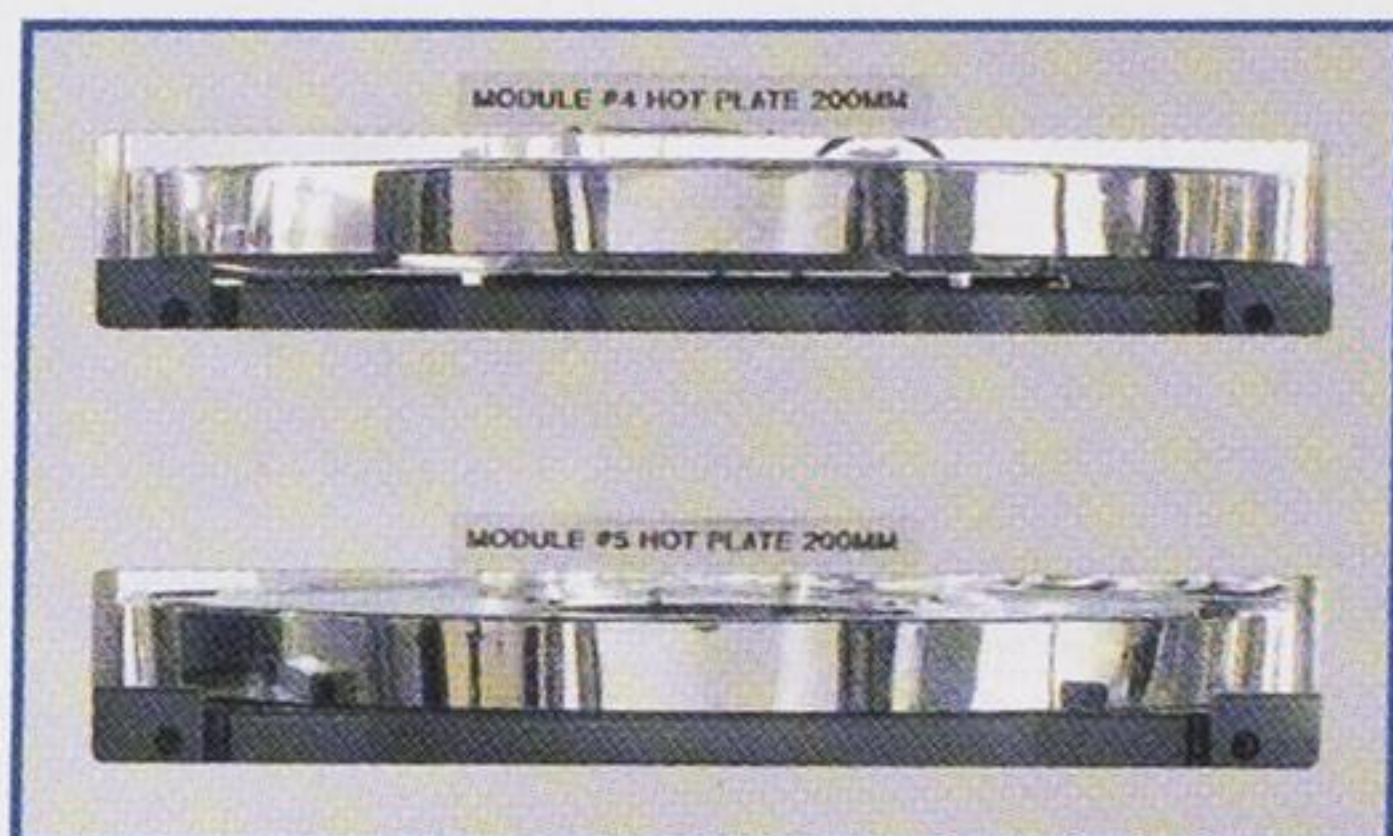
Spray Etch



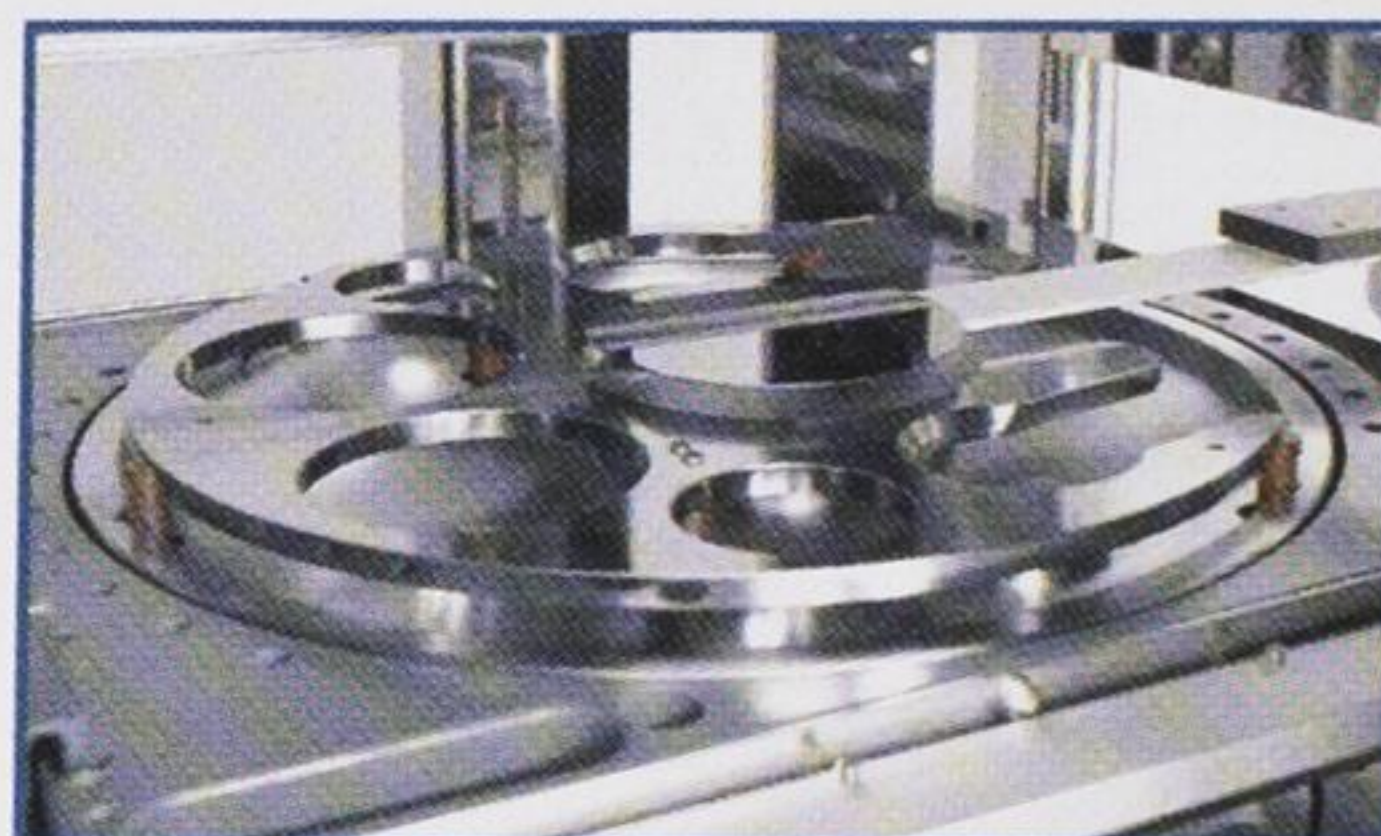
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## EQUIPMENT SALES

## MOCVD suppliers see order push-outs

Aixtron and Veeco are set to expand their spending on research and development next year, even as orders for their systems continue to fall.

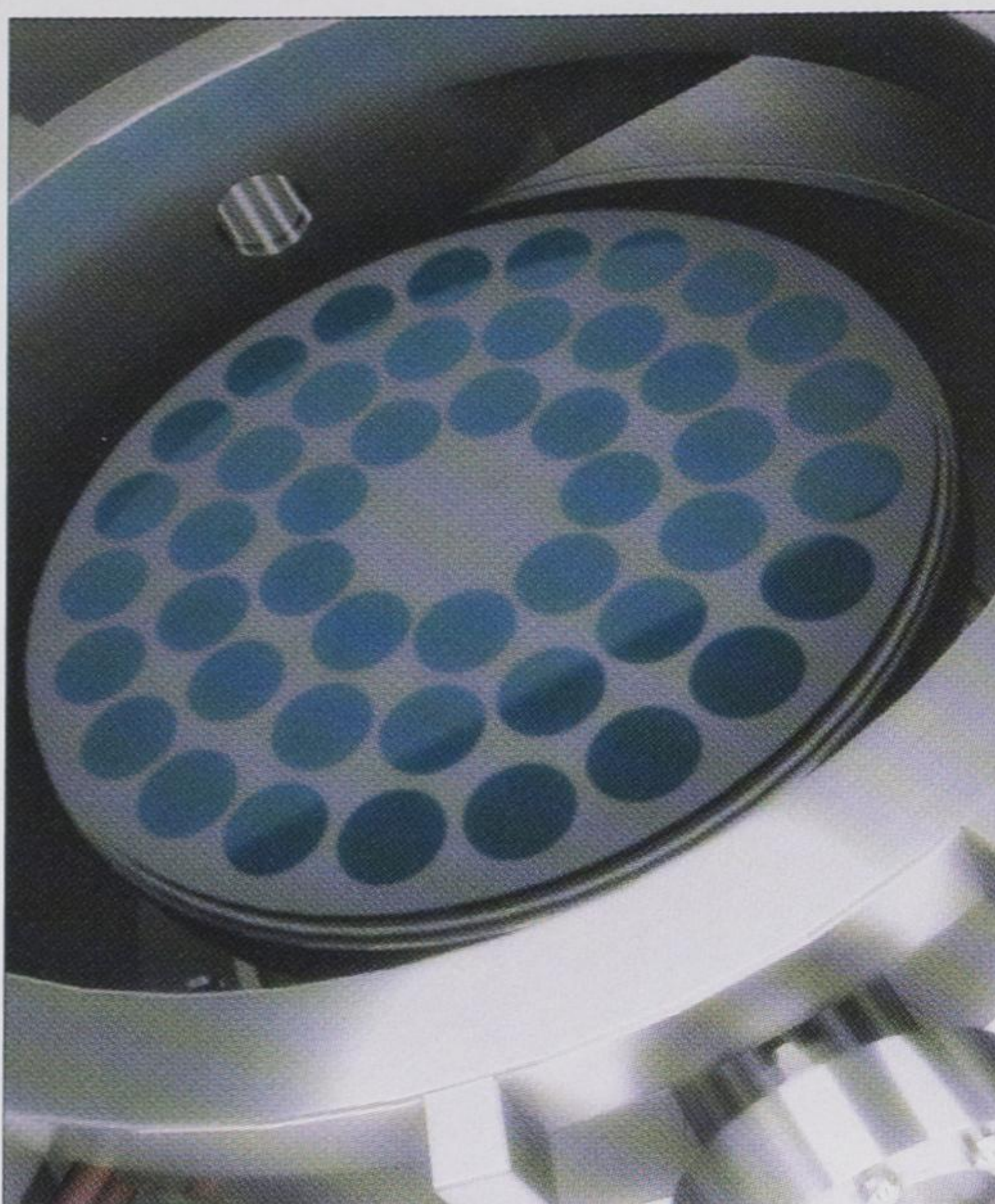
Orders for Veeco Instruments' solar and LED equipment fell by half between the second and third quarters of 2008 as system usage declined at some LED wafer manufacturers. The business unit took \$26 million of orders in the three months to September, as sales also dipped to \$41 million from \$45 million in the previous period.

The Plainview, NY, tool producer fell foul of \$9.8 million in delayed sales in the September quarter arising from high-brightness LED makers. "While we expected some fall-off in orders due to the significant MOCVD capacity build-up in Taiwan, the decline was greater than originally anticipated," commented CEO John Peeler.

The LED industry is again digesting a large number of recently installed production systems, which have been purchased in expectation of increasing demand. However, demand has not uniformly increased to the same extent as capacity, leading to lower average equipment usage.

"The utilization rates of some of the customers are still going down," Peeler commented. "Others are still buying for capacity and managing ramp-ups of new factories for their particular applications. It's a mixed bag."

This digestion situation last arose as recently as 2005, when Veeco's orders recovered within nine months, but Peeler accepts that things could be different this time. "It's difficult to tell if this is a flat spot or a downturn," Peeler said.



**After the success of Veeco's K465 reactor** (shown here) and Aixtron's Crius and G4 systems, the companies will now invest in developing next-generation reactors for LED production.

Having only regained profitability in June, Veeco slipped to a net loss of \$1.7 million from \$115.7 million overall revenue in the September quarter.

Veeco says that it will record less revenue in 2009 than in 2008, driven largely by the LED shortfall. This, and the impact of the global economy in its other markets, is now leading the company to make cost-cutting plans. "Our management team is conducting a comprehensive review of our global workforce, and we're planning reductions in the current quarter," Peeler said.

Regardless of these issues, Veeco is continuing strategic investments to build on its high-throughput K465 GaN MOCVD system's success. "Our goal is to emerge from this cyclical pause with a better product line-up," Peeler said.

Meanwhile, despite entering digestion, Aixtron is emphasizing that its €158.1 million (\$204.2 million) order backlog remains much stronger than it was at this time last year. Regardless of the uncertainties posed by what the German company called "unprecedented" economic circumstances, CEO Paul Hyland rejected suggestions that some customers had pulled their orders.

"There have been no cancellations," said Hyland, although he did acknowledge that some scheduled deliveries may be delayed, possibly pushing out some sales revenues from 2008 to 2009.

The MOCVD producer will now use its substantial cash reserves to accelerate development work, which Hyland sees as essential for Aixtron to maintain its edge. "There is no room for complacency," he said.

For the first nine months of 2008, Aixtron posted total revenue of €192.1 million, up 20% on the 2007 figure. In the latest quarter, sales totalled €63.9 million, yielding €5.5 million profit. The company expects total sales for 2008 to total at least €270 million – meeting the lower end of expectations set at the start of the year.

Hyland explained that while 2009 will be a challenging year for everybody, there continue to be positive trends for Aixtron. "We stand to gain from the continued adoption of LEDs – the fundamentals remain as good as they were a year ago."

## MARKET REPORT

## LED backlights to grab TV share in 2009

Significant penetration of LEDs in LCD television backlights will begin next year, suggest analysts at the Korean market research company Displaybank.

Already becoming popular in smaller LCD units, such as those used for notebook computers, LEDs have not yet been able to displace traditional light sources in TVs. This will change next year, as Sharp, Philips, Hitachi and LG launch TVs incorporating the solid-state technology, joining

pioneers Samsung and Sony.

"The shipment of LCD TVs with LED backlights will begin to be active in 2009 and [the technology] is likely to account for 6.4% of the total LCD TV market (or 10.9 million units) by 2010," predicted the Displaybank report.

The bullish prediction goes on to forecast that more than 25 million such units will be shipped in 2011, doubling to around 52 million the following year – equivalent to a quarter of all LCD TV shipments. Surprisingly, Displaybank researcher Allen Ji reckons that the driving force behind the displacement of cold-cathode fluorescent lamps (CCFLs) will be pure aesthetics –

specifically the extra-slim designs that LEDs enable.

In the past, superior color rendering, particularly in the red end of the visible spectrum, had been expected to push LED backlighting. However, CCFL producers countered that threat with improved lamps.

More recently, it has been the energy-saving potential of LEDs that has been highlighted as the key advantage of notebook computers. However, the battery life that this brings is not a consideration in TVs, and the cost of the several hundred individual LED chips that are used in a typical TV backlight has so far resulted in CCFLs maintaining their dominance.



# EPITAXY

# HVPE promises high-indium LEDs

Hydride-vapor phase epitaxy (HVPE) has successfully made stable  $\text{In}_{0.43}\text{Ga}_{0.57}\text{N}$ , giving it a great chance of becoming the leading green LED production system. The approach of Technologies and Devices International (TDI) to producing high-indium-content material adds support to its claim that HVPE could advance LED manufacturing technology.

Alexander Syrkin, deputy director at TDI, told *Compound Semiconductor* that trichlorogallium and trichloroindium precursors are critical to achieving the level of indium that is needed for green GaN-based LEDs. "Temperature is the main variable that influences the indium content when used in MBE and MOCVD," he said. "The thermal stability of InGaN is a key parameter but has a narrow range."

By selecting precursors with the right chemical and thermodynamic behavior, TDI has maintained process temperatures between 680 and 710°C, ensuring that the InGaN layer stays intact. "Our 43% InGaN material has been thoroughly investigated by the most renowned transmission-electron microscopy specialists in the field," Syrkin asserted. "We are confident that there are

no indium precipitates."

Using ammonia as the nitrogen source, TDI produced epilayers on GaN-on-sapphire template substrates at a rate of up to 2  $\mu\text{m}/\text{h}$ . Simple heterostructures made from n-doped InGaN layers containing various levels of indium and p-doped GaN, exhibited electroluminescence across the whole 450–690 nm range.

As well as examining device properties, Syrkin and colleagues are continuing to investigate the physical properties of the material coming out of this latest process. Although it can make fully strained or partially relaxed material, TDI is still working to understand what controls the relaxation.

This work continues several years of InGaN HVPE development that has helped to establish the company as a leader in the technology. "TDI has introduced several non-traditional elements into the process and the tool that have allowed us to resolve some issues that others are still struggling to overcome," Syrkin said.

The company's success in HVPE was a key factor in its purchase by Oxford Instruments, an equipment manufacturer with a strong focus on the LED industry, in April.



**UK supermarket Sainsbury's** has been the first retailer to deploy Philips' LED cabinet lights that use Luxeon Rebel LEDs made by its San Jose subsidiary Lumileds. There have been 15,000 Philips Affinium freezer lighting modules equipped across 350 stores, cutting each freezer's energy bill by 75%. Philips says that the annual energy savings per freezer are equivalent to half the yearly electricity bill of an average household.

US supermarket Walgreens expects a similar energy saving when it installs LED lighting from Powersecure International in its new stores from 2009.



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### ...SemiLEDs buys lithography kit

After winning a multi-tool order with US-headquartered LED manufacturer SemiLEDs, Ultratech says that it could sell hundreds of its lithography systems into this industry. The San Jose, CA, company's CEO, Arthur Zafiropoulos, says that its Star 100 systems' low-cost high-resolution projection stepper lithography technology would benefit LED makers. "Yield is becoming a major issue. They need projection alignment systems," he said.

### ...Crunch impacts wafer sales

Rubicon will swing from \$1.6 million profit for the three months to September, to a loss that could be as large as \$2 million for the year's final period. The Illinois-based sapphire substrate maker's CEO, Raja Parvez, said: "The global economic downturn has impacted our customers. We expect the fourth quarter to be challenging for us as they work through their inventory."

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LASER DIODES

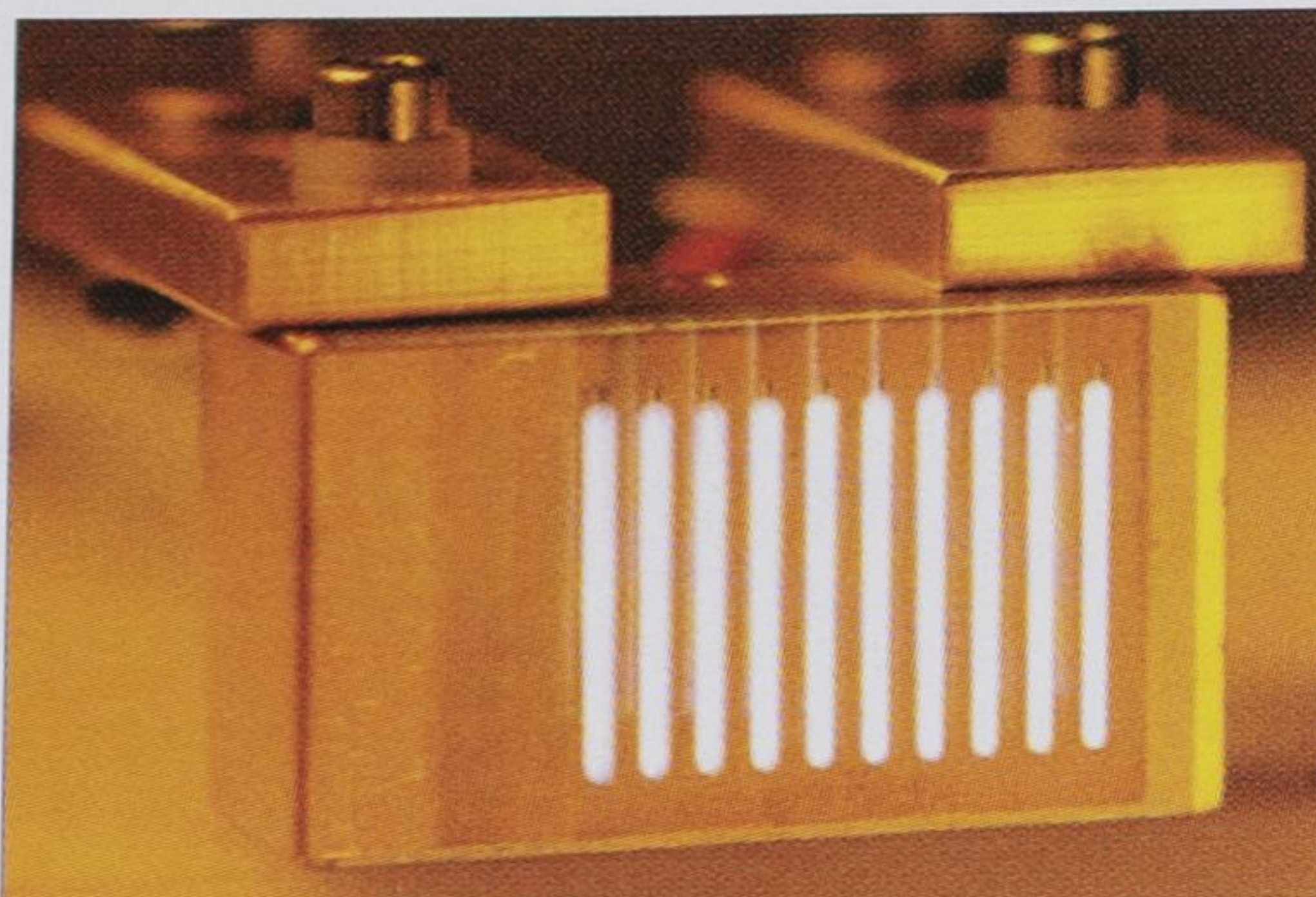
# Finisar readies bailiffs as QPC defaults

Semiconductor laser maker QPC Lasers said at the beginning of November that it was due to enter bankruptcy within days, after failing to make its interest payments. Despite discussions with numerous potential investors, QPC said, the company was still suffering from "a severe liquidity crisis".

Fiber-optic component maker Finisar was set to remove assets belonging to QPC on November 7, after QPC failed to pay it the interest due on a loan note. According to QPC's own filings with the US Securities and Exchange Commission, it missed an interest payment of around \$44,000 that was due to Finisar on October 18.

A letter sent on October 30 by Finisar's legal counsel demanded "that [QPC] assemble all of the collateral securing [QPC's] obligations under the Finisar note at its Sylmar, CA, address and permit Finisar to enter to take possession and remove the collateral for later sale".

In short, Finisar threatened to send in



**QPC Lasers' efforts to gain funding** based on its surface-emitting diode lasers, which have 45° mirrors in their epitaxial structure, have failed.

the bailiffs to settle the outstanding loan amount – \$5.4 million plus the unpaid interest – in full. The collateral upon which the loan note is based includes not just the physical assets at QPC's MOCVD fab, but also the company's intellectual property.

QPC, which manufactures laser chips

using some innovative process technology, had only resumed limited operations on October 20, having initially suspended much of its activity on October 12. When contacted by *Compound Semiconductor* on October 21, a spokesperson confirmed that QPC's workforce had been cut from 60 to approximately 20 employees days before.

The firm posted sales of only \$1.3 million in the quarter that ended June 30, while the high cost of research and development efforts contributed to an overall net loss of \$4.7 million. QPC currently owes more than \$25 million and is obliged to pay out nearly \$6 million during 2009 to service that debt.

Financed by an increasingly complex combination of loans in recent years, QPC had been attempting to raise more funding since April amid the credit crunch.

Although CEO Jeffery Ungar underlines that QPC has more than \$14 million in orders, that does not appear to have been enough to convince potential investors to save them.

OPTICAL COMMUNICATIONS

## Falling sales trigger upheaval at JDSU

Optical communications and commercial lasers look set to escape lightly as JDSU cuts 400 jobs, despite these divisions recording the company's biggest falls in revenue in the last quarter. Instead, cuts will be focused on its test and measurement unit, where 19 research sites will be cut to just 12, and at least three factories will be closed.

CEO Kevin Kennedy unveiled his rationalization plan on October 29 as he discussed JDSU's financial results for the latest quar-

ter, shortly before announcing his resignation. The lay-offs come as JDSU recorded a third consecutive quarterly loss in the three months ended September, narrowing to \$16.6 million from \$29.8 million in the previous period. The Milpitas, CA, firm slimmed its losses even as sales fell 2.5% to \$380.8 million, which reflects the early stages of the latest rationalization.

Revenues in optical communications fell by 3.1% sequentially to \$140.6 million as it stopped selling some less profitable 2–4 GHz data communications lines. "Growth was suppressed due to the management decision to prune unprofitable legacy products from the portfolio," Kennedy explained.

In place of the pruned products the company will focus on more highly integrated offerings to retain high profit margins. It will also emphasize the manufacture of high-value components including pump lasers and VCSELs.

A further consolidation step sees optical communications merge with JDSU's commercial lasers business, where sales fell 3.2% from the previous quarter to \$21.4 million. Kennedy attributes this to lower demand from semiconductor equipment manufacturers. In combining the two units, JDSU is introducing laser diodes originally developed for optical communications into its commercial laser range.

CHIP-TO-CHIP INTERCONNECTS

## Quantum-dot VCSELs further chip comms

A German collaboration has increased the likelihood of replacing chip-to-chip electrical communication with optical data transmission, by making VCSELs that can operate at 120°C.

Dieter Bimberg's group at Technical University (TU), Berlin, produced the 20 Gbit/s, 980 nm InGaAs quantum-dot (QD) lasers described in *Electronics Letters*.

"Where VCSELs are used in chip-to-chip optical interconnects the operation temperature of the device should be adjusted to the CMOS chip temperature," Bimberg said. "Operation should be stable beyond 100°C." Bimberg's team designed and processed VCSELs based on MBE-grown epiwafers provided by its compatriot laser makers Innolume.

Quantum-well VCSELs have proved capable of maintaining high gain and bandwidths at 100°C, by suppressing the escape of non-equilibrium carriers at high temperatures. By choosing a deposition method that

produces sub-monolayer (SML) size islands that behave as QDs, the 120°C VCSEL benefits from an even higher modal gain.

"Vertically correlated growth of SML QDs creates a significant potential depth to suppress in-pane mobility of non-equilibrium carriers," Bimberg explained.

TU Berlin is also working with QD epiwafers that are provided by German optoelectronic firm VI Systems on 850 nm SML VCSELs. Additionally, TU Berlin and VI Systems are currently working with Intel's Irish operations on the €3.2 million (\$4 million) European project, VISIT.

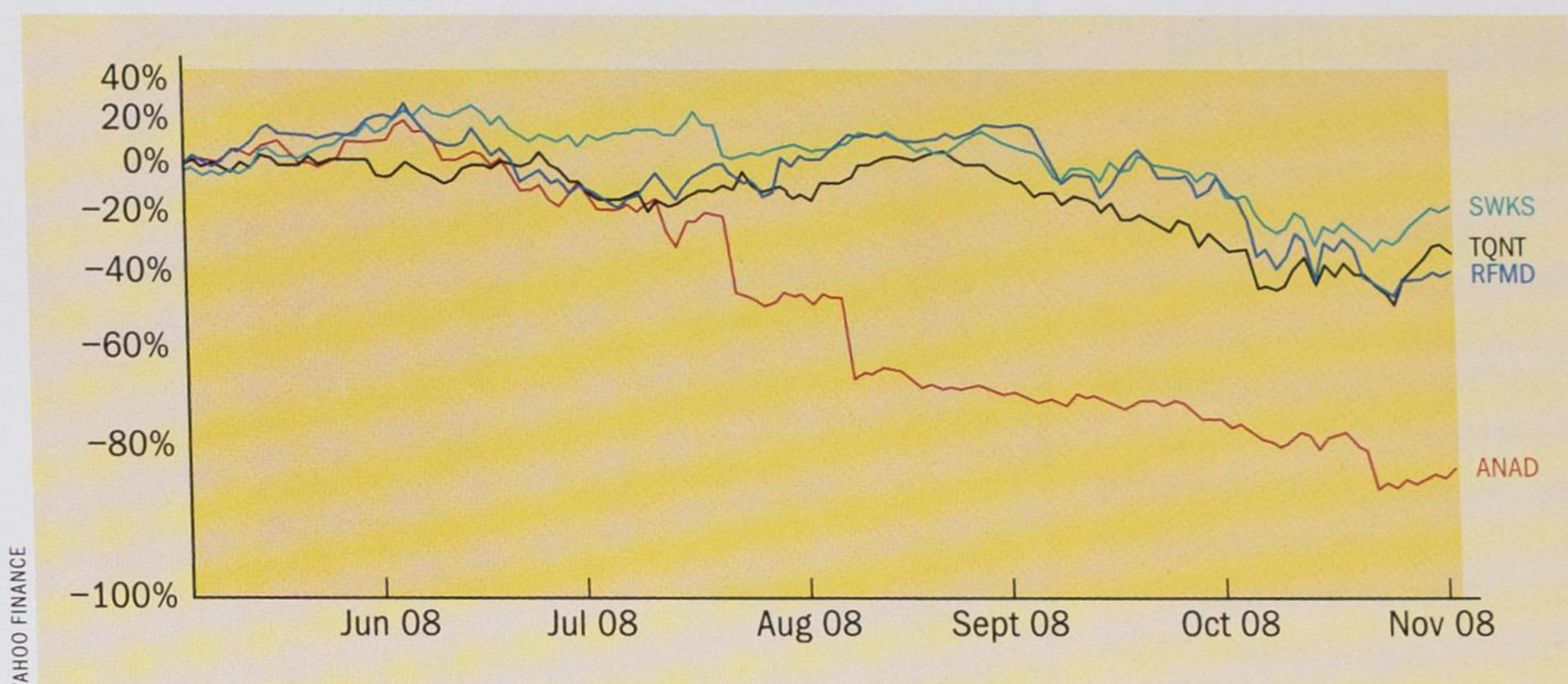




## CREDIT CRASH

# QPC's demise heralds consolidation

In early November, QPC Lasers filed for bankruptcy and became the first direct compound semiconductor casualty of the 2008 global financial crisis. Is this a sign of things to come, or an isolated incident, wonders **Michael Hatcher**.



YAHOO FINANCE

**Fig. 1.** Among GaAs companies, Anadigics' stock has been hit hardest in the general market turmoil. Over the past six months, it has lost some 80% of its value, while direct rivals RFMD, Skyworks and TriQuint have dropped between 20 and 40%.

Like 1929 and 1987 before it, 2008 will go down in history as a momentous year for stocks – and for all the wrong reasons. But what will be the real effect on the compound semiconductor economy?

Ask around at the moment, and the most common response that you get is “it’s too early to tell”. Put simply, if Nokia isn’t sure how many phones it will be shifting next year, then RF Micro Devices won’t know how many power amplifiers to manufacture. Go down the supply chain to suppliers such as IQE and AXT, and the crystal ball becomes more murky.

While it might be too early for some, it is certainly too late for one company. QPC Lasers, which manufactured high-power laser chips at its MOCVD facility in Sylmar, went to the wall in early November when senior creditor Finisar called in a \$5.4 million debt through a repossession order.

Will this be a sign of things to come? No doubt there are some in the compounds community who are at risk – as in the wider world, the companies with high levels of debt and weak balance sheets.

But the good news is that many of the companies regularly covered in these pages are substantially debt free. In fact, the positions of these companies could end up being very advantageous if, as seems likely, a mood to consolidate emerges from the credit-crash gloom. Of the public companies listed on US exchanges, none of Cree, Bookham, TriQuint, Emcore or IPG Photonics shows significant long-term debt on the balance sheet.

Of those that do show larger debt positions, such as RF Micro Devices and JDSU, the terms of these debts do not appear to pose any short-term risks.

The most notable change among the GaAs manufacturers is the sudden volatility in market share that has resulted from Anadigics' lack of focus. The New Jersey company's inability to meet the previ-

ously rampant demand for its popular chips has already seen CEO Bami Bastani ejected, along with 100 employees – 15% of the workforce.

To his credit, stand-in Anadigics CEO Gilles Delfassy did not hide behind macroeconomic trends in the company's recent trading update, going on record to say that the chief reason for missing its financial target was entirely of Anadigics' own making.

It had been through a spell of stellar growth between 2006 and 2008, but with companies like Intel demanding more and more of the multi-band power amplifiers and high-spec front-end modules in which Anadigics specializes, the failure to meet that demand has come at a damaging cost.

RF Micro Devices and Skyworks Solutions both say that they have gained market share in the aftermath of this slip-up. Meanwhile, Anadigics' share price – which had been one of the best performing among compound semiconductor stocks since 2005 – has collapsed. Even accounting for the general stock market carnage of 2008, the company has suffered in comparison with its peers (figure 1).

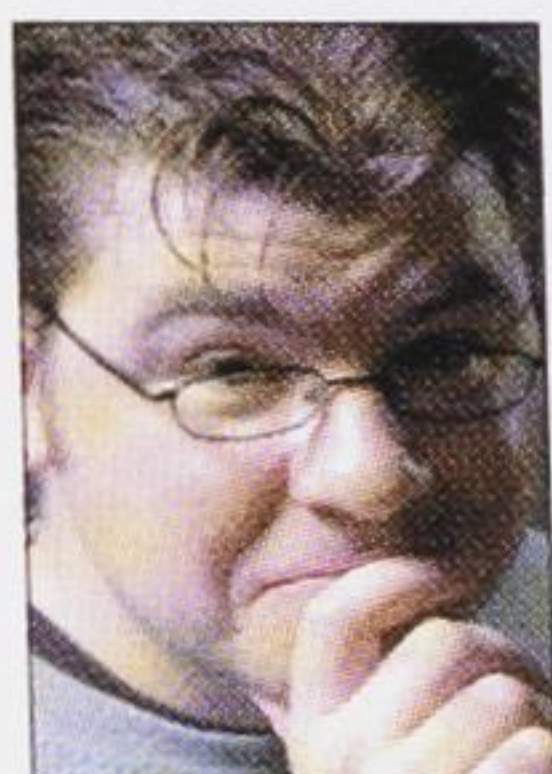
Anadigics' balance sheet shows \$38 million in long-term liabilities. But even when added to the \$15.5 million loss from its latest quarter, the \$130 million cash and cash equivalents that are also listed on its most recent balance sheet should provide a buffer.

Skyworks, perhaps the greatest beneficiary of Anadigics' difficulties, used some of the \$111 million net profit that it made in the fiscal year ended October 3 to reduce its own debt exposure. The Woburn-based company retired \$62.4 million in convertible long-term debt on its balance sheet, reducing that liability to \$137.6 million.

One company where existing liabilities might pose more of a problem could be equipment provider Aviza, which is exposed to a \$12.3 million long-term debt. Certainly the stock market appears to think so, dragging the company deep into the realm of penny stocks over the past 12 months. Now facing almost certain expulsion from the Nasdaq index, which does not allow shares to trade below \$1.00 for an extended period, the market capitalized Aviza at a measly \$3.5 million on November 7 (\$0.16 per share).

With such depressed valuations, the industry ought to be ripe for some serious consolidation – driven by the companies with little or no exposure to debt. In the fiber-optic component sector, which many believe still supports too many chip manufacturers, that consolidation might be imminent.

For those brave enough to take the risk, there are some rich pickings on offer.



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



## MOCVD EQUIPMENT

# We ate with scalpels and tweezers

Twenty-five years ago, two scientists at Aachen University in Germany joined forces with a local businessman to launch an equipment company. The result: the world's leading MOCVD tool supplier. **Richard Stevenson** talks to Aixtron co-founder **Holger Juergensen** about the early days.

The III-V community was the butt of quite a few jokes in the early 1980s. "GaAs makes papers and silicon makes money" was one popular wisecrack, alongside the famous one-liner: "GaAs is the material of the future and always will be."

Like all bitter jokes, they featured an element of truth. Back then research efforts overshadowed device manufacture and production was limited to fabrication of rather dim green, orange, yellow and red LEDs based on AlGaAs, GaAsP and GaAs – even infrared lasers for future CD players were still under development.

But this community was undergoing a transition, with research edging towards commercially viable applications. Success, however, would hinge on the development of stable, consistent manufacturing methods for making epiwafers. Into this breach stepped a couple of German researchers at the University of Aachen, and the rest, they say, is history.

Aixtron co-founder Holger Juergensen was one of these researchers. "By 1982, it became clear to Meino Heyen and me that the time was right to offer well developed, standardized equipment to researchers that allowed them to obtain reproducible results in a uniform manner on full wafers. Even in those early days, we had started to conceptualize MOCVD equipment growing III-V films on a full 2 inch wafer. This was revolutionary – at the time most researchers could only grow on a few square centimeters."

Premises for the company were secured in Aachen, which is close to the borders with Belgium and the Netherlands. "The proximity to the university was a key to Aixtron's success," said Juergensen. "Our first location was inside a university technology center that offered attractive conditions to start-up companies." That kind of set-up might seem normal these days, but incubator-style technology centers were a radical idea at that time.

Launching any company requires much more than a good idea and business premises – healthy finances underpin everything. This is where Heyen's father in law, the successful businessman Heinrich Schumann, stepped in as Aixtron's third founder.

Although this triumvirate offered the ideal mix of III-V expertise and business acumen, they still found it tough to generate the cash needed to start



BOTH IMAGES: AIXTRON



In 1983 Holger Juergensen, Meino Heyen and Heinrich Schumann founded an MOCVD company in Aix-la-Chapelle, France. The town's French name – Aix-la-Chapelle – and to target customers in the optoelectronics industry. The company's first product was a single wafer 2 inch tool with an AIX 200 quartz reactor cell (left). Aixtron's first local

the company. Securing some public funding to build an initial prototype was the breakthrough that they needed. "It took us about a year to identify and qualify appropriate suppliers, get the first team together and fix the design," said Juergensen. According to him, the biggest challenge was converting a research tool into a user-friendly, reliable piece of kit that could be built and sold commercially.

The founders then received some great assistance from the III-V team at AEG in Ulm, Germany, who wanted to create faster GaAs-based communication chips. "They simply went ahead and bought Aixtron's first MOCVD equipment with an upfront payment," recalled Juergensen. In addition, the founders secured a small loan from a local bank. "The loan in itself was almost revolutionary, as we could not provide any of the typical securities."

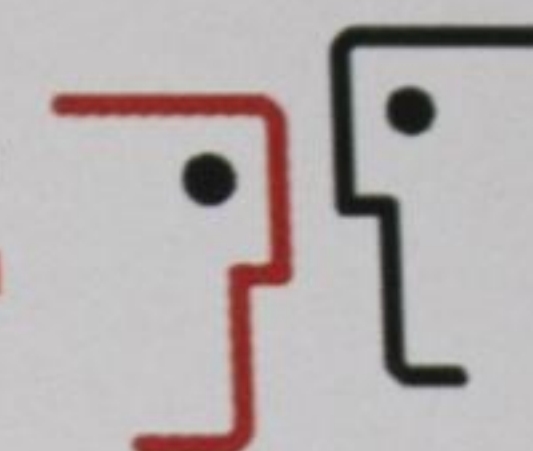
Europe is well known for its 35 hour working week, with the focus on time with the family and vacations that knock out August. But the founders of Aixtron bucked this trend by working day and night, and through weekends and holidays.

This complete commitment to the company was exemplified by the relationship with AEG. Teething trouble with this lead company's reactor led to visits to Ulm, a city at the opposite end of Germany, four

**"We paid and took low salaries, keeping all of the cash within the company."**

Holger Juergensen, Aixtron founder





# eezers, says Aixtron founder



ounded an MOCVD equipment company in Aachen. They called it Aixtron, to reflect the optoelectronics community. AEG of Ulm ordered the company's first reactor, and its first location was the Aachen University technology center (right).

or five times a week. "We often worked 10–12 hours and drove 1100 km per day," said Juergensen. "I don't remember how we got any sleep."

Heavy workloads are not unusual for the founders of start-up companies, who can find themselves eating together at their premises in the evenings. For a semiconductor equipment firm, even this poses some unique challenges. Understandably tired, the Aixtron pioneers sometimes forgot to bring knives and forks through the lab's airlocks. "We had to enjoy the great variety of lab food using small medical scalpels and tweezers that were used to cut and handle GaAs wafers," reminisced Juergensen.

## Legacy products

Aixtron's first shipment, which went to the researchers at Ulm, was a single 2 inch machine with an AIX 200 quartz reactor cell, which shares many similarities with the firm's current product range. It featured computer control, safety interlock systems and many other hardware details that were maintained in future designs. "That said, it's a bit like comparing an old and a new Mercedes E class," said Juergensen. "Although today's generation shares the same heritage as those first generation tools, the performance is of a completely different class."

The early years of a start-up often include times when money runs out, and founders have to beg for cash. But Aixtron managed to steer a far safer course and was profitable from its very first year. "I don't think we ever came close to a really dangerous situation," said Juergensen, "but that is due to the strong focus we put on financial management. We paid and took low salaries, keeping all of the cash within the company."

Ulm's breakthrough order was followed by others from SEL in Stuttgart (which later became part of Alcatel) and the Universities of Berlin and Duisburg. Later, Aixtron shipped a tool to Philips in Eindhoven, the Netherlands, to develop the first commercial red AlInGaP lasers for DVD players. This signaled the start of an international business, and it wasn't long after that when AIX 200 reactors were dispatched to AT&T for growing InP-based lasers and detectors at its sites in Murray Hill, NJ, and Reading, PA.

In 1988 Aixtron launched its first multi-wafer reactor. "For the first time, this reactor enabled high-volume, industrial-scale manufacturing of III-V compounds," remarked Juergensen.

The 1990s witnessed the launch of more tools and the emergence of what is now the firm's key application: nitride-based high-brightness LEDs.

The growing company targeted manufacturers of the first blue, green and white LEDs, and in late 1997 the Aachen outfit launched itself on Frankfurt's "Neuer Markt" stock exchange. The capital raised ultimately enabled expansion of the company through acquisitions of Thomas Swan Scientific Equipment and Epigress AB in the 2000s.

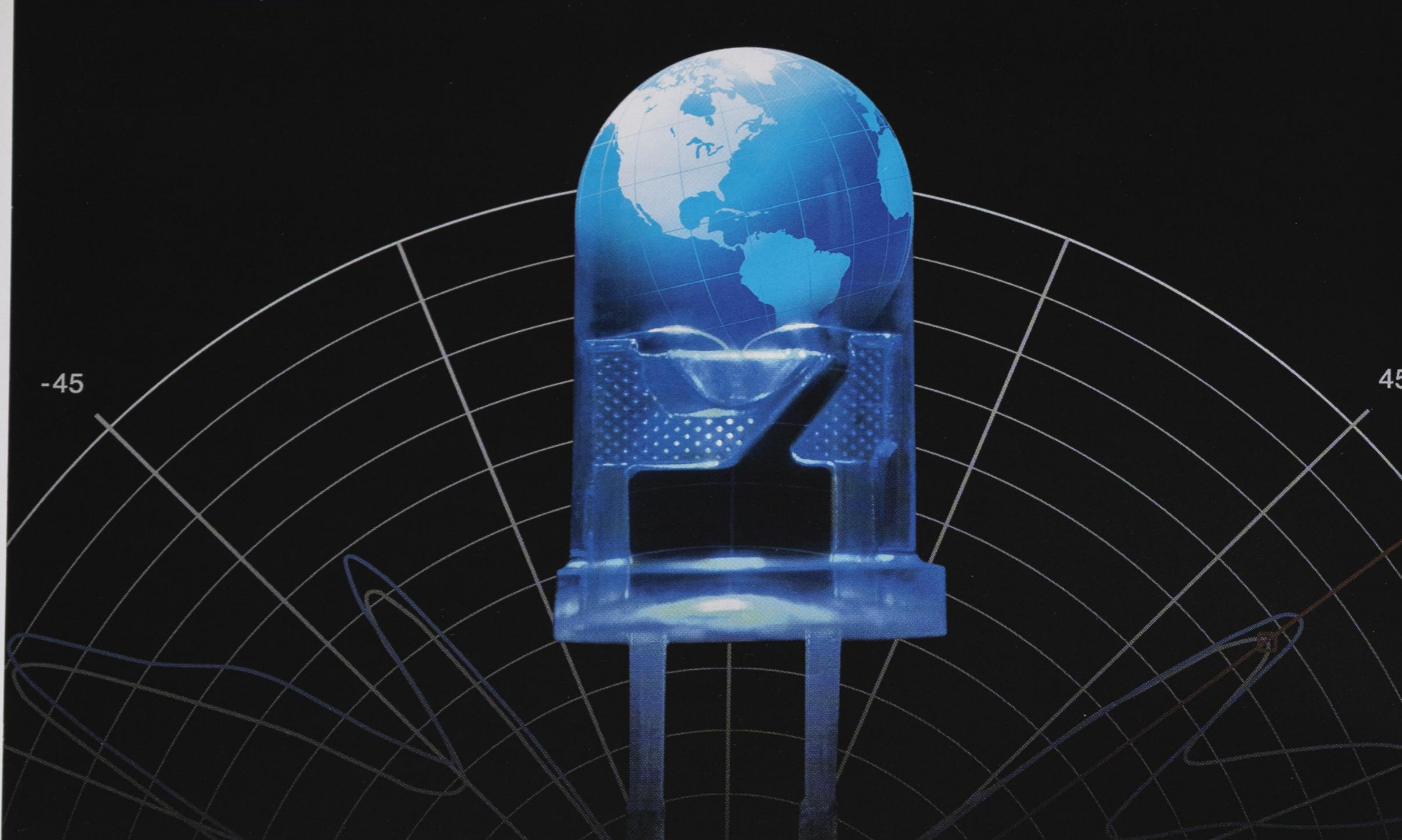
Diversification has been the latest theme. The focus on gas-phase deposition equipment remains, but the company is now looking to cover a broader range of materials. This includes the development of a deposition technology for making organic LEDs, and a product line for silicon-related materials via the further acquisition of the California-based equipment manufacturer Genus Inc in 2005.

"These are meaningful events," said Juergensen, "because they mark our commitment to developing technology to meet the inevitable convergence of compound and silicon technologies." Aixtron's tools are in fact already appearing in silicon fabs, where they are used to deposit hafnium-based gate material. Far from being the butt of the silicon community's jokes, MOCVD is now becoming a technique that is central to its future.

Who would have spotted that marriage on the horizon when Aixtron launched the first MOCVD tool 25 years ago, amid the taunts of the blinkered silicon community?



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R. STEVENSON

# Different faces fit for GaN researchers

Researchers can choose between non-polar, semi-polar and polar substrates for nitride growth. But what are the benefits of one of these faces over another? **Richard Stevenson** reports.

The locations for the last two nitride conferences couldn't have been more different. A year ago delegates found themselves in the heart of the world's gambling capital, Las Vegas. But this year it was the turn of quiet, picturesque Montreux, which sits in the Swiss Alps on the eastern shore of Lake Geneva.

Any attendees with an interest in mountaineering will have enjoyed looking up at the snow-capped peaks as they walked along the shoreline. And it's possible that they would have asked themselves: what is the easiest route to the top? OK, that face is smooth, but it's covered in snow and prone to avalanche, so the more rugged alternative might actually be the better bet.

The question of the most promising face is not just an issue for those heading off in search of the summit. It's also a central question for researchers developing GaN light emitters, who may have the choice of growing on either non-polar, semi-polar or more conventional polar substrates (figure 1, p18).

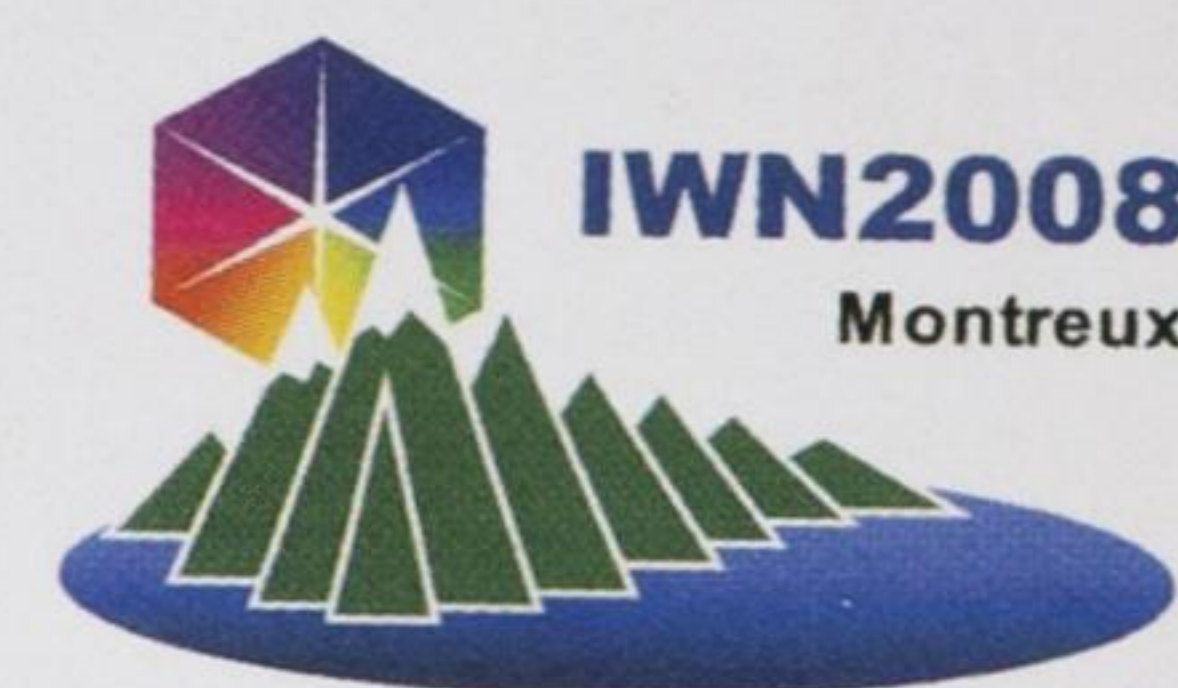
Rohm of Japan and the University of California, Santa Barbara (UCSB), are currently leading the development of light-emitting structures on the semi- and non-polar faces, and delegates at the International Workshop on Nitride Semiconductors were given an overview of the latter's efforts by Steven DenBaars. He began by reminding the audience that the benefits of moving to these planes include a substantial reduction in the internal electric fields that pull apart the electrons and holes in conven-

tional nitride devices. This produces a blue-shift in emission that increases with current density. With semi-polar and non-polar structures, wavelength shifts with current are far smaller, and the performance can be improved through the introduction of far thicker quantum wells. "But LEDs still suffer from droop," warned DenBaars, who didn't elaborate on the potential causes of the decline in external quantum efficiency (EQE).

UCSB researchers have been developing non-polar devices for several years, but early progress was held back by *r*-plane sapphire substrates that led to a very high density of stacking faults in the nitride epilayers. A switch to Mitsubishi Chemical's GaN substrates overcame that hurdle and opened the door to a range of high-performance devices.

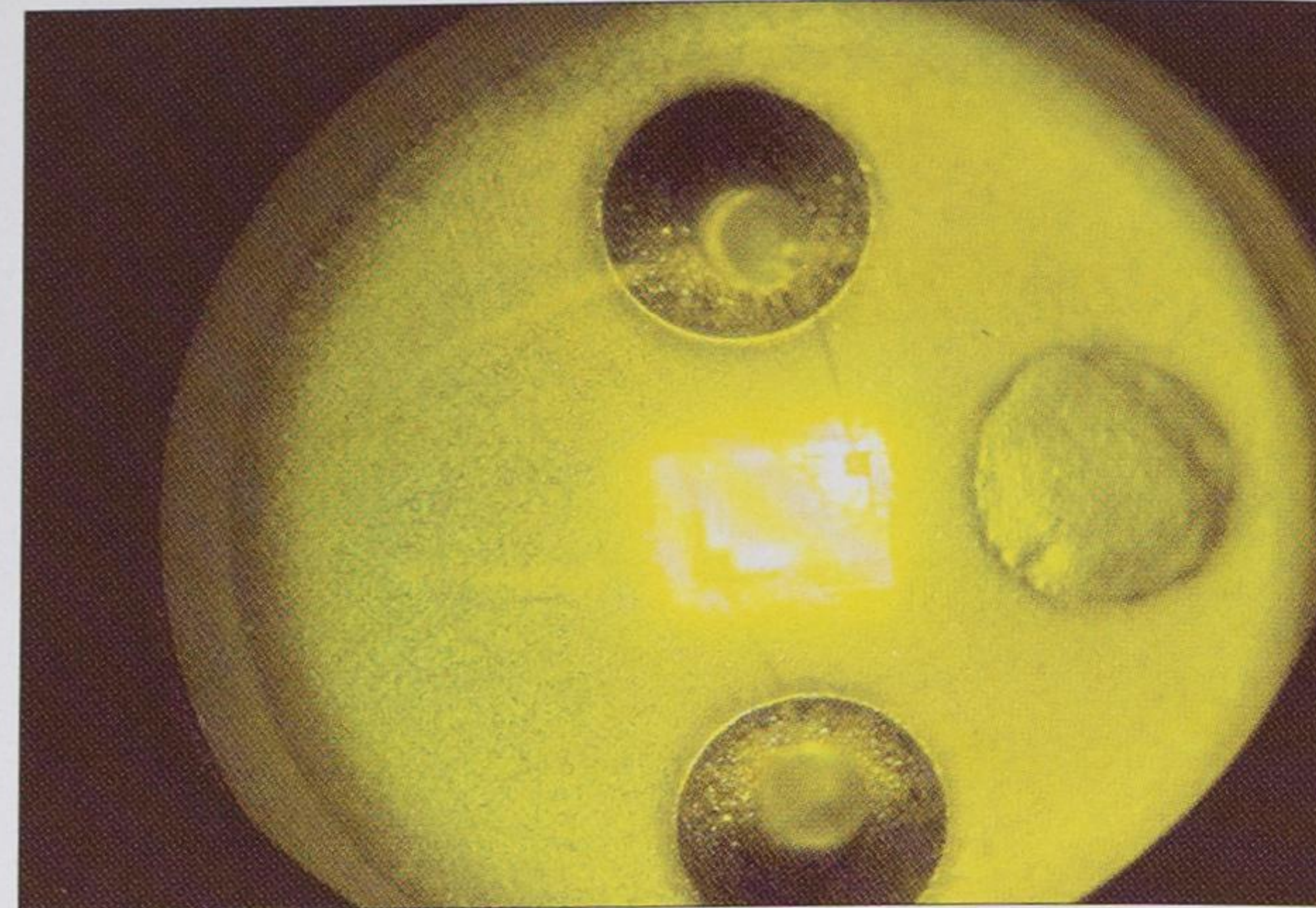
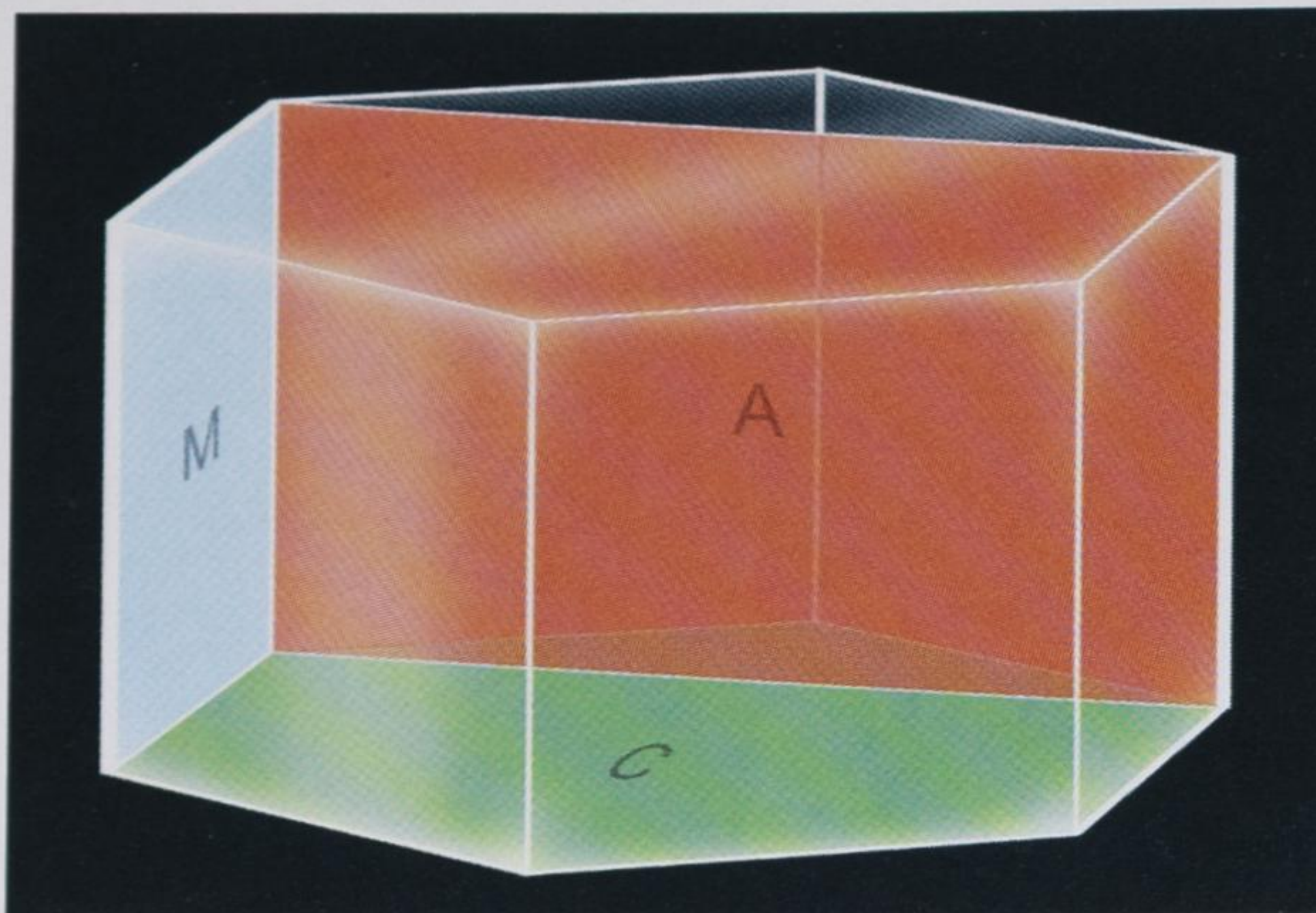
DenBaars' team has made good progress with its violet lasers over the last two years. The latest designs avoid the need for the problematic AlGaIn cladding layer, which causes cracking through tensile strain, a higher voltage operation and reduced yield. Mirror quality has also improved thanks to a switch to focused ion beam etching, which has helped to cut the pulsed threshold current density from 4.6 kA/cm<sup>2</sup> to 2.2 kA/cm<sup>2</sup>.

Rohm and UCSB want to increase the operating wavelength of their emitters, and DenBaars explained that his group was having a lot of success on the semi-polar plane. This provided a better basis than its non-polar cousin for growing the



**More than 650 delegates** attended the International Workshop on Nitride Semiconductors 2008, which was held in Montreux, Switzerland, on October 6–10.





**Fig. 1.** (left) GaN has a hexagonal crystal structure. Internal electric fields plague devices grown on the *c*-plane, but can be avoided by turning to GaN's *m*-plane. Efforts at the UCSB, have extended nitride LEDs into the yellow (right). These emitters, grown on semi-polar (11 $\bar{2}$ 2) GaN, show a far smaller decline in output power with increasing temperature than their AlInGaP equivalents.

highly indium-rich layers needed to push emission out to the green and yellow, but didn't suffer from the large blue-shift that plagues conventional polar *c*-plane devices.

In a separate talk, Anurag Tyagi from UCSB detailed recent efforts relating to green-laser development on the (11 $\bar{2}$ 2) plane. His device is similar to a *c*-plane laser, but incorporates a thick p-type AlGaIn layer rather than a GaN/AlGaIn p-type superlattice. Pumping this laser structure with a titanium-sapphire laser revealed a stimulated emission peak at 514 nm.

Even-longer wavelengths have been reached with LEDs on (11 $\bar{2}$ 2) substrates, according to another UCSB speaker, Hitoshi Sato. He told delegates about a device with a 3.5 nm thick InGaIn quantum well that produced 563 nm emission. Under pulsed operation with a 10% duty cycle, output powers and EQEs at 20 and 200 mA were 5.9 mW and 13.4%, and 29.2 mW and 6.4%, respectively.

### GaN boule growth

Although these results are very encouraging, the tiny pieces of GaN used as a growth platform are clearly unsuitable for high-volume manufacturing. However, Mitsubishi Chemical's Toshinari Fujimori said that 18 mm × 18 mm pieces should be available in the near future. And more importantly, the company expects to develop 2 inch material by 2010.

Hitting that goal would be a tremendous achievement, but production costs would still prevent non-polar substrates from being used for LED manufacturing. However, Steve Hersee from the University of New Mexico is pioneering a novel method for non-polar LED fabrication on polar substrates.

Hersee's trick is a scalable, uniform process that promises to build LED arrays based on nanowires. He's developed an interferometric process to create the template for these nanocolumns, which can be 0.5–20  $\mu$ m long and 90 nm to 0.7  $\mu$ m in diameter.

The big attraction with these nanowires is the absence of any defects, despite growth on typical GaN-on-sapphire surfaces, which have defect den-

sities of  $10^9$ – $10^{10}$  cm $^{-2}$ . Some future goals include the production of highly n-doped columns that are coated with an additional active region and p-type layers to make an LED array.

The leading LED manufacturers continue to advance the performance of polar devices. Osram Opto Semiconductors, Cree and Philips Lumileds all took the opportunity to unveil their personal bests.

Nathan Gardner from Lumileds unveiled the Californian chip maker's hero results in a talk that focused on the origins of droop – the reduction in EQE at higher drive currents. Interestingly, Gardner did not reveal any detail about the active region, even though his presentation detailed the benefits of a thicker well that combats droop through a reduction in the carrier density.

Lumileds' best results in the lab for a 1 mm × 1 mm white-emitting chip with a color temperature of 4600 K are 140 lm/W at 350 mA, 112 lm/W at 1 A and 100 lm/W at 1.5 A. These are all driven with 10  $\mu$ s pulses and a duty factor of 1%. Cranking the current up to 2 A increased output to 562 lm, which Gardner claimed to be comparable to the output of a 40 W incandescent bulb.

Cree's James Ibbetson decided to focus his talk on the performance of the company's best LED products. Many of the company's 1 mm × 1 mm chips are housed in the 7 × 9 mm XR-E package and put into a performance bin matched to the lumen output at 350 mA. The top bin contains 107–114 lm LEDs that are based on 450–460 nm blue-emitting chips delivering 500–540 mW. This equates to an EQE of 54%, which falls by 14% as the current is ramped to 1 A.

Ibbetson also mentioned the company's current lab record – a 141 lm white LED, which featured a 620 mW blue chip. This LED suffered from less droop than the company's commercial LEDs, but Ibbetson admitted that this partly resulted from the use of a larger chip with undisclosed dimensions, which cuts the current density.

Johannes Baur revealed that Osram's best lab result at 350 mA is slightly better than Cree's – the German chip maker can hit 643 mW. Baur also



detailed the results of another  $1\text{ mm} \times 1\text{ mm}$  developmental chip with an output of 601 mW at this drive current, which can form the backbone of a 155 lm output white LED. This blue emitter delivers 1.97 W at 1.4 A and 3.2 W at 3 A.

Non-polar nitrides on sapphire are being used as the basis for the latest ultraviolet (UV) LEDs that are targeting polymer curing, and air, water and food purification. Vinod Adivarahan from Nitek, a spin-off of Asif Khan's group at the University of South Carolina, revealed a new contact geometry that can boost device output. He explained that the effects of current crowding can be minimized by switching from a traditional single contact to an array of independent pixels.

A UV LED with this design that features an array of  $10 \times 10$  contacts, each  $20\text{--}30\text{ }\mu\text{m}$  in diameter, operates at 5.2–5.5 V at 20 mA. Light output power saturates at a higher value than standard LEDs and lifetime “looks good”, according to Adivarahan.

The company has also built a  $3\text{ mm} \times 3\text{ mm}$  chip that features several  $10 \times 10$  arrays of contacts and delivers 35–37 mW at 800 mA. “Lifetime tests on this LED are underway,” said Adivarahan.

Sensor Electronic Technology, an earlier offshoot of the University of South Carolina, also detailed its latest advances in chip design. Yuri Bilenko said that the firm has been developing LED lamps that

can incorporate 90 individual chips. These require massive heat sinks, but can deliver a continuous output of more than 80 mW at 275 nm and a drive current of 1.4 A. “265–285 nm lamps will be delivered to customers in their hundreds,” claimed Bilenko.

The week-long conference also included several reports of developments of nitride materials and devices on the cheapest of all platforms – silicon. Sudhiranjan Tripathy from Singapore's Institute of Materials Research and Engineering is pioneering a novel twist on this theme, by switching the growth platform to a silicon-on-insulator (SOI) wafer. This has one major advantage over silicon for blue and green light emitters – any light entering the substrate is reflected rather than absorbed.

Tripathy's team has produced crack-free epiwafers on 6 inch SOI substrates and he sees no reason why this process can't be scaled up to 8 and even 12 inch material. His team has produced  $0.3\text{ mm} \times 0.3\text{ mm}$  LEDs with a 5-period InGaN/GaN multi-quantum well that emits at 525–530 nm, but delivers only 1.2 mW at 20 mA. Tripathy admits that his devices are not all that bright: “We need more research and development efforts to improve their internal and external quantum efficiencies.” But there's no doubt that this platform, and the more exotic surfaces of GaN, are already offering a host of opportunities to extend the performance of nitride emitters. ●

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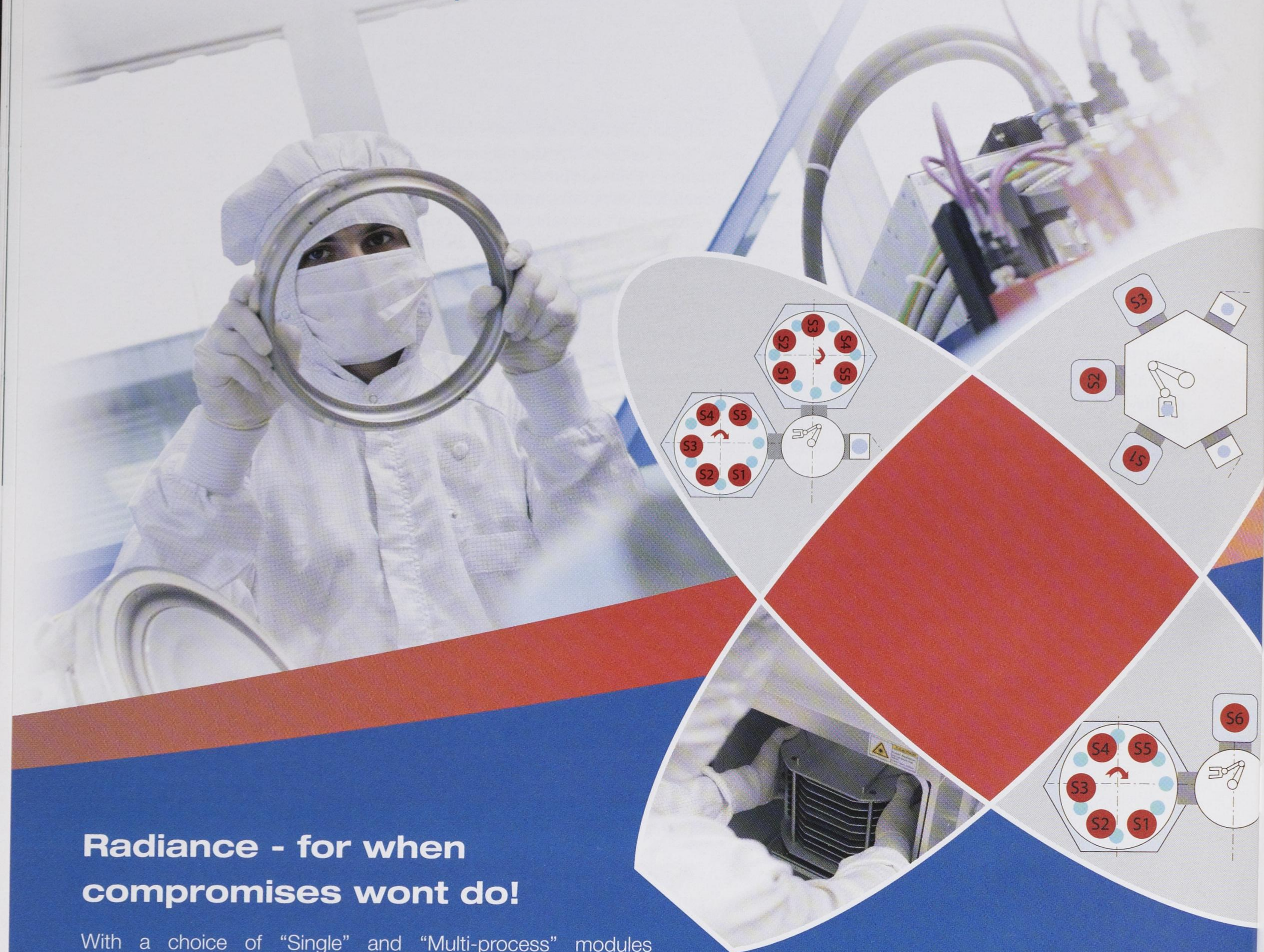
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# Avago shrinks its chip footprint

Surface mount processes that populate printed circuit boards with passives can now add active die too, thanks to Avago's WaferCap technology. This ultimately opens up a path to low-cost amplification for cable TV, base stations and instrumentation, says the company's **Jim Roland**.

There are numerous uses of wireless connectivity. It's employed for simple tasks, such as opening a garage door, through to highly complex military applications that demand ultra-small radio sensors.

In many cases, the manufacturers of these wireless products are looking for RF components that meet three criteria: a very thin profile; the ability to support high data rates; and competitive pricing, which is a big factor for products that are launched in consumer markets.

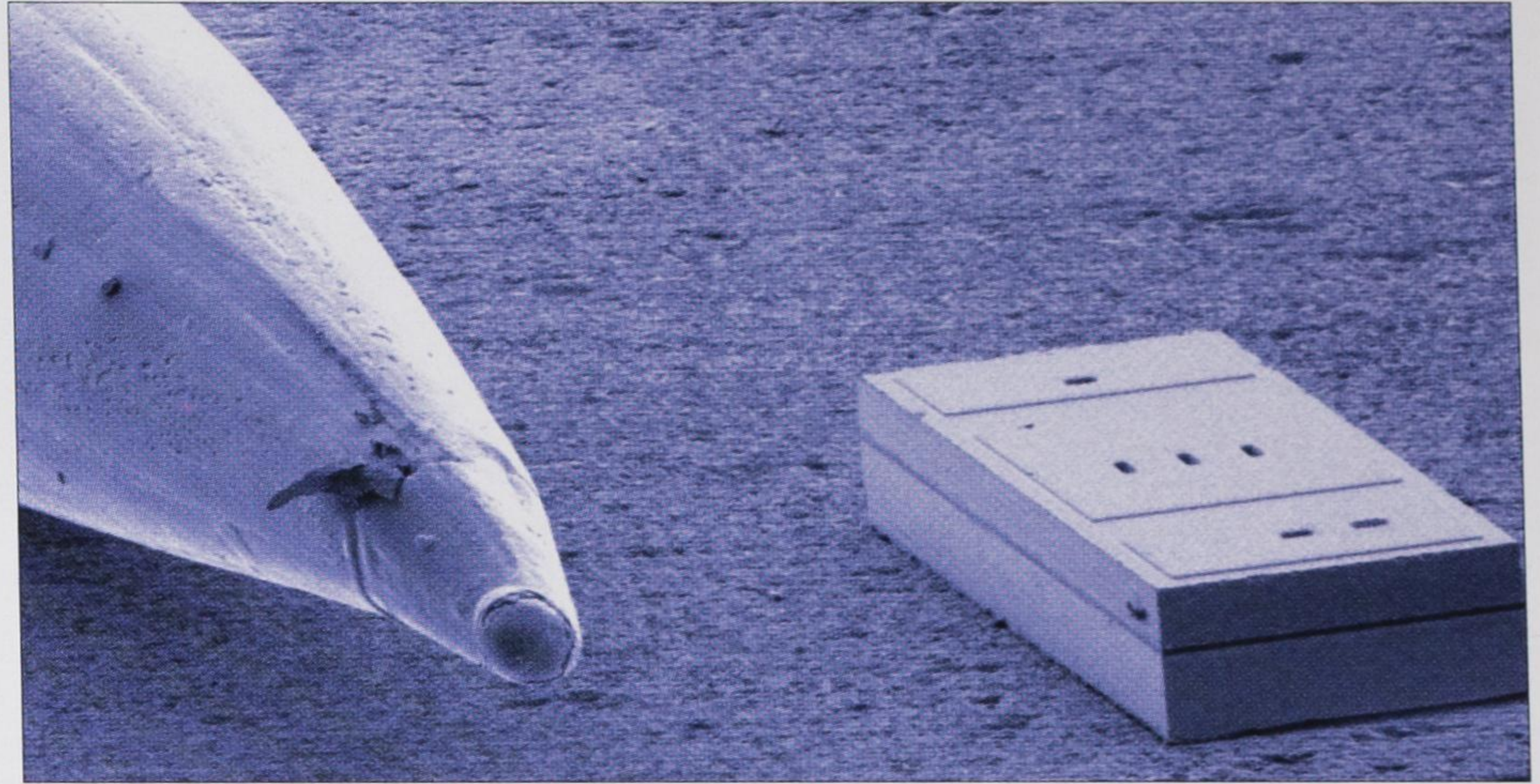
At Avago Technologies' Wireless Semiconductor Division, which is headquartered in San Jose, CA, we fulfill all of these requirements with our innovative WaferCap packaging technology.

WaferCap is a process that joins a 6 inch GaAs wafer with processed transistors to a bare wafer of the same dimensions with a polymer gasket seal. This encloses the perimeter of the die to create an air-cavity wafer-scale package, which differentiates it from the majority of chip-scale packaging technologies that are currently in use. The bonded wafers are then cut up into thousands of individual, robust packages that have the potential to operate at up to 100 GHz, thanks to the low dielectric constant of the air cavity above the active region.

The production of a typical RF package involves wafer manufacture and die packaging at separate locations, using different equipment and process skills. But with our approach we can greatly simplify the supply chain, because the same site is used for wafer fabrication, wafer bonding, via and pad formation, test and dicing.

Our WaferCap package is intentionally the same size as the widely used 0402 component – 1 mm × 0.5 mm × 0.25 mm. This is compatible with standard tape and reel sizes, and means that printed circuit boards can be populated with our die using inexpensive surface mount technology that is normally restricted to passive components. Both active and passive components can be attached during the same process, leading to time and cost savings. The WaferCap format shrinks the RF device's footprint on a printed circuit board by up to 50% compared with a standard package.

This approach compares favorably to that used for the more common bare die, which have a more complicated supply chain. For bare die, after they are attached with conductive epoxy and wire-bonded, an



**Avago's WaferCap die** is comparable to the size of a pinhead. It measures just 1 × 0.5 × 0.25 mm.

**Table 1. Amplifiers employing WaferCap technology**

| Part      | Type                         | Market                                        |
|-----------|------------------------------|-----------------------------------------------|
| VMMK-2103 | 1–6 GHz bypass LNA           | wireless data and voice-receiver applications |
| VMMK-2203 | 1–10 GHz high-gain LNA       | wireless data and instrumentation             |
| VMMK-2303 | 0.5–6 GHz low-voltage LNA    | wireless applications, 1.8 or 3.0 V supply    |
| VMMK-2403 | 2–4 GHz IP3 LNA              | low-noise RF applications                     |
| VMMK-2503 | 1–12 GHz wide-band amplifier | wide-band gain block                          |

additional polymer coating is needed to protect the exposed wire bonds and the die's active surfaces.

With the approach that we advocate, surface mount attach costs are minimized through screen printing with lead-free solder paste, helping parts to self-align on the printed circuit board. Passives are added, along with other elements with solderable pads, before the entire assembly is transferred to an oven to complete the soldering process.

The solderable pads for WaferCap are designed in the same way as the pads for a typical passive component. They are terminated with a solderable metallic layer, typically copper or nickel, and coating this layer or chemically treating it prevents oxidation. Neither approach inhibits the solder contact.

Another consideration for the WaferCap solderable pads is to protect the underlying metal, which is used to make electrical contact through backside vias, from the solder environment. This is done by inserting a conductive barrier layer between the



## Manufacturing at the legendary Ft Collins fab

Avago developed WaferCap at its Ft Collins, CO, facility. Hewlett-Packard first owned this chip-making fab, but it was transferred to its spin-off Agilent Technologies in 1999, and became part of Avago Technologies in December 2005.

For more than 30 years the facility has been responsible for leading-edge, flagship central processor unit manufacturing, support chips, NMOS, CMOS, bipolar, CMOS image sensor and other technologies. This roll call has occurred despite significant outsourcing of US semiconductor manufacturing capacity over the same time period. More recently, business needs have required new technologies including MEMS and advanced RF GaAs, and



silicon and GaAs wafer-scale packaging.

Today, Avago's captive manufacturing facility allows the co-development of design and focused manufacturing capability, which can combine to match the needs of the pending design. This approach cuts the turnaround times that occur in development and ultimately ensures a faster time to market.

solderable metal and underlying pad metal.

Soldered parts that have been attached to the pads in this manner have passed several qualification tests, including multiple reflow and shear, drop, cycle bending, vibration and thermal cycle.

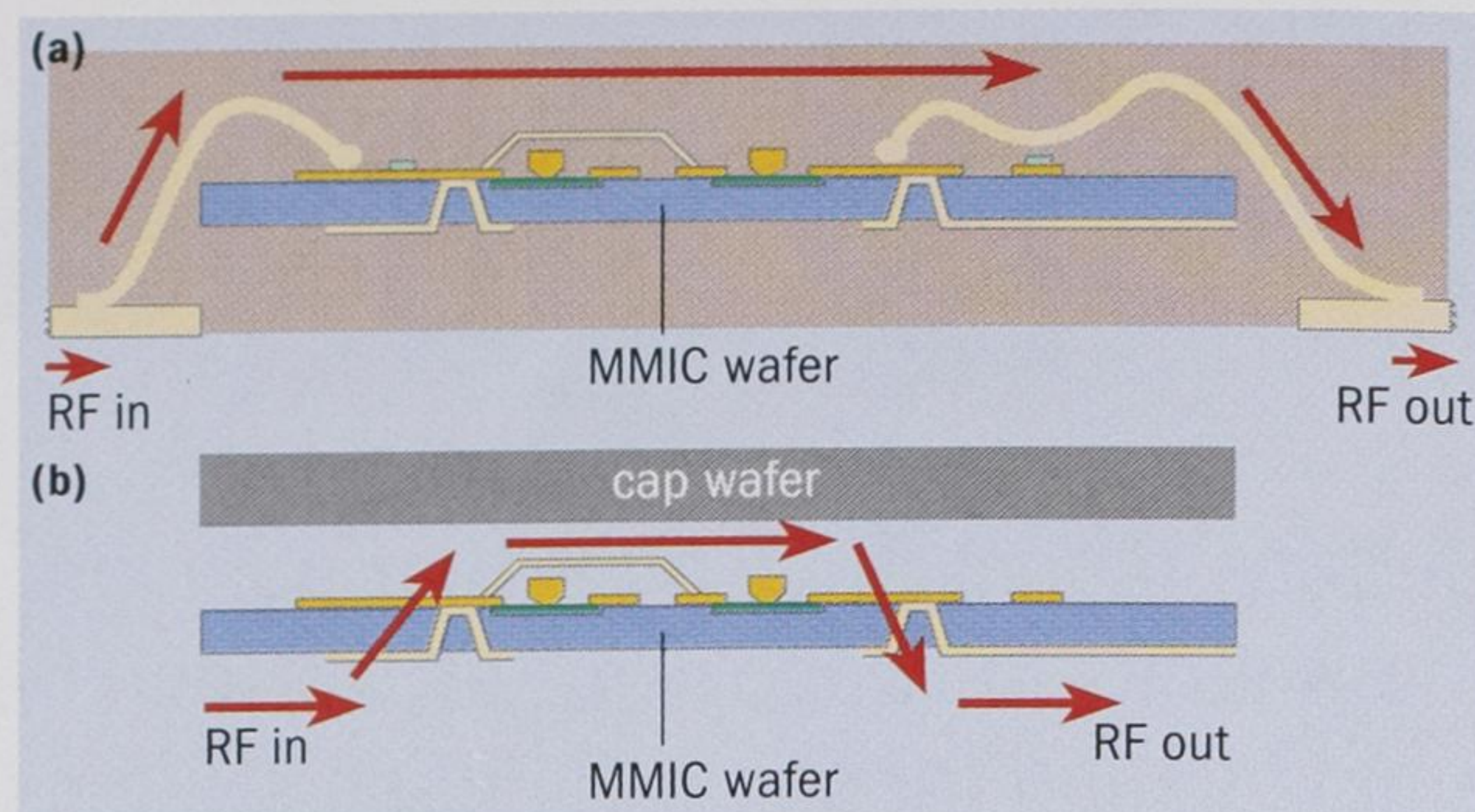
### RF performance advantages

Our WaferCap design provides short lead lengths, minimal inductance with low variability and RF transitions with minimal parasitic loss, thanks to routing of input and output signals along the back-side of the device wafer through via holes. This is a massive improvement over conventional plastic packages, which have higher parasitic losses that degrade performance. Their inferiority results from the high-dielectric-loss carbon polymer that encapsulates bond wires and active circuits. Our approach also delivers a greater consistency of the lead design, which removes the need to tune wire bonds.

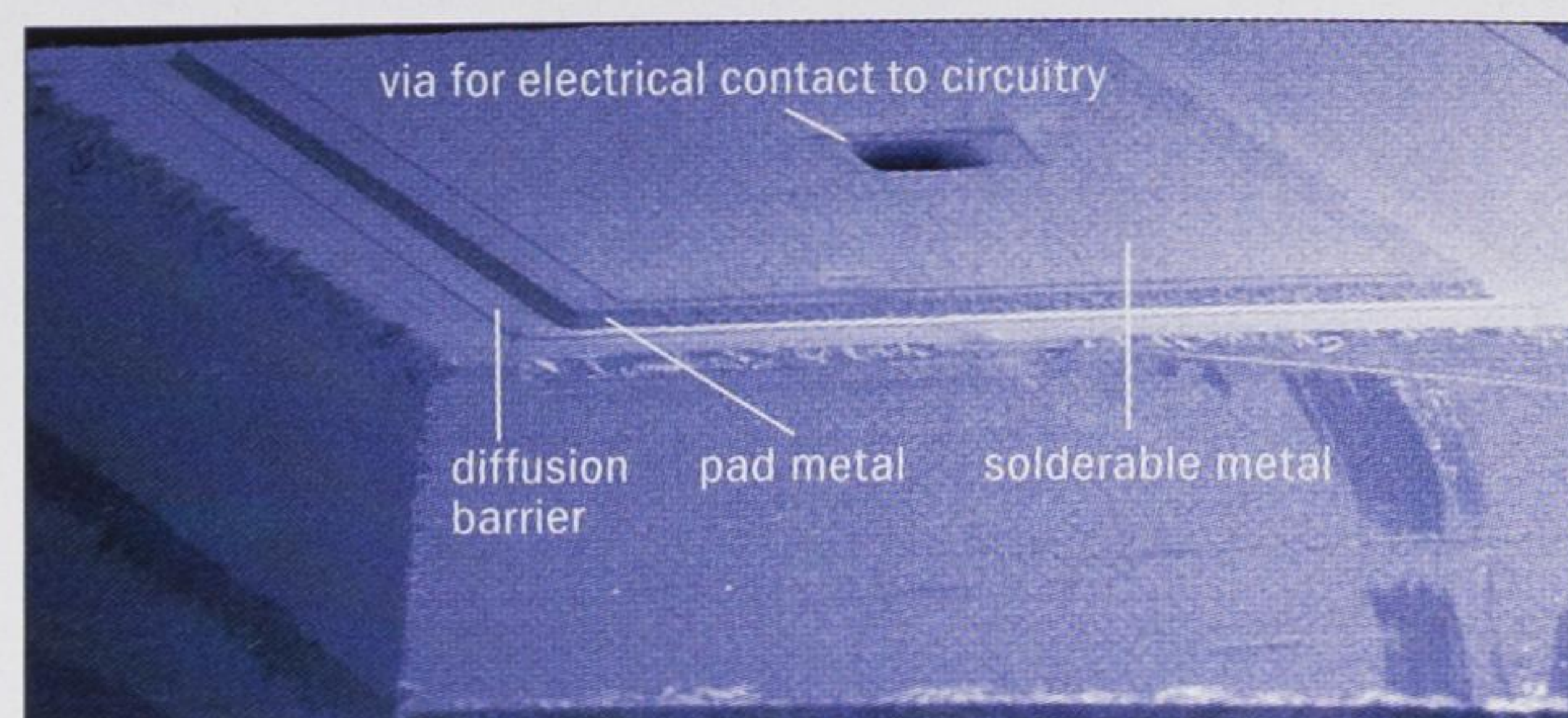
Device modeling suggests that our devices can form amplifiers operating in the 17–33 GHz range (*Microwave Journal* August 2008). These simulations show that our chips are capable of operating well beyond 50 GHz and we believe that they have the potential to stretch to 100 GHz.

We have investigated several applications that can derive the biggest benefit from the unique properties of WaferCap technology. Three different amplifier designs have been developed – a 1–12 GHz 50  $\Omega$  gain block, a 0.5–6 GHz bypass low-noise amplifier (LNA) and a 1–6 GHz low-voltage LNA. We have recently detailed each of these designs at the European Microwave Conference, which was held in Amsterdam, the Netherlands, on October 27–31.

These three amplifiers could serve many commercial wireless applications in the 0.5–12 GHz range. However, we believe that they will also prove their worth in other markets. They could be used to pro-



**Fig. 1.** Typical radio-frequency packages feature bond wires and active circuits encapsulated in high-dielectric-loss polymers, which increase parasitic loss and degrade device performance (a). Avago's WaferCap technology features a shorter lead length that cuts inductance and its variability (b).



**Avago Technologies' WaferCap die** have dimensions that are the same as many passive components and they can be mounted on printed circuit boards using similar processes.

vide broadband amplification to signals transmitted through coaxial cable for cable TV, or deliver amplification in base stations and instrumentation.

We have started by incorporating our enhancement-mode PHEMT technology into WaferCap products. This creates high dynamic range, ultra-low-noise integrated circuits with high gain, which can operate from a single positive DC supply.

Our next step will be to design additional products into the 0402 package format. Customers are currently evaluating some of these parts (see table 1, p21, for details), which could form the building blocks of circuits targeting specific applications.

Further down the road we will be launching a two-pronged process development program. One aim is to extend our WaferCap technology to include other types of transistor, such as enhancement-mode and depletion-mode HEMTs. We are also aiming to extend it to other standard package sizes. Going smaller will cut costs, while increasing size promises more integration and greater performance. We're planning to release products based on this development in 2009, which will allow our customers to enjoy more benefits from this technology.

### Further reading

An interactive video presentation describing Avago's WaferCap technology can be seen at [www.avagotech.com/pages/products/wsd-vmmk/](http://www.avagotech.com/pages/products/wsd-vmmk/). More information is available at [www.avagotech.com/pages/wafercap](http://www.avagotech.com/pages/wafercap).



### About the author

**Jim Roland** is a process integration engineer at Avago Technologies. He is responsible for developing new or evolved processes for manufacturing.



# IMEC enlarges nitride epiwafers

GaN FETs grown on large silicon wafers should make a big impact in the multi-billion dollar power electronics market. They can operate at breakdown voltages of up to 800 V, offer superior switching efficiencies to silicon incumbents and give little away in cost, says IMEC's **Marianne Germain**.

Tune in to the news and two of the phrases that you'll probably hear repeatedly are "energy scarcity" and "sustainable energy generation". Many nations considering these issues have decided to try to reduce their dependence on oil and gas imports, which makes even more sense given the recent volatility in the energy markets. Greener forms of domestic power generation are now viewed as the way forward, alongside more-efficient energy usage.

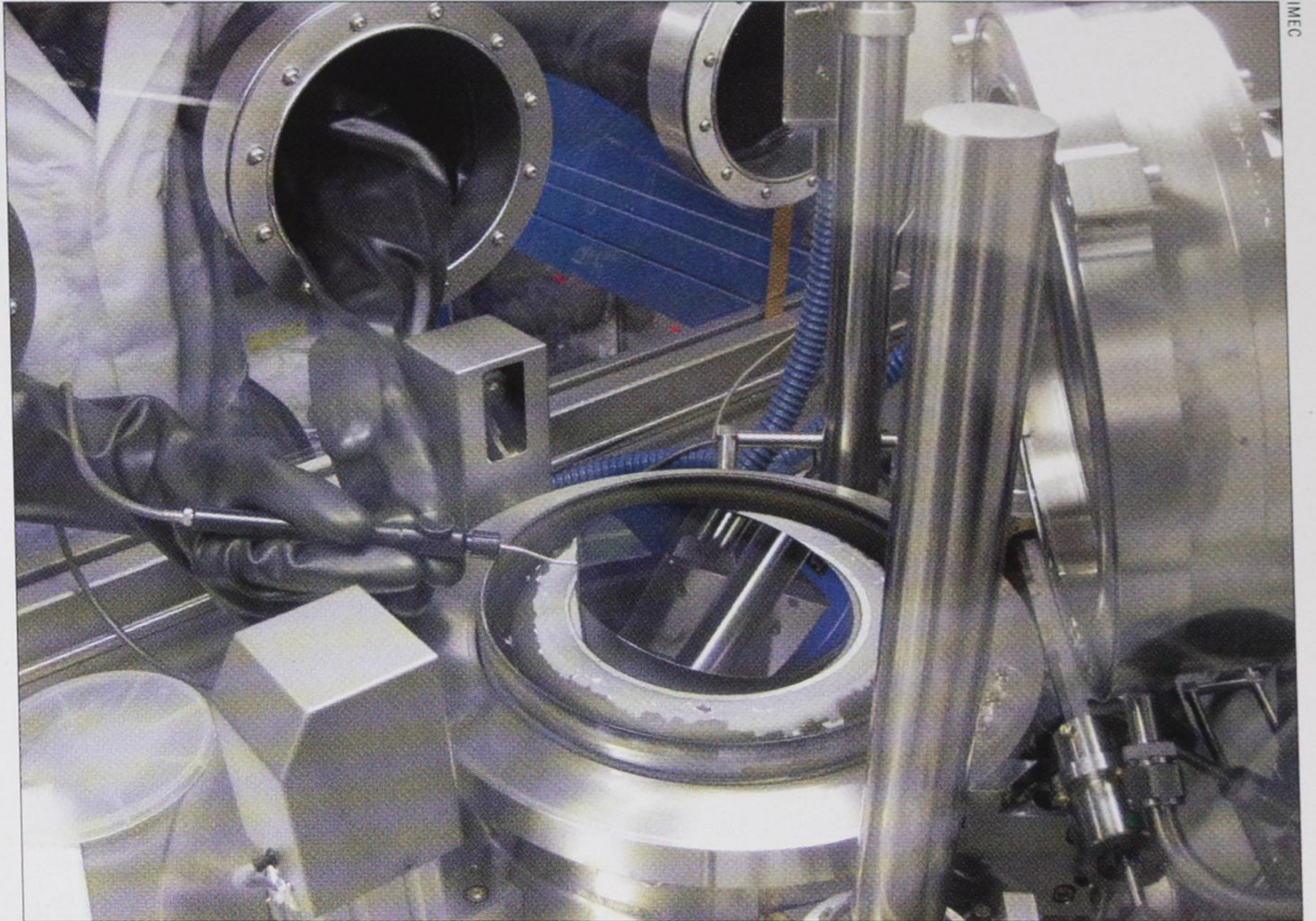
Power electronics has a big role to play in these endeavors because it influences the operating efficiencies of existing electrical equipment and that of emerging renewable technologies. This form of electronics is already incorporated in computer switch-mode power supplies, and it is also deployed in the electrical conversion systems found in hybrid electric vehicles and solar power plants.

Unsurprisingly, revenue generated by power electronics is rising substantially. According to French market research firm Yole Développement, power electronics currently accounts for 10% of the total semiconductor market. Sales from this sector are increasing at a compound annual growth rate of more than 11%, which is 4% faster than the overall semiconductor market.

Although power electronics has a healthy outlook, improvements in component operating efficiencies are minimal. Silicon is the overwhelmingly dominant technology and it has already been optimized. Today, for example, the best silicon MOSFET already slightly outperforms its unipolar limit.

To significantly improve efficiency, what's needed is the development and commercialization of devices built from new materials. This effort is already well underway, and academic and industrial researchers around the globe have been developing devices based on wide-bandgap materials that have far higher breakdown voltages and operating temperatures. Our independent research center, the Interuniversity Micro Electronics Center (IMEC) in Belgium, is part of this effort, and we have been working on GaN-based devices.

GaN has one major advantage over the other popular wide-bandgap material, SiC – it can form an epitaxial heterostructure with AlGaN. This combination creates a two-dimensional electron gas with excellent transport properties at its interface, and ultimately leads to transistors with the best com-



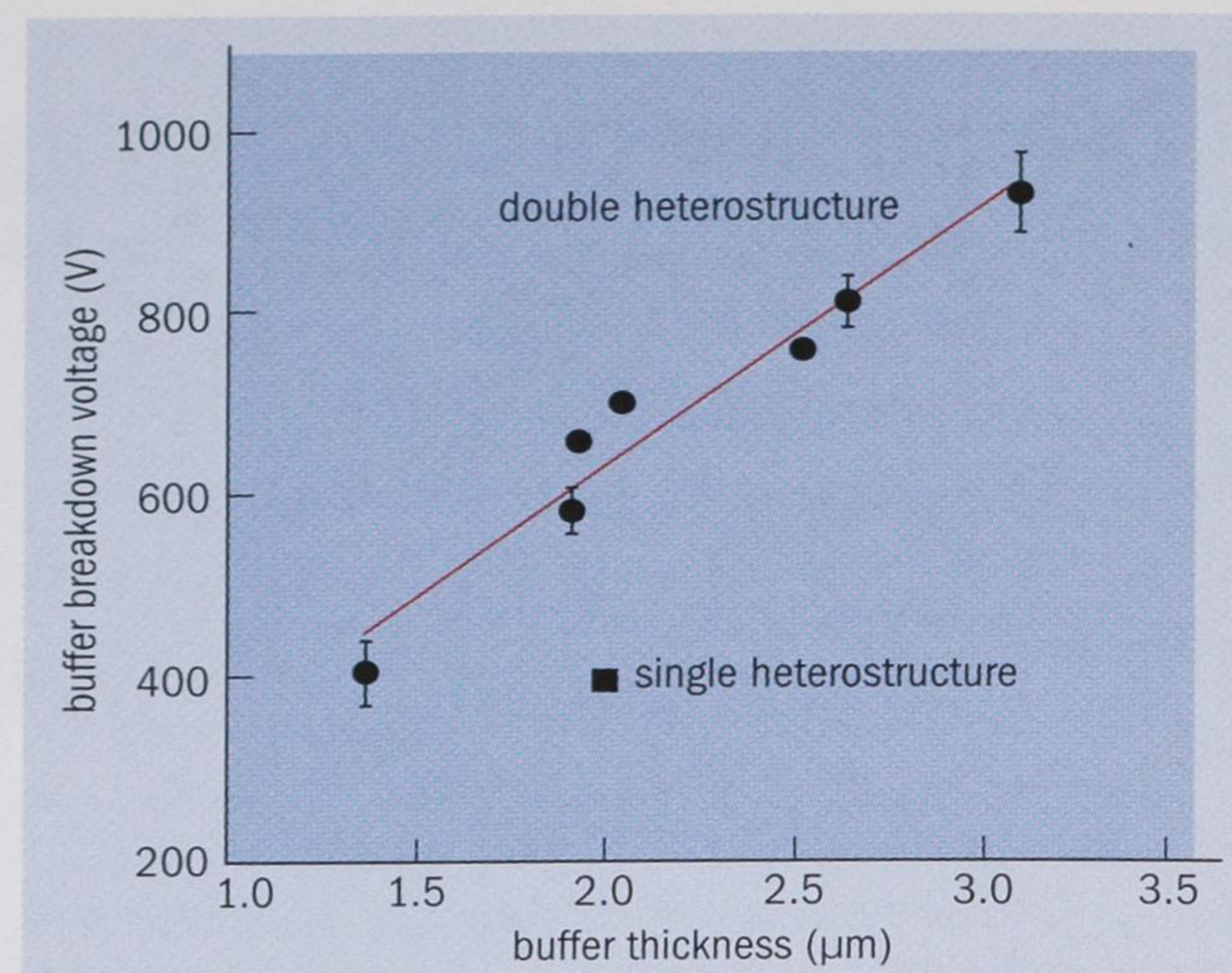
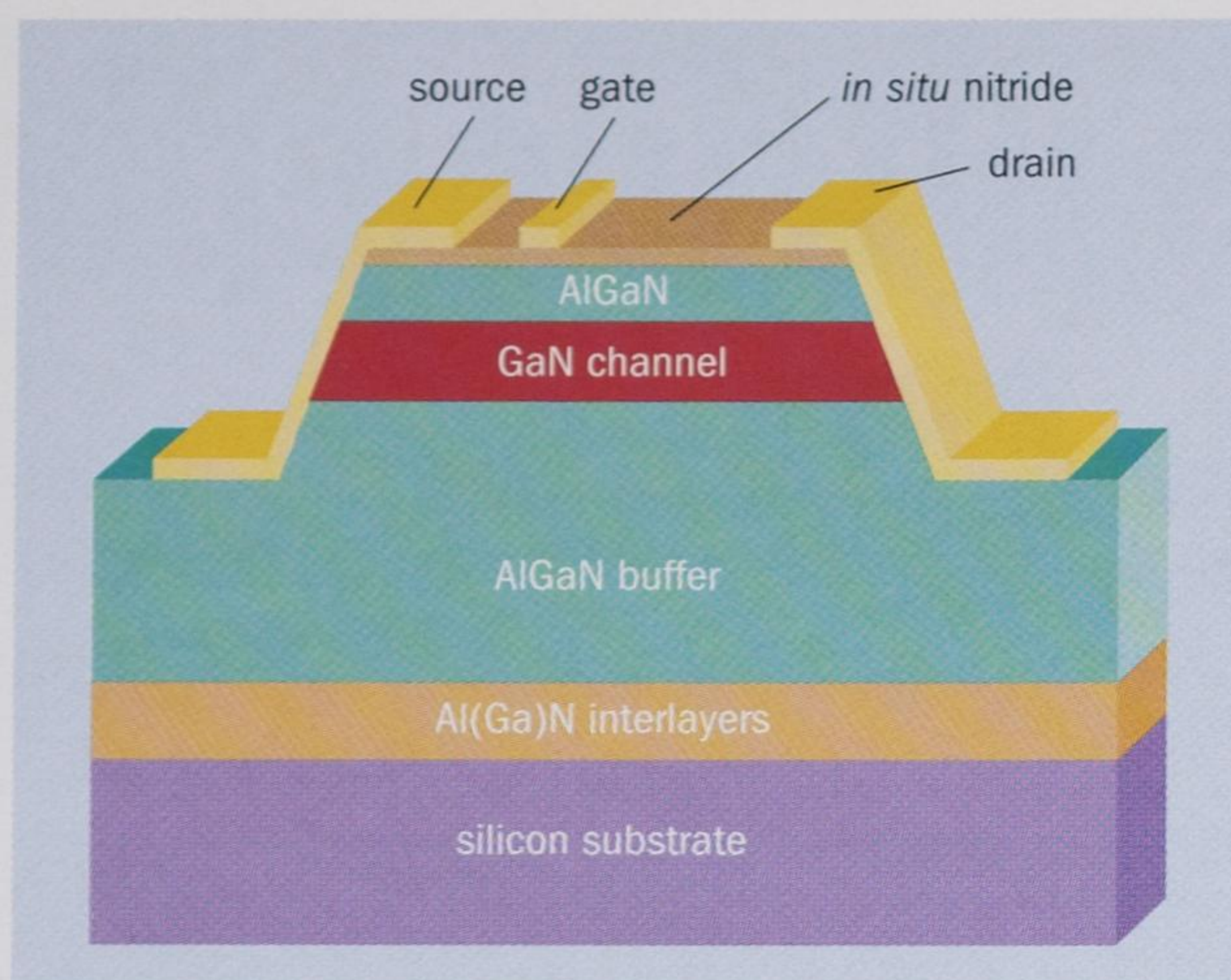
IMEC produces its AlGaN/GaN FETs on 150 mm silicon substrates using an Aixtron MOCVD tool.

bination of high voltage and high electron velocity. This type of device also delivers very low switching and conduction losses – lateral GaN HEMTs are three to four orders of magnitude better in this regard than vertical silicon MOS structures.

However, GaN-based power electronics with this array of characteristics will only generate substantial sales if prices are comparable to those of silicon devices. This means that manufacture must be carried out on a low-cost platform that is easy to process. Silicon substrates meet these requirements, particularly when they have diameters of at least 150 mm. If reliable devices with 600–1000 V breakdown voltage and a low specific on-resistance can be reproducibly manufactured on this platform, then there is a good opportunity for a chip maker to grab a significant share of the power electronics market.

At IMEC, we have started to develop a process for this type of chip manufacture and have reproducibly fabricated large, crack-free, GaN-on-silicon epiwafers. These can be processed to form FETs with breakdown voltages of more than 600 V and specific on-resistances that are an order of magnitude lower than commercially available silicon MOSFETs.





**Fig. 1.** (left) Diagram of the double-heterostructure (DH) FET. **Fig. 2.** (right) Voltage breakdown measurements are performed between two ohmic contacts processed on two different mesas. The novel DHFET structure increases the breakdown voltage by 50% for equivalent buffer thicknesses. Further improvements to 1000 V and beyond can result from thicker buffer layers.

### LEDs on silicon

IMEC is developing new processes for the fabrication of green LEDs on large-diameter silicon and sapphire substrates. Increasing the device efficiency in the green gap is crucial for display applications. By incorporating SiN interlayers, the threading dislocation density of GaN-on-silicon material has already been lowered by one order of magnitude and the dislocation density is now comparable to GaN-on-sapphire. The program's next challenge is to grow InGaIn quantum wells with sufficient indium for green emission.

Our growth is carried out on silicon (111), the cheapest form of silicon substrate that is suitable for III-nitrides. We've been developing our growth process on this material for several years, and in 2006 we produced the first crack-free AlGaIn/GaN HEMT epiwafers on 150 mm silicon for RF applications. This was followed up by a collaboration with the German MOCVD equipment manufacturer Aixtron that led to the growth of a 1 μm thick crack-free epitaxial layer of GaN on a 200 mm silicon substrate, which we announced this June.

### Stresses and strains

Controlling the stress within the epilayers is a major challenge for III-nitride growth on silicon. Stress engineering in the heterostructure is the only solution for deposition on large-diameter substrates, and our approach involves the addition of sufficient compressive strain during growth. This strain can balance the tensile stress that results from the post-growth wafer cooling.

We employ various tools to assist our strain engineering that provide *in situ* measurements of temperature and wafer bowing. This includes "Argus", a temperature measurement tool co-developed with Aixtron that features a calibrated photodiode array. We use an interferometer that monitors epi-

wafer reflectivity and also provides data that can reveal growth rates and surface roughness. This tool has been modified to detect any deviation of the laser beam and reveal any bending or bowing in the wafer. These tools have played a crucial role in the development and implementation of our growth processes, which can now produce crack-free, mirror-like epiwafers with acceptable levels of wafer bow for processing.

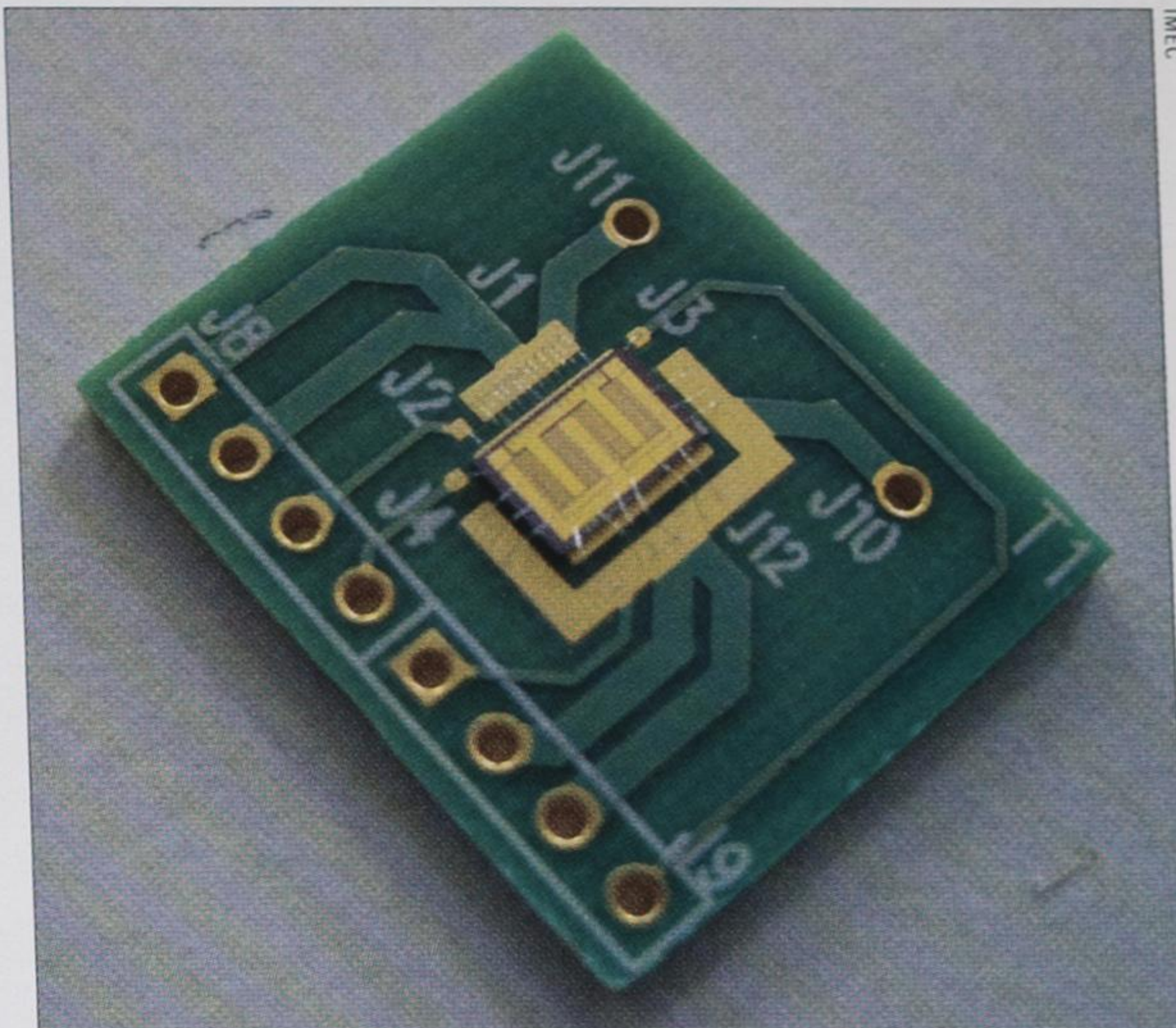
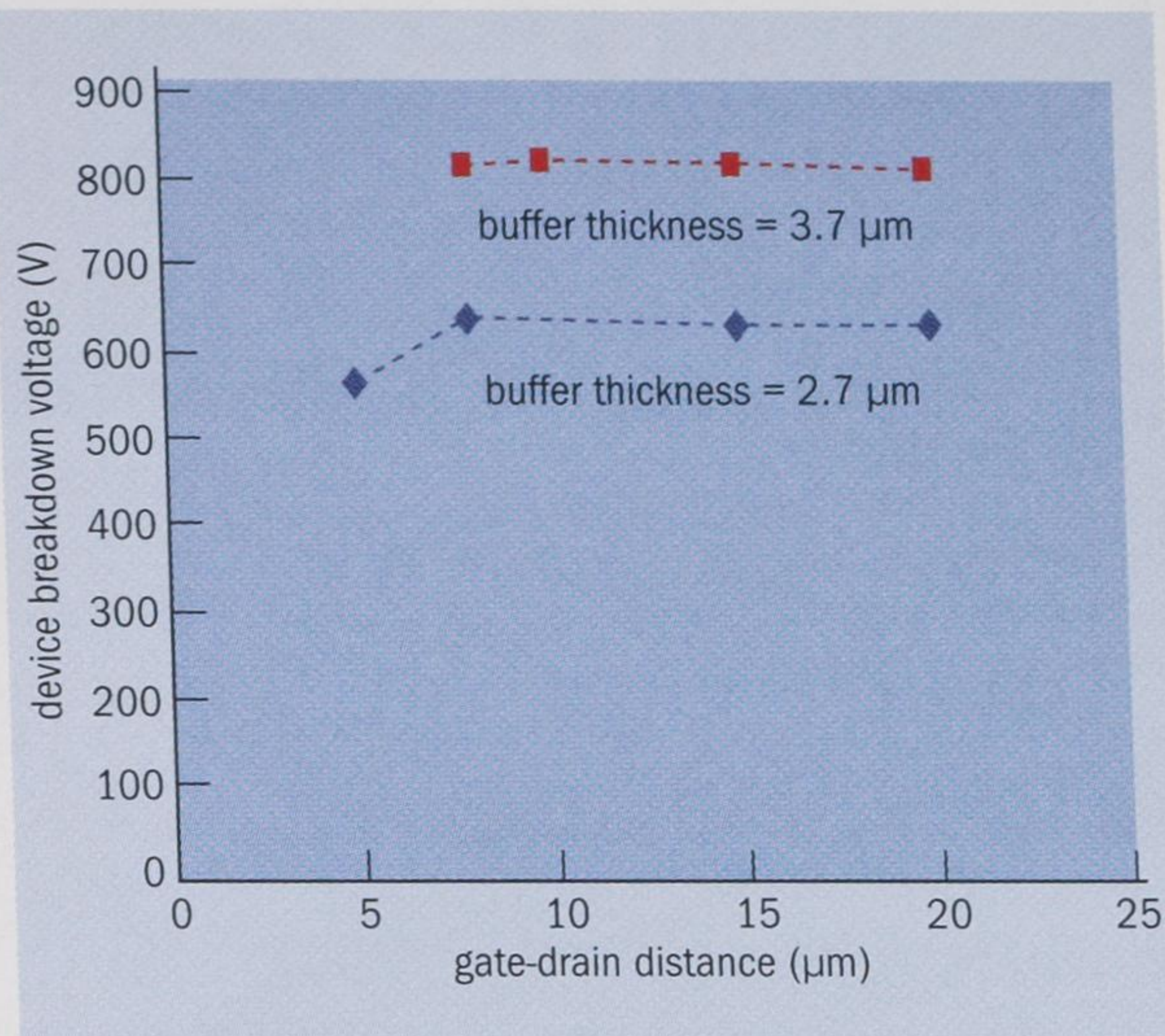
Material for power electronics must also be able to withstand high operating voltages. We have found that although the standard AlGaIn/GaN HEMT structure is suitable, breakdown voltages can be increased by more than 50% by adopting a double-heterostructure design. This improvement is delivered without any increase in the separation between the source and drain contacts, and can produce devices that reach a breakdown voltage of 1000 V at a buffer thickness of 3.7 μm. Performance gains result from greater confinement of electrons in the channel and increased aluminum content in the AlGaIn layers (figure 2).

We have also discovered that the breakdown voltage is actually limited by the silicon substrate, rather than the AlGaIn layer, if the contacts are separated by more than 5 μm. Increasing the buffer thickness can deliver further gains in breakdown voltage, as long as the stress is controlled.

After our epitaxial structure has been deposited, a Si<sub>3</sub>N<sub>4</sub> layer is added *in situ* by MOCVD to protect the underlying III-nitride layers. This patented deposition process creates a smooth, passivated surface that is stable up to 900°C and suitable for device processing.

Our *in situ* SiN passivation process has several unique features. It prevents the AlGaIn surface from reacting with air and it allows deposition of high-quality AlGaIn layers with higher aluminum content, by preventing relaxation of this layer. Higher aluminum-content AlGaIn layers bring several benefits, including a reduction in sheet resistance





**Fig. 3.** (left) Breakdown voltage of lateral SiN/AlGaIn/GaN/AlGaIn double-heterostructure (DH) FETs deposited on silicon substrates versus the gate-drain distance. For thick layers, a device breakdown of more than 800 V can be demonstrated for gate-drain distances as low as 6 μm. **Fig. 4.** (right) IMEC's SiN/AlGaIn/GaN DHFET, deposited on silicon and mounted on a test board.

and a lower on-resistance. We can employ our Si<sub>3</sub>N<sub>4</sub> deposition process in a controllable and repeatable way to regularly produce double-heterostructure FET epiwafers with *in situ* SiN passivation on 100 and 150 mm silicon.

Material produced by this approach has been processed into FETs with breakdown voltages of up to 800 V. These devices have the smallest gate-drain distances for a transistor with this breakdown voltage, despite the absence of field-plates that reduce peak electric field strength. This result illustrates the promise of III-nitride devices, which have the potential to overturn silicon equivalents that currently dominate the power electronics industry.

### Lateral thinking

Our small gate-drain distance – it is only 5 μm in our transistors with a 600 V breakdown voltage and their 800 V equivalents with a 3.7 μm buffer thickness – improves device performance. This is because the channel resistance restricts the performance of these lateral devices, which feature source, gate and drain contacts on the top surface. However, the effect can be minimized by placing the source and drain contacts closer together.

The on-resistance of our GaN-on-silicon double-heterostructure FETs is more than one order of magnitude smaller than silicon devices. The specific on-resistance of our 600 V transistors is just 4 mΩ cm<sup>-2</sup>, which is comparable to the best values obtained by other GaN-on-silicon developers. However, our transistor combines its low on-resistance with increasingly small lateral device dimensions. It is possible that more device improvements could result from better designs and further reductions in contact resistance.

Silicon MOSFETs have been criticized for relatively high losses during switching. Fortunately, our GaN transistors don't seem to suffer from the same fate and ongoing studies show that they have prom-

ising switching characteristics (reduced transient times). Silicon devices are still plagued by Miller capacitance – the parasitic capacitance between gate and drain – which leads to charging of the gate and ultimately inefficient device switching. Our devices, on the other hand, have a much lower Miller capacitance and its effect on the switching performance is negligible.

One of the drawbacks of these GaN HEMTs is that they operate in depletion mode. Enhancement-mode devices are preferred from a safety perspective in power-conversion applications because they are normally off. But we have produced some normally off HEMTs that have a positive threshold voltage of 0.3 V and a current density of more than 0.3 A/mm. The process used to make these devices included a fluorine implantation below the gate. However, this is not ideal because it causes local damage below the gate of the channel, leading to large current dispersion and instability at high temperature.

We are planning to improve the performance of our enhancement-mode HEMTs by optimizing the top layer stack. Other efforts over the next few years will include the development of transistors with breakdown voltages of 1000 V and a reliability study of our devices. We've also noticed that standalone GaN devices are being sampled to the market and we believe that the integration of Schottky AlGaIn/GaN diodes and transistors on the same die, processed within the same flow, offer an extremely promising technology for making power-converter modules. This type of technology could, for example, integrate solar-power inverters closer to solar cells, thereby reducing the complexity and size of solar systems.

### Further reading

K Cheng *et al.* 2008 *Phys. Stat. Sol.* **5** 1600.  
D Visalli *et al.* 2008 *Ext. Abstr. IEEE Int. Conf. on Solid State Devices and Materials, Tsukuba* 148.



### About the author

**Marianne Germain**  
(Marianne.Germain@imec.be) has a PhD in electrical engineering from the Université de Liège, Belgium. She joined IMEC in 2001 and since 2007 has led the NEXT/III-V group, focusing on III-nitrides. She thanks S Degroote, M Leys, K Cheng, J Derluyn, M Van Hove, D Visalli, J Das and F Medjdoub for the development of GaN-on-silicon epiwafers and associated high power, and Prof. G Borghs for the scientific leadership of the program.



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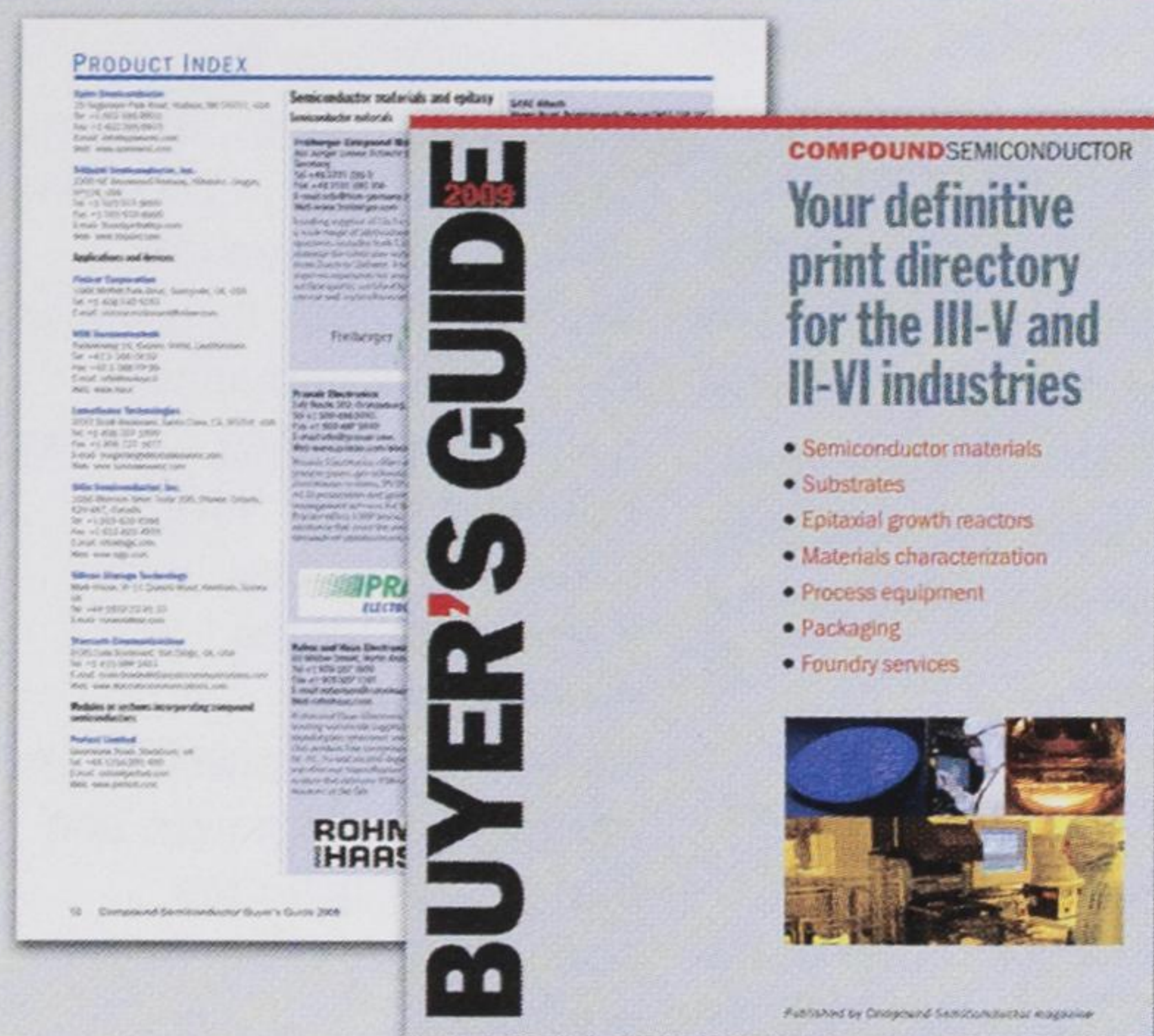
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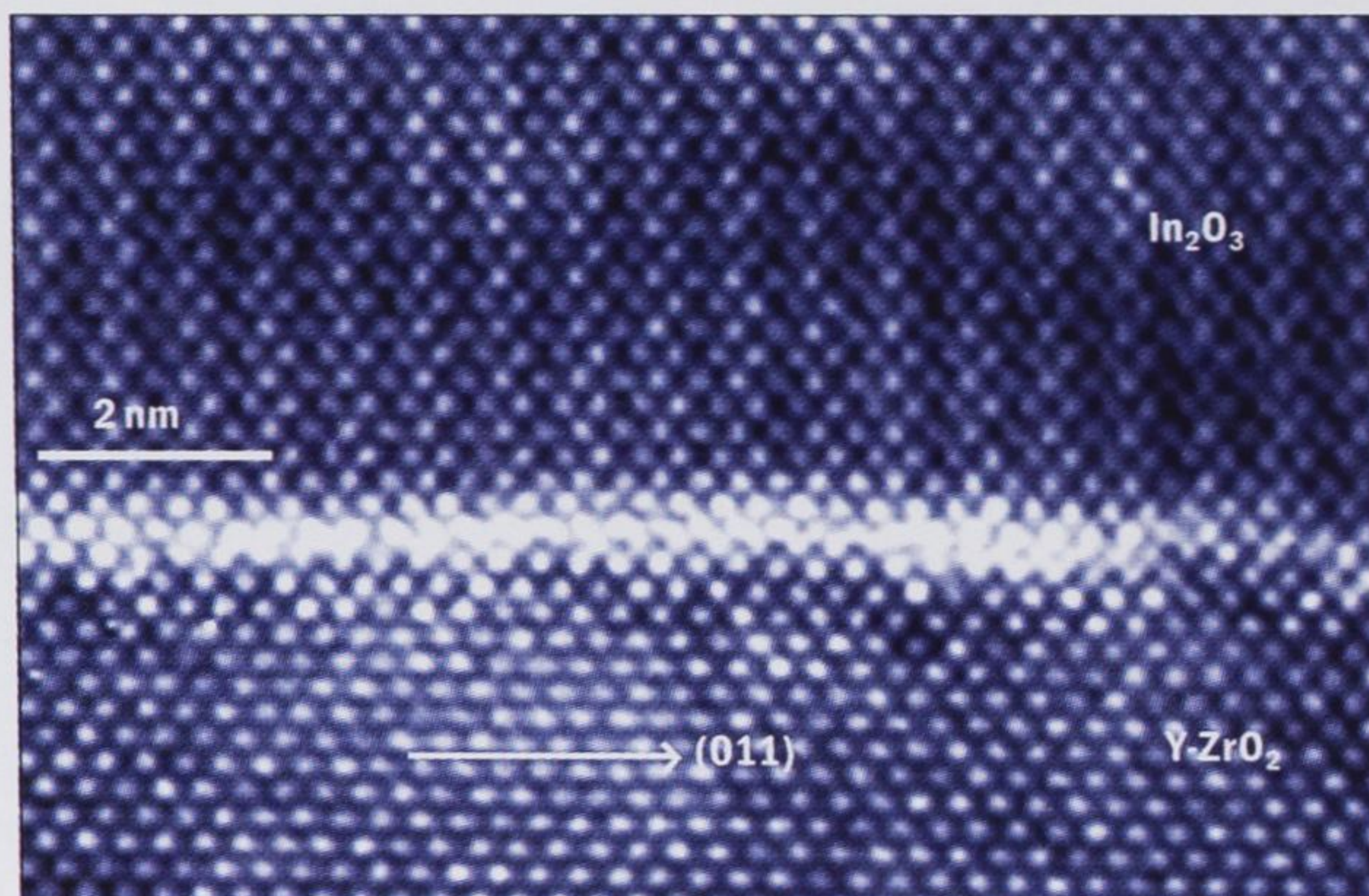


## TRANSPARENT OXIDES

# MBE unmask the real indium oxide

Indium oxide was thought to be a very wide-bandgap material with no carriers close to its surface. But recent results suggest otherwise and indicate that this material could generate terahertz radiation, says a team of UK researchers.

**Fig. 1.** Transmission electron microscopy images reveal the high quality of the  $\text{In}_2\text{O}_3$  films that are grown by MBE on yttria-stabilized cubic zirconia substrates at the University of Oxford. X-ray photoemission spectroscopy measurements of high-quality  $\text{In}_2\text{O}_3$  revealed that the bandgap may actually be as low as 2.6 eV.



Materials widely used in high-volume electronics manufacture do not always have to be well understood. Take  $\text{In}_2\text{O}_3$ , for example. Doped with tin, this conductive oxide provides the transparent contact in flat-panel displays and solar cells. However, despite its widespread deployment, the fundamental properties of this material are only just starting to emerge.

For years its character has been camouflaged by high defect densities that result from the high-speed techniques employed for its deposition, like sputtering or spray pyrolysis. At the UK universities of Oxford and Warwick, our team has recently addressed this by turning to oxygen plasma assisted MBE for high-quality crystal growth, which is a relatively radical shift in growth technology for metal oxides. Thanks to this switch, we're now starting to understand the true characteristics of this material.

We produce our high-quality  $\text{In}_2\text{O}_3$  films at the University of Oxford by RF plasma assisted MBE on yttria-stabilized cubic zirconia substrates. This platform provides a good lattice match to the deposited layer and ensures the growth of body-centered cubic  $\text{In}_2\text{O}_3$ , which is known as the bixbyite phase. This has excellent crystal quality, according to transmission electron microscopy images (figure 1).

Armed with high-quality material, we have uncovered the fundamental properties of  $\text{In}_2\text{O}_3$  for the first time. This revealed that the bandgap of  $\text{In}_2\text{O}_3$  is not 3.7 eV, the value widely attributed to it for many years. In fact, it's actually less than 2.9 eV, according to independent X-ray photoemission spectroscopy measurements at Daresbury Laboratory and the European Synchrotron Radiation Facility. It may even be as low as 2.6 eV, which is a value previously assigned to an indirect bandgap within the material.

These findings agree with some *ab initio* band-structure calculations by our collaborators. Aron Walsh and colleagues at the US National Renew-

able Energy Labs, and Frank Fuchs and Friedhelm Bechstedt at Friedrich Schiller University of Jena, Germany, have found no evidence for any significant indirect nature of the fundamental bandgap, and their calculations suggest that the bandgap of  $\text{In}_2\text{O}_3$  is significantly lower than 3.7 eV.

The lower bandgap might seem to contradict the transparent nature of  $\text{In}_2\text{O}_3$ . However, NREL's calculations suggest that the transition between the conduction band and the top-most valence band is very weak, which explains why this bandgap has not been revealed in optical measurements. Similarly, theorists at Friedrich Schiller University claim that optical transitions remain small up to 1 eV above the bandgap energy.

The dramatic improvement in material quality has also enabled us to determine the intrinsic electronic state of indium oxide. In the past, researchers have claimed that there are no carriers close to the material surface, but our recent measurements show the very opposite –  $\text{In}_2\text{O}_3$  can actually sustain a large build-up of electronic charge at its surface.

The key to this discovery has been the growth of undoped  $\text{In}_2\text{O}_3$  thin films with very low free electron concentrations. In these materials the surface Fermi level is pinned at around 0.4 eV above the conduction-band minimum, which allows electron accumulation in low carrier density  $\text{In}_2\text{O}_3$ . As expected, electron depletion kicks in as n-type doping levels increase.

## Terahertz contender

There is a good chance that  $\text{In}_2\text{O}_3$  will be an excellent material with which to exploit the terahertz spectrum. This is because InAs and InN, which are today's best materials for terahertz generation, have inherent surface electron accumulation. Terahertz generation in these – which is thought to result from surface field acceleration and the creation of an electric dipole at the surface – allows them to be used for applications as diverse as medical imaging, detecting concealed weapons and measuring water content in cheese.

$\text{In}_2\text{O}_3$  is also a promising material for making chemical and gas sensors, such as detectors of ozone and nitrous oxides. Prototypes have been fabricated at the Technical University of Ilmenau, Germany, and our efforts could improve detector performance through advances in understanding the semiconductor.

We'll continue to advance the growth technology for  $\text{In}_2\text{O}_3$  and study this material's properties. But in addition we'll be branching out to other semiconducting metal oxides, such as  $\text{SnO}_2$  and copper-containing p-type oxides. It will be interesting to see what useful properties these materials might have in store.



### About the authors

**Tim Veal** (top left), **Phil King** (top center) and **Chris McConville** (top right) are researchers at the University of Warwick.

**David Payne** (bottom left), **Anne Bourlange** (bottom center) and **Russ Egdell** (bottom right) are researchers at the University of Oxford.





## MOSFETs

# Luminescence interrogates interfaces

A US team is championing photoluminescence intensity (PLI) as a complementary technique to capacitance-voltage (CV) spectroscopy for determining the quality of interfaces between III-Vs and dielectrics.

These interfaces play a key role in the performance of compound semiconductor MOSFETs, which have the potential to extend Moore's law, so understanding their quality is of paramount importance.

Complexity plagues CV spectroscopy, used much more widely for measuring interface state densities, and care is needed to obtain meaningful results.

"Unfortunately, CV is probably one of the most widely misinterpreted techniques on non-silicon semiconductors," said Matthias

Passlack, a former Freescale researcher who is now collaborating with the University of Glasgow, Scotland.

"In contrast, PLI data interpretation is rather straightforward," explained Passlack. That's because the only variable in the measurement is the laser excitation intensity.

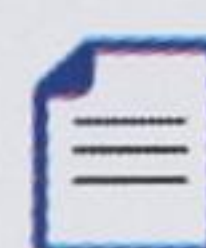
Interface state densities are extracted by PLI measurements with a model that produces a numerical fit of the experimental data.

This approach to analyzing interface quality is certainly not new. "Hasegawa's group at Hokkaido University in Japan experimented with the technique in the early 1990s, we built some rudimentary PLI at Bell Labs in 1994–1995, and the set-up in its current configuration was built between 1996 and

1997 at Motorola," explained Passlack.

His latest publication outlines a more comprehensive study, which incorporates investigations of 22 material systems on GaAs, including GdGaO,  $\text{In}_2\text{O}_3$  and  $\text{Ga}_2\text{O}_3$  dielectrics. The latter material was the only dielectric that provided a device-quality interface.

Passlack wants to analyze InGaAs MOSFETs using PLI, and he is assisting efforts led by Iain Thayne's team at the University of Glasgow, UK, which is building an experimental set-up that can perform this measurement.



## Journal reference

M Passlack et al. 2008 *IEEE Electron Dev. Lett.* **29** 1181.

## SOLAR CELLS

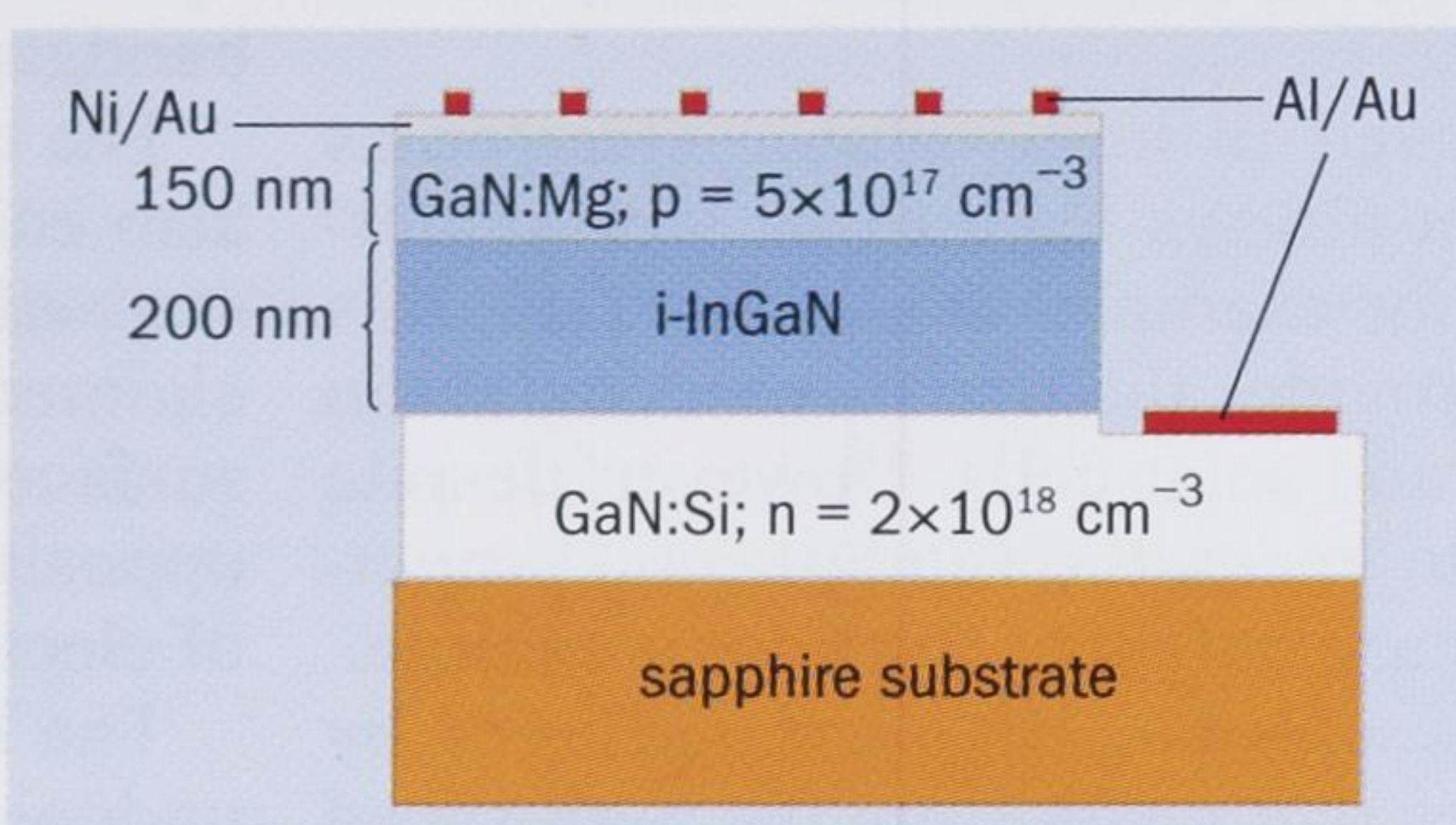
## Nitrides deliver high ultraviolet efficiencies

III-nitride (III-N) solar cells can now deliver external quantum efficiencies of more than 60% in the ultraviolet, thanks to the University of California, Santa Barbara (UCSB).

"In the short term, we see III-Ns complementing existing multi-junction solar-cell technologies," said UCSB's Carl Neufeld.

These III-Ns could increase the efficiency of multi-junction cells for terrestrial and satellite applications by generating energy from ultraviolet photons. At the moment, the performance of GaInAs Ge/GaInP falls off dramatically below 400 nm.

UCSB's InGaN/GaN-on-sapphire cells were grown by MOVCD and comprised a silicon-doped buffer, a 200 nm thick undoped  $\text{In}_{0.12}\text{Ga}_{0.88}\text{N}$  layer, a 150 nm



## Contact lithography and inductively coupled

plasma etching produces 0.5 mm × 0.5 mm mesas from the epiwafers. Electron-beam evaporation adds a semi-transparent ohmic nickel and gold contact that is annealed under oxygen at 500 °C for 5 min, before an Al/Au grid is added. The grid has 5 μm wide lines and center-to-center spacings from 25 to 166 μm.

thick magnesium-doped GaN cap, a semi-transparent Ni/Au ohmic contact and an Al/Au grid (see figure).

External quantum efficiencies peaked at

63% at 392 nm, and varied by less than 3% between 370 and 410 nm. Internal quantum efficiency reaches at least 94%, according to calculations that include surface reflections, absorption in the semi-transparent contact layer and incomplete absorption in the InGaN layer.

The long-term challenge for the researchers is to build a multi-junction cell based solely on III-Ns, which would have a very wide absorption range.

But this quest faces two major problems – the huge lattice mismatch between InN and GaN, and difficulties associated with fabricating tunnel junctions. "The large bandgap is a huge barrier to tunneling," said Neufeld, "and it is very difficult to get the high doping needed for a traditional tunnel junction."



## Journal reference

C Neufeld et al. 2008 *Appl. Phys. Lett.* **93** 143502.

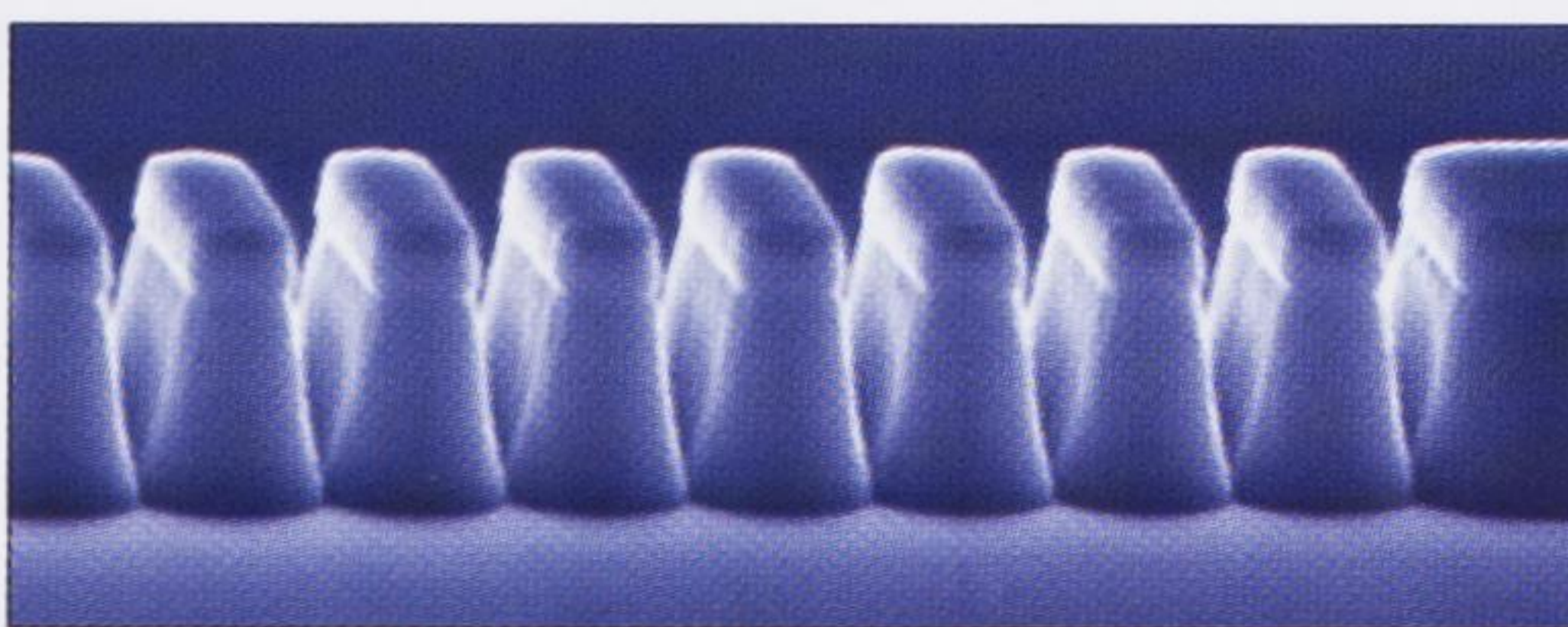
## INFRARED EMITTERS

## Single-frequency laser hits 12 W power record

Researchers from the Ferdinand Braun Institute for High-Frequency Technology in Berlin, Germany, have built a 979 nm distributed Bragg reflector tapered laser with a record output power of 12 W.

Frequency doubling this laser's emission with a non-linear crystal could create a visible source that is used as a more efficient alternative to 488 nm argon-ion lasers.

The laser features a ridge waveguide sec-



**A distributed Bragg reflector** ensures single longitudinal mode emission from the 979 nm laser.

tion that guides the lateral mode and a tapered region that provides optical amplification.

Vertical asymmetry of the waveguide suppresses lasing of higher-order modes. "By moving the quantum well we can give

more gain to the desired ground mode," explained lead author Christian Fiebig. The laser features relatively thin p-doped layers because this material has higher optical losses and electrical resistance than its n-type equivalent.

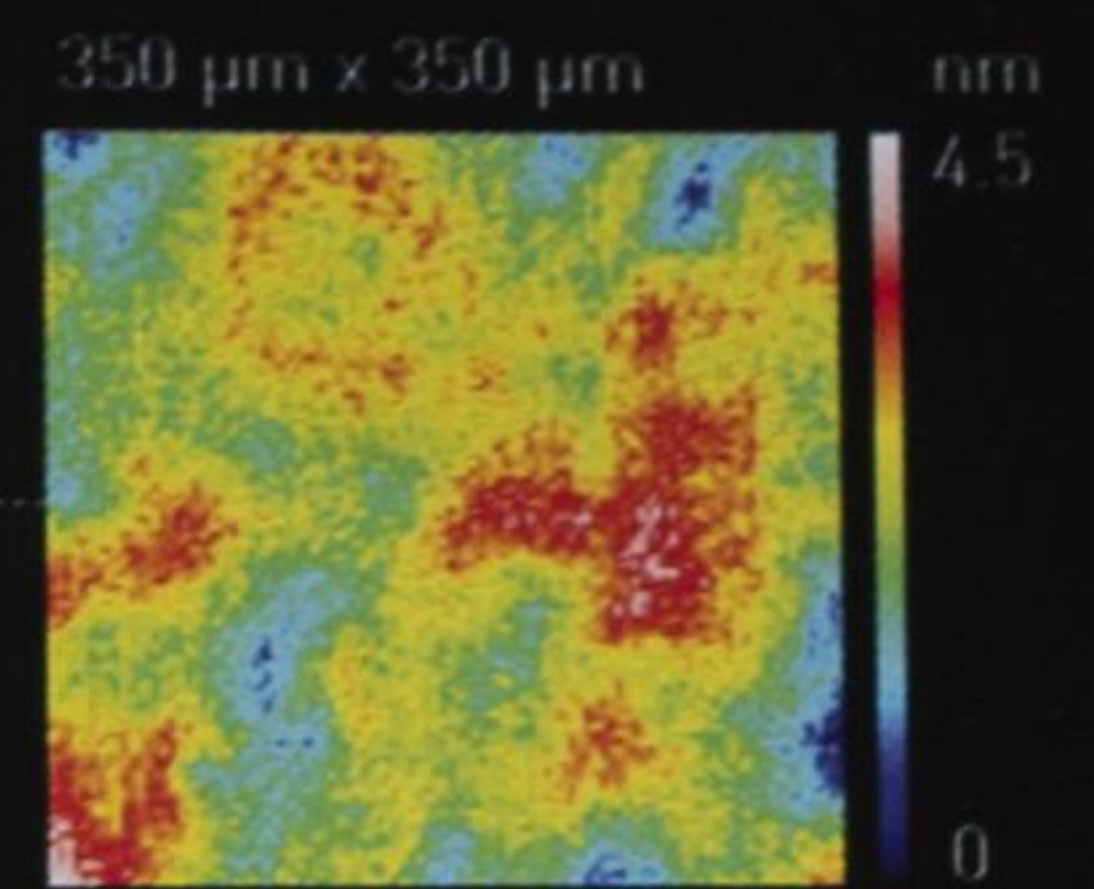
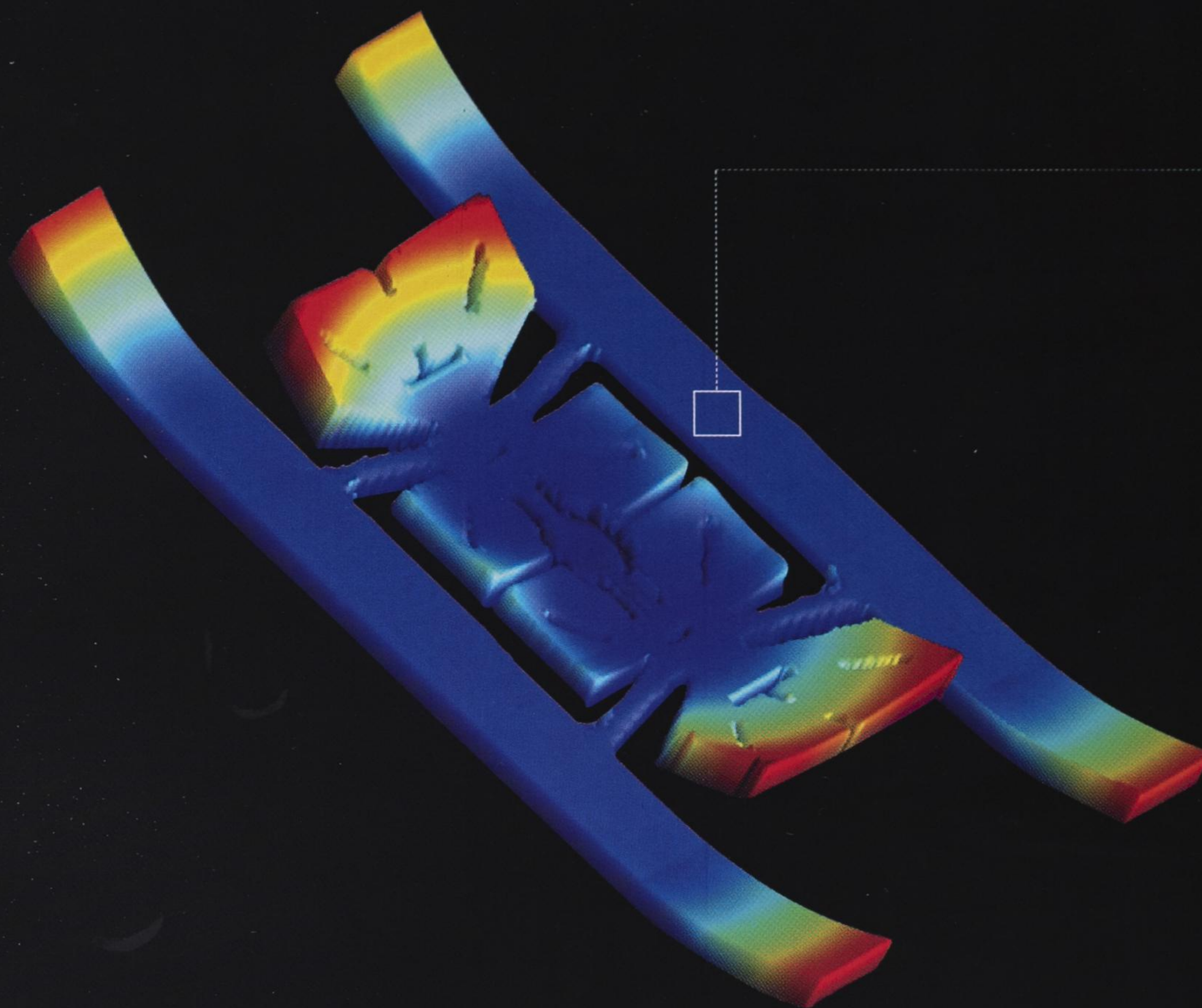
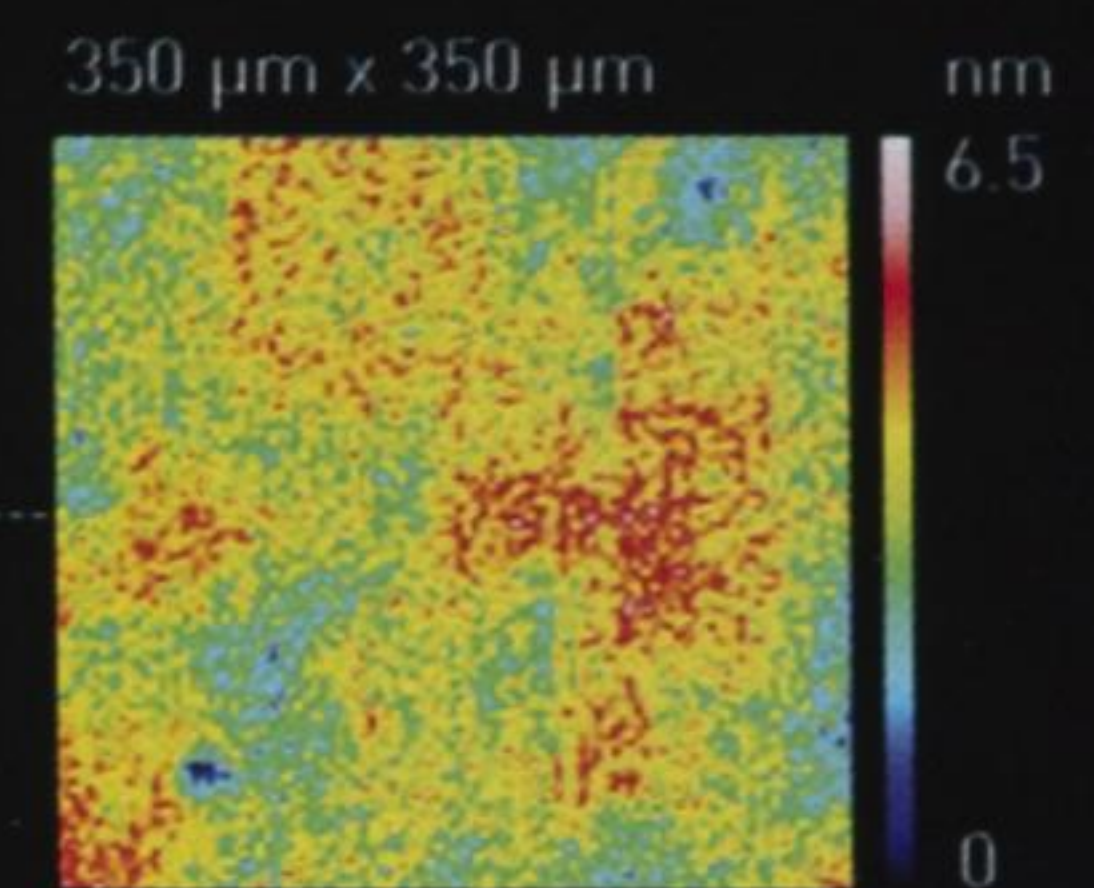
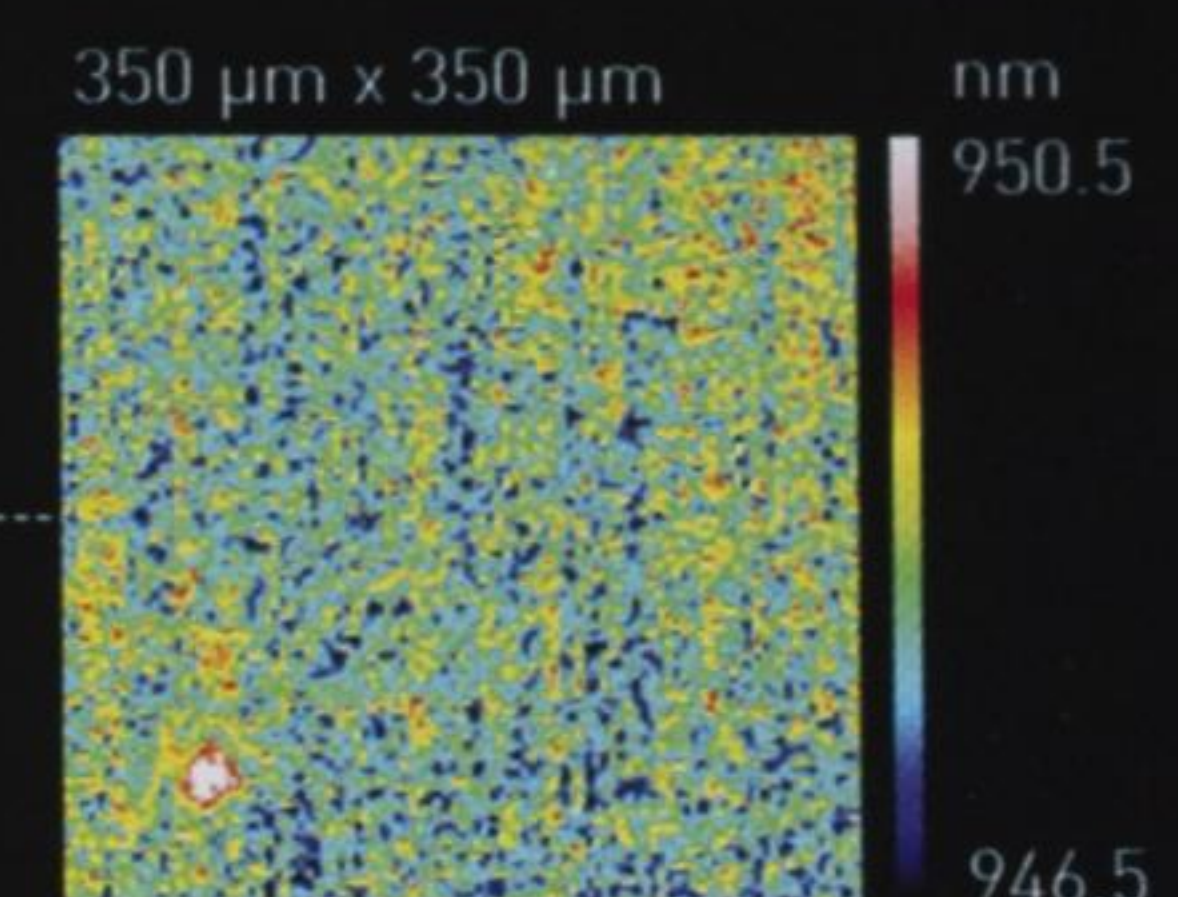
Improvements in output power to 15 W are planned, and a boost in efficiency from the current value of 44% to 50%. "The main focus will be to improve beam quality and especially to achieve more power in the central lobe," explained Fiebig.



## Journal reference

C Fiebig et al. 2008 *Electron. Lett.* **44** 1253.

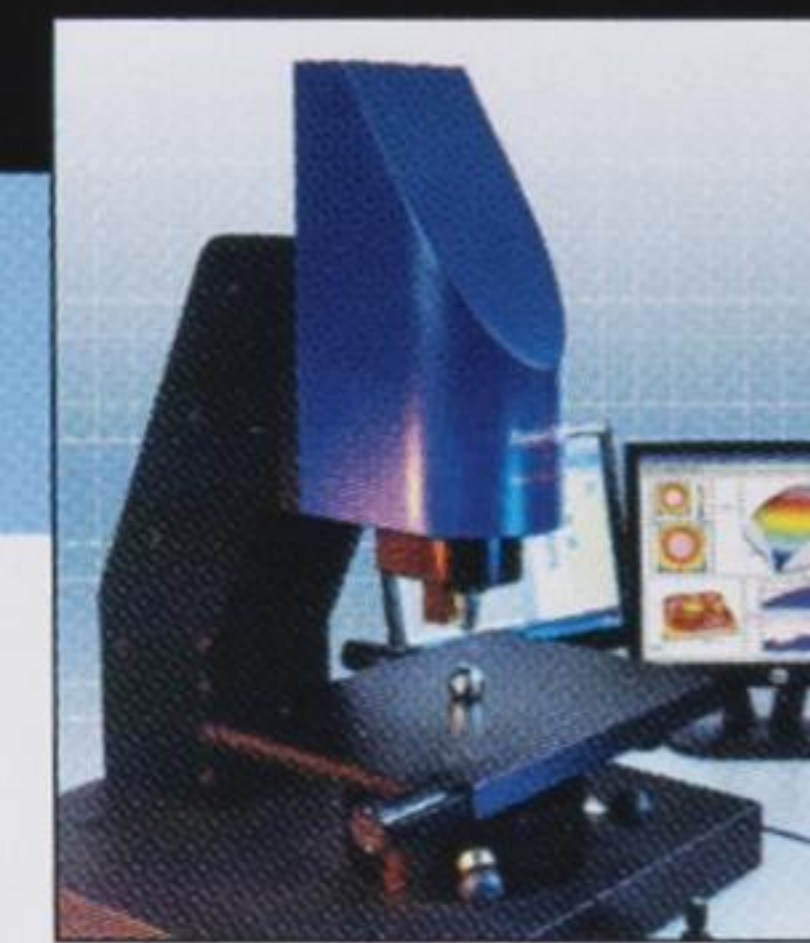


Top Surface (air / Si O<sub>2</sub>)Bottom Surface (Si O<sub>2</sub> / Si)

Film thickness uniformity

## FPD / MEMS / Wafer

### Advanced non-contact film analysis



- ✓ New feature - measures substrate roughness through coating
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- ✓ Dimensional measurement - industry leading 4 million data points

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