

COMPOUND SEMICONDUCTOR

January/February 2009 Volume 15 Number 1

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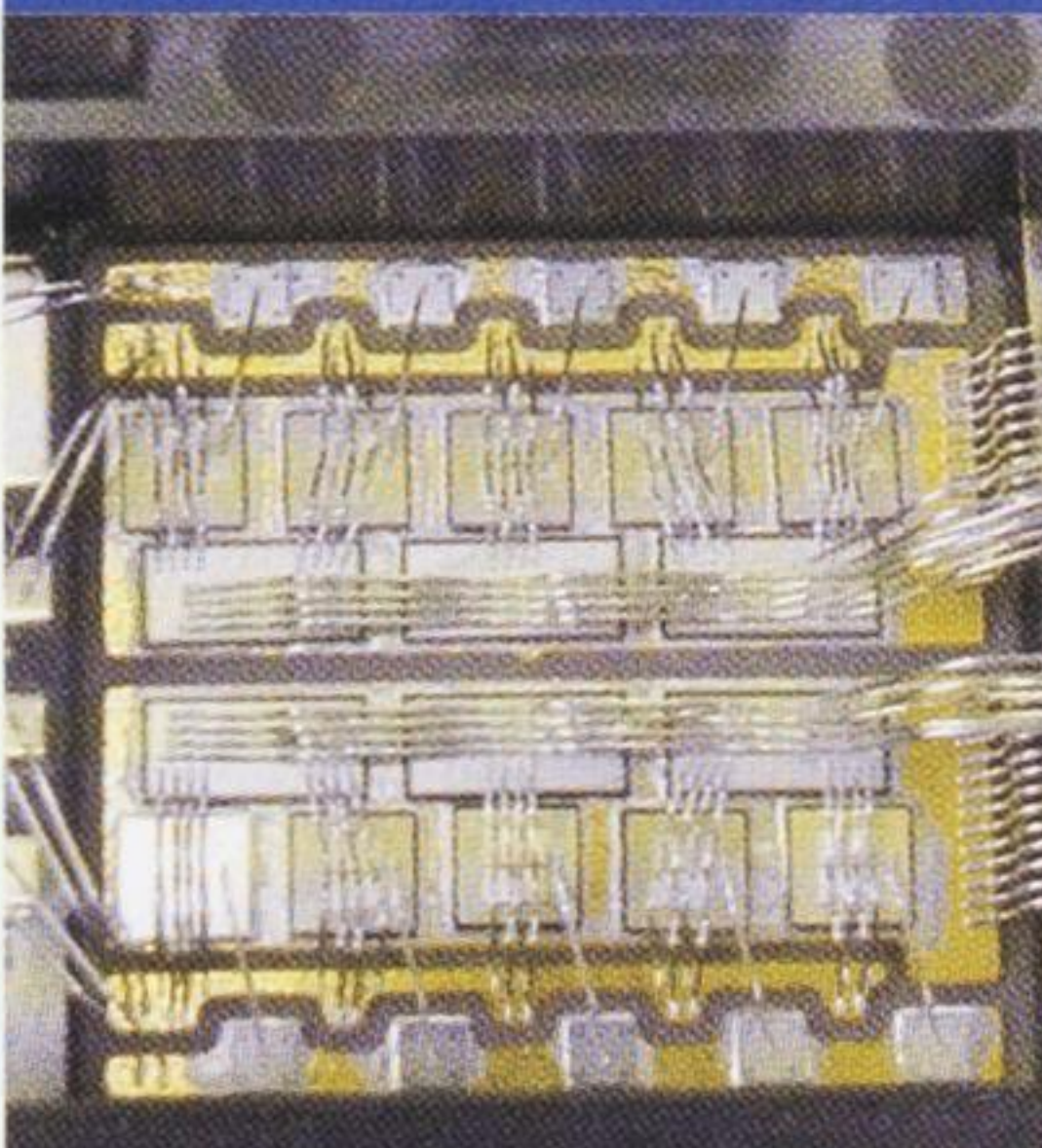
GAN LEDs

**Smooth layers
close the
green gap**

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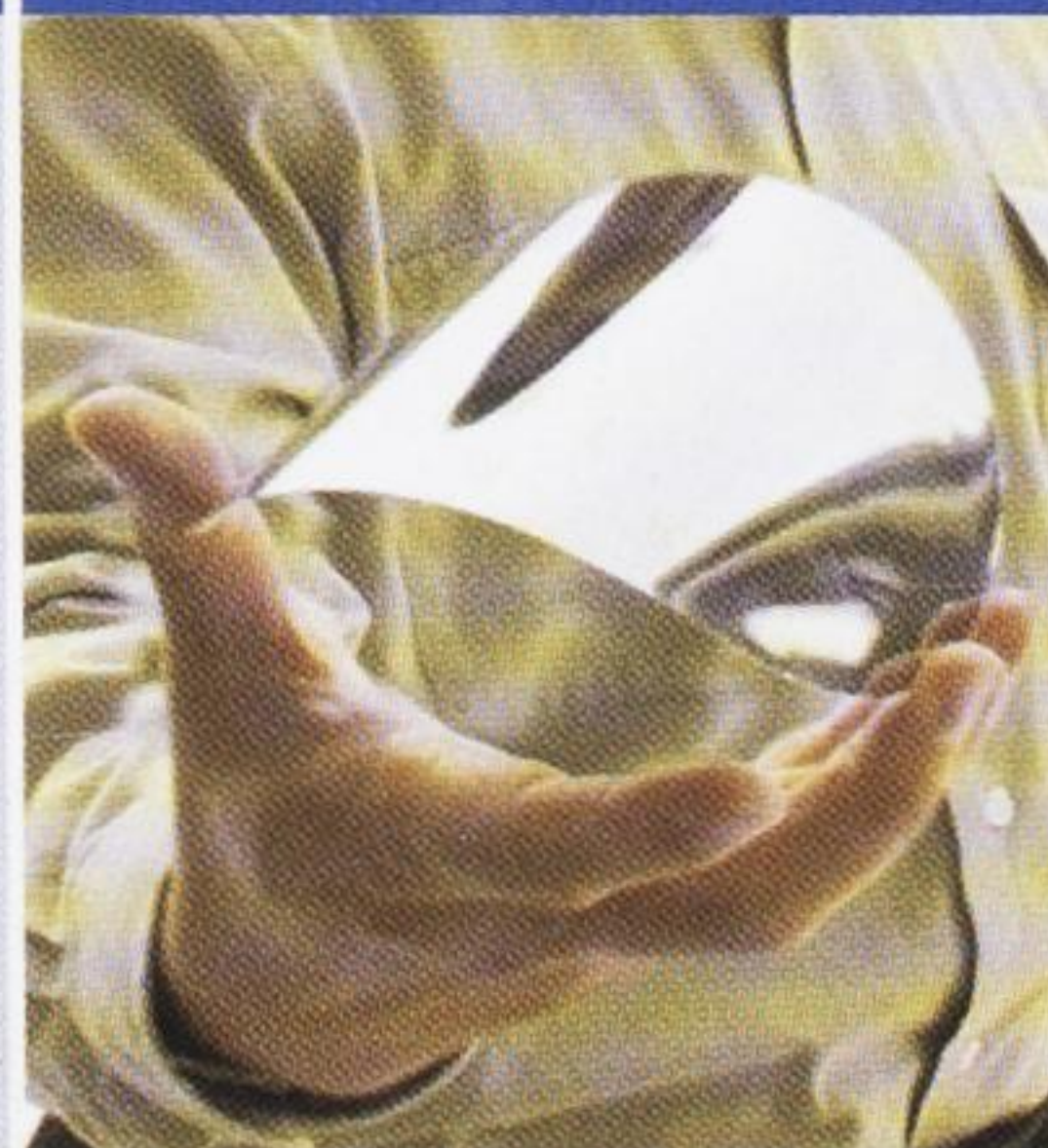
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HIGH-BRIGHTNESS LEDs



Flexible friend

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First Solar's CdTe panels have enjoyed substantial deployment in the German solar farms that receive generous financial subsidies. **p18**

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Main cover image: On-wafer measurements have gauged the performance of green LEDs produced by researchers at Rensselaer Polytechnic Institute. See p21. Credit: RPI.

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IOP Publishing

The right frequency



They say that time flies when you're having fun, and the five years that have passed since I began editing this magazine have certainly raced by.

Over that time there has been no shortage of industry ups and downs to report on, and the compounds business has changed at a sometimes mesmerizing pace.

But it isn't just the semiconductor industry that is changing. The publishing business has also been going through a protracted shift in priorities, as editors and their colleagues try to find the right balance between printed and electronic formats.

For *Compound Semiconductor*, the upshot is that we are changing the magazine's frequency in 2009. Most of you now find your news online, and that is increasingly where our own efforts are focused. News breaks on a daily, sometimes hourly, basis and our website is the place to go to find out about the latest developments.

While the magazine will maintain a round-up of all of the key recent developments, its focus will be very much on analysis and technological progress – making sense of industry trends, bringing you exclusive reports on the application markets served by compound semiconductor devices and showcasing state-of-the-art technologies with articles from the industry's leading lights.

This issue highlights that focus, with an examination of the changing landscape in fiber-optic pump lasers (p14), an exclusive interview with MBE equipment pioneer Riber (p16) and an article from Rensselaer Polytechnic Institute (p21) showing how world-leading research at the New York lab is set to close the so-called “green gap” in LED technology.

We will publish eight issues of *Compound Semiconductor* magazine this year, augmented with a series of new supplements that will put the spotlight on emerging applications and related technologies. We will also produce a unique industry guide that captures all of the essential information that you'll need relating to compound semiconductor manufacturing and markets, in a single, handy package.

With 2009 already up and running, the *Compound Semiconductor* team wishes you all a very happy and successful new year.

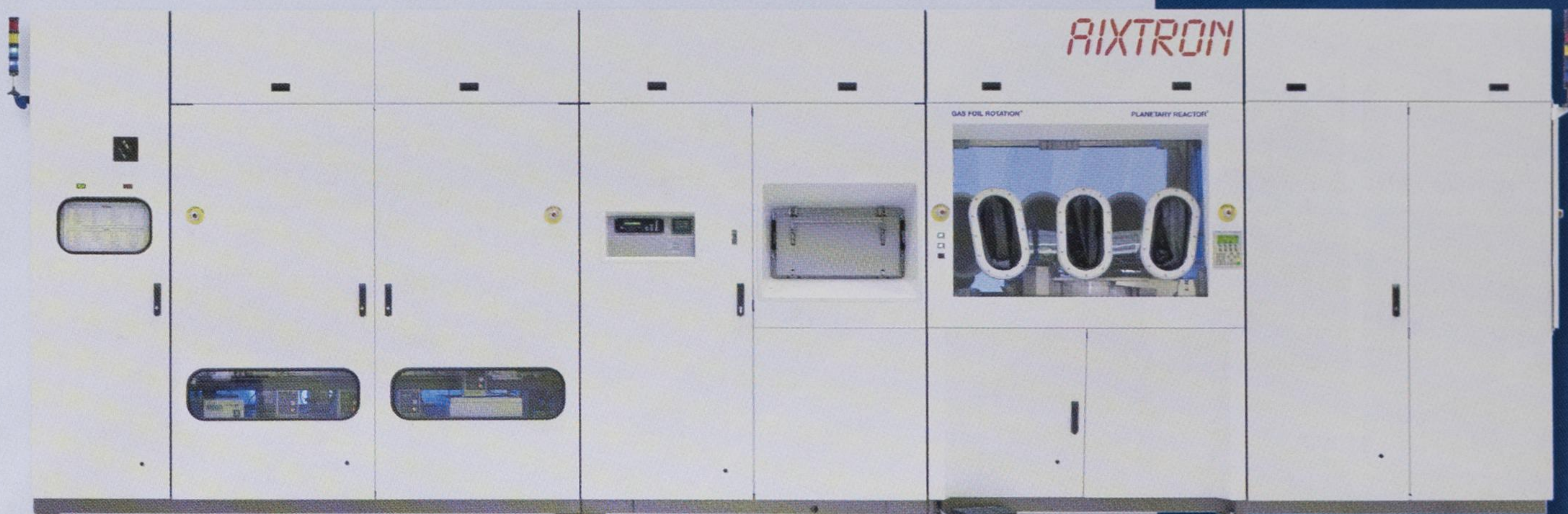
Michael Hatcher *Editor*

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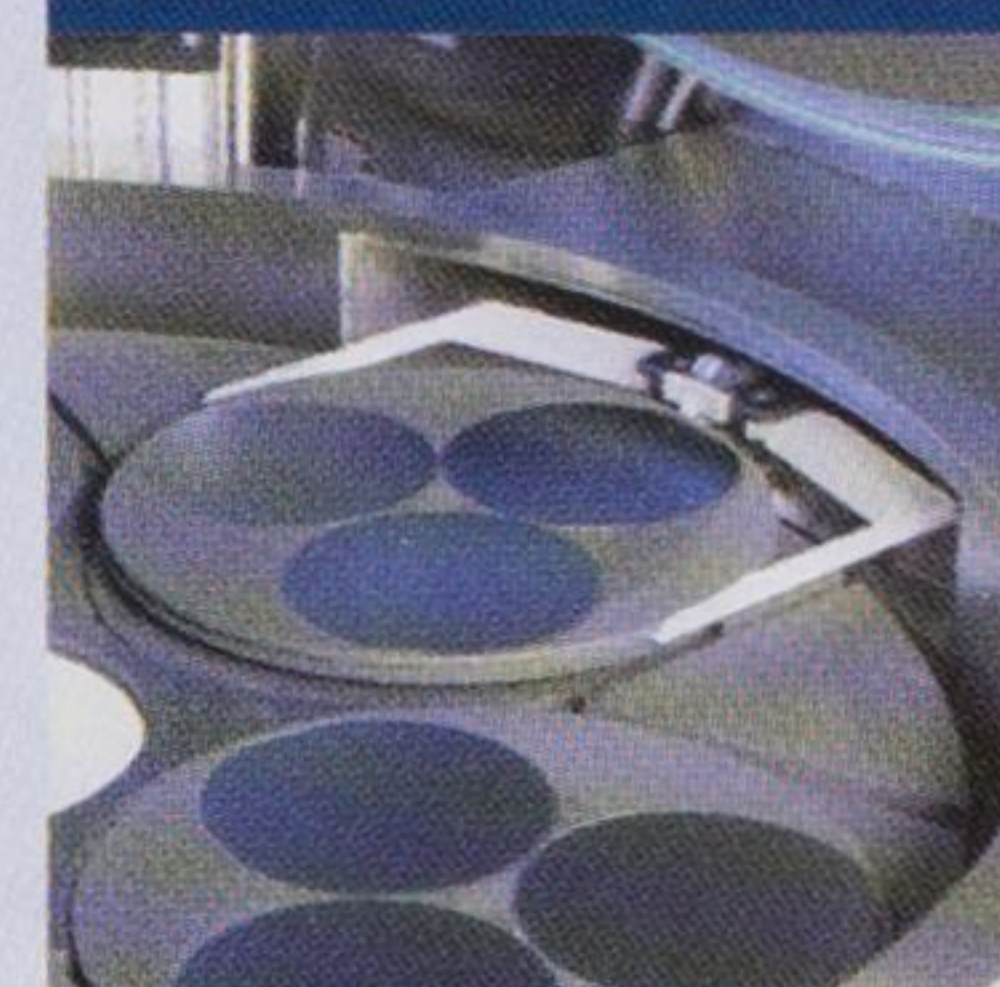
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RF INTEGRATED CIRCUITS

GaAs firms slash costs as recession hits

The top three cellphone power amplifier (PA) manufacturers have all revised their year-end 2008 earnings predictions downwards due to weak demand across all of their businesses.

RF Micro Devices, Skyworks Solutions and TriQuint Semiconductor each trimmed their sales predictions for the final quarter by more than 10%. TriQuint and RFMD also moved to reduce their expenses, with RFMD cutting 250 employees in its GaAs fabs. The industry's largest revenue earner is putting the 4 inch HBT fab where it first began wafer production in Greensboro, NC, on ice at the cost of 150 jobs. The idling process, which will freeze 10% of the firm's GaAs manufacturing capacity, will occur over the first three months of this year.

It has also made up to 99 employees redundant as it moves its UK PHEMT facility from 24/7 operation to more conventional office hours. This move was completed in December 2008. "I've seen a lot of these cycles, but I can't say I've ever seen one get this severe so quickly," RFMD executive vice-president and co-founder Jerry Neal told *Compound Semiconductor*.

TriQuint has eliminated temporary workers and planned shutdowns over the December holiday, saying that it will swing to a loss in the quarter. That is partly because it is also intending to take charges to reduce its valuation of recent acquisitions WJ Communications and Peak Devices. This will bring the company's judgement of its worth closer to its stock market valuation, which at \$488 million on January 2 is now lower than its balance sheet figure of \$682 million.

Market analyst Strategy Analytics has



RFMD's first GaAs fab is to be mothballed until the demand for cellphone PAs starts to increase again.

now revised its forecast for the GaAs industry's revenues through to 2012 to include a 5% contraction in 2009. It says that the market expanded 9% to \$3.9 billion in 2008, but has reduced its estimate of average growth through 2012 to 7%.

Real problems in the sector became evident on December 4, 2008, as number-one handset manufacturer Nokia cut its shipment volume outlook for the quarter for a second time. The Finnish giant's latest guidance did not make a specific volume prediction, but set a glum tone for what is traditionally its strongest sales quarter.

"The mobile handset industry stuffed the channel in Q3, expecting a seasonal Q4 in developed markets," said Panmure Gordon analyst Nick James, "but the sell-through has been far below expectations."

This sentiment was backed up by Skyworks' CEO David Aldrich, after his company had reduced its revenue estimate for the December quarter from \$240 million to \$215 million. "We've seen a lot of uncer-

tainty in our customers concerning sell-through of handsets," he told analysts on December 3, a day after revising Skyworks' outlook. "That's resulted in a contraction as our customers want to hold less inventory."

James highlights the figures from research company Gartner saying that the growth of smartphone sales in the third quarter of 2008 was the lowest ever. With smartphones often using three or more PAs, they have been hailed as a key driver for GaAs revenues.

In a report also published on December 4, Gartner says that smartphone volumes grew by 11.5% from Q3 2007 levels to 36.5 million units. Nokia estimated that year-on-year growth had been 39% and industry sales were 44.2 million units. "The industry appears to have overstated the growth of smartphones," explained James.

He says that industry supply chain players like IQE will also be hit, while Strategy Analytics predicts a 10% fall in GaAs substrate sales for 2009.

PHOTOVOLTAICS

Silicon photodiode threatens III-V detectors

Intel has added germanium to silicon to create an avalanche photodiode (APD) that is better at detecting high-speed, low-intensity signals than existing devices. The results were published online in the journal *Nature Photonics* on December 7, 2008.

"This is the first time that a silicon photonics device has better performance than any recorded performance from an equivalent device in III-V materials, specifically InP," claimed Mario Paniccia, Intel fellow

and director of the company's photonics technology lab.

While silicon is not the optimal photonic material, its electronic properties can be exploited in an APD to create gain. The APD's performance is measured as its gain-bandwidth product. This quality, which is the gain of the device multiplied by the speed at which it operates, is fixed for a particular type of material. For an InP APD the figure is typically around 120 GHz.

In the *Nature Photonics* paper, the researchers report devices operating at a wavelength of 1300 nm and a data rate of 10 Gbit/s, which had a gain of "more than 30". The best result was a "world record"

gain-bandwidth product of 340 GHz.

Intel's silicon photonics work is mostly aimed at short-reach connections, between or even inside electronic chips, but the silicon APD would probably find its first applications in mainstream telecoms, where it could provide a low-cost replacement for detectors in long-haul links.

In 2006 Intel demonstrated a hybrid silicon laser, which integrated a tiny piece of InP onto a silicon-based structure to provide light emission. According to Paniccia, Intel believes that the hybrid silicon laser is the way forward for silicon photonics, rather than the all-silicon laser based on the Raman effect that Intel demonstrated in 2005.

MARKET REPORT

LED illumination will triple in five years

The consumption of LED chips in solid-state lighting (SSL) applications will continue to boom over the next five years, say market forecasters in the US. According to analysts at Electronicast, who have just updated their LED market predictions, the current economic gloom will do little to dampen SSL prospects between now and 2013.

Stephen Montgomery, director of LED research projects at the Californian consultancy, expects exterior and architectural applications to continue to dominate the SSL market, while the much smaller sign, interior lighting and specialist LED-lighting segments will grow very quickly.

Montgomery valued the 2007 market for all LEDs used in SSL at a shade under \$284 million, with architectural and other exterior-lighting applications accounting for 86% of that total.

By 2013, he reckons that this figure will have more than tripled and that LEDs for SSL will represent a near billion-dollar sector. Architectural deployments will still be dominant, but their share will have diminished to around two-thirds of the \$937 million total.

Growing rapidly in value will be interior SSL, as well as the channel lettering niche for sign applications and other uses of the technology, for example, aircraft, military and medical applications.

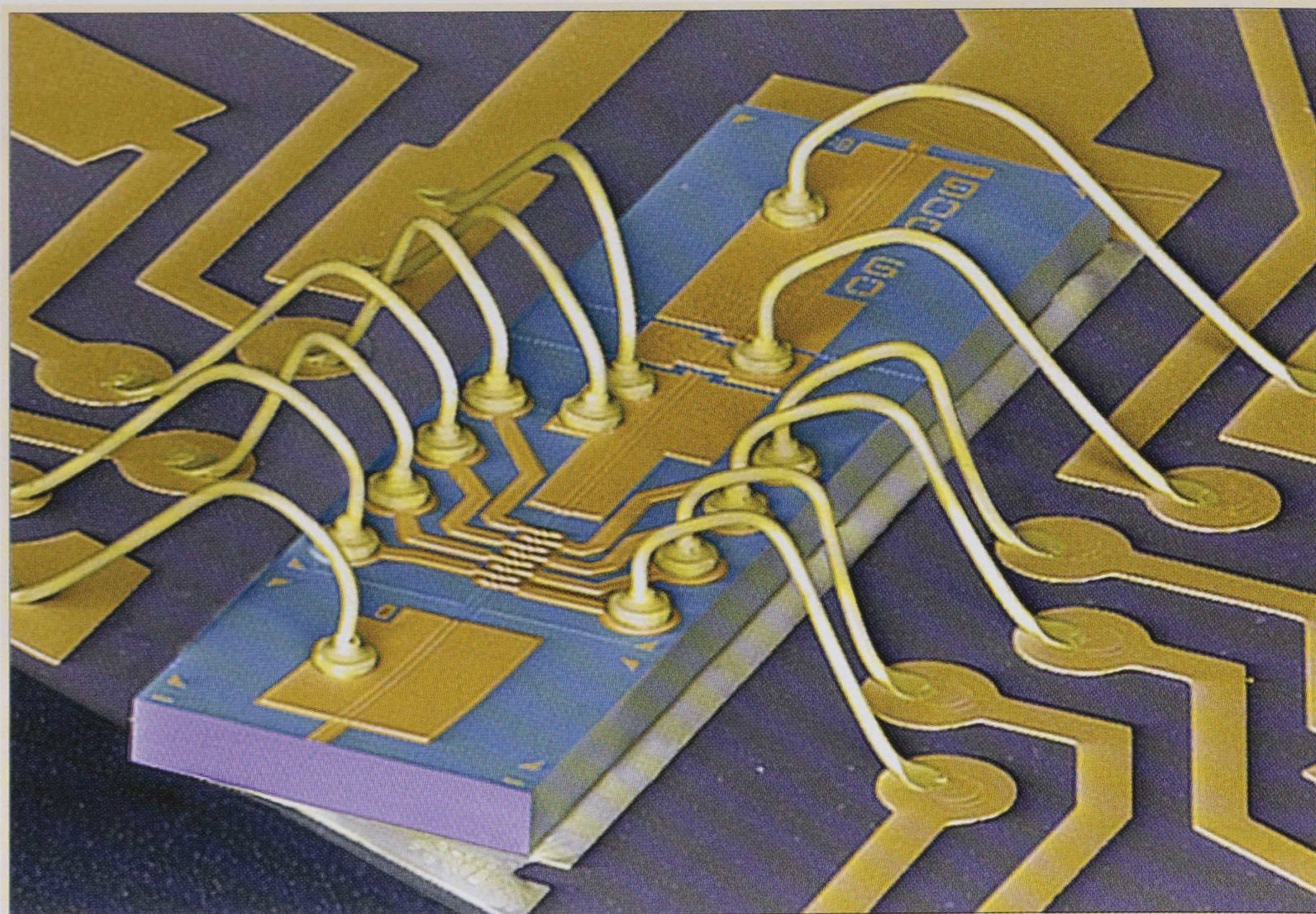
The new US presidential administration looks likely to be beneficial to the SSL industry too, with pre-election policy documents from Barack Obama highlighting high-efficiency technologies as a key part of the president-elect's energy strategy.

GLOBAL COMPETITION

European decline 'risks 500,000 jobs'

SEMI has told politicians that allowing the European semiconductor industry to lose more share in the global market could put as many as 500,000 jobs at risk. On December 9, the industry group visited eight European Union officials and departments, calling on them to provide more investment for the industry.

"If semiconductor manufacturers leave Europe, indigenous equipment and materials producers will face an uncertain future," said Franz Richter, chairman of the SEMI European Advisory Board. "Support-



Optical communications giant JDSU wants the US government to ban imports of tunable lasers made by its rivals Bookham (whose tunable DS-DBR chip is pictured above) and Syntune, who it says infringe its patents.

In its filing to the International Trade Commission (ITC), the Milpitas, CA, firm is also seeking a ban on imports of modules and systems that use the competing technology. JDSU has named CyOptics, which it says integrates chips sold by Sweden's Syntune into such products at its Mexican facility, in the suit. A hearing date is yet to be set.

The suit also names Nortel, Tellabs and Ciena – network equipment manufacturers that JDSU listed as customers in its most recent quarterly financial results, but which are using Bookham's tunable lasers. Another Bookham customer, German network equipment producer Adva Optical Networking, is the final company involved in the ITC case.

The dispute hinges on two US patents – 6,658,035 and 6,687,278 – that JDSU owns through the 2005 purchase of Agility Communications. The first of these covers the manufacture of a monolithically integrated InP laser chip, containing a widely tunable laser, amplifier and curved waveguide. The second concerns the use of the monolithically integrated chips to generate constant, high-power signals across a range of wavelengths.

"I have reason to believe, based on reasonable investigation, that Bookham manufactures tunable laser chips that infringe the 035 and 278 patents," said director of corporate development at JDSU and former Agility employee, Chris Coldren, in the complaint.

ing a robust and competitive semiconductor industry in Europe is critical to keeping jobs across all industries and supporting key European economies."

In 2007, 45 European countries shared the lowest semiconductor device market share of any participating global region. At just 16%, this share has contracted by a quarter in two years. However, European manufacturers are frequently key customers for chip makers and the semiconductor industry also helps to provide the knowledge base that allows such companies to flourish.

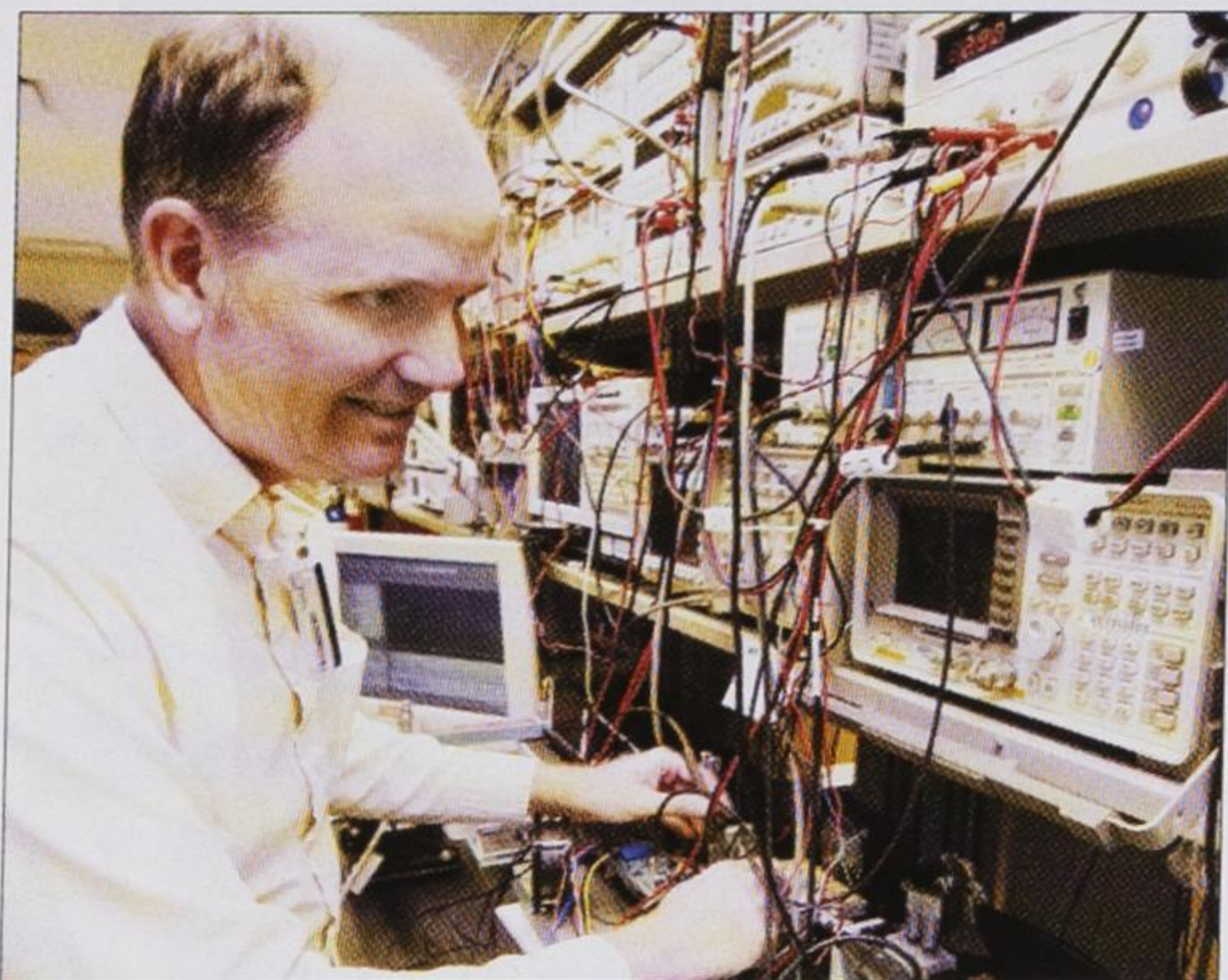
Approximately one-third of expenditure on wireless communication semiconductors comes from European companies, with two-thirds of this figure being spent in European territory. Wireless is the major

focus for GaAs power-amplifier producers, although currently none of the top-line GaAs manufacturers are based in Europe. With companies like NXP Semiconductor and Infineon's majority-owned DRAM venture Qimonda currently losing vast amounts of money, other chip-making sectors are heading in the same direction.

SEMI is therefore lobbying figures like Viviane Reding, European Commissioner for Information Society and Media, to revive competitiveness in the region's semiconductor industry and to ensure that its knowledge survives. It argues that the continent is well placed to reap the financial benefits from specialized semiconductor applications, where compound semiconductors are likely to make a contribution.

CELLPHONE BASE STATIONS

TriQuint set to deliver record-efficiency PAs



TriQuint has supplied HV-HBT PAs to Donald Kimball of the University of California, San Diego, who showed that they could operate with the highest efficiency for a wideband CDMA base station.

TriQuint Semiconductor is ramping commercial production on GaAs amplifier products that have recently claimed a cellular base-station efficiency record.

Low-volume initial production will begin on high-voltage HBT (HV-HBT) devices early in 2009 and ramp into 2010 in response to a strong interest in the technology's power-saving potential. "I've got more customers coming to me asking for samples, data and evaluation boards than I can possibly deal with today," Doug Slansky, TriQuint's base-station product marketing manager, told *Compound Semiconductor*.

In October 2008, Donald Kimball of the University of California, San Diego

(UCSD), underlined the technology's potential at the Compound Semiconductor Integrated Circuit Symposium. At the Monterey, CA, event Kimball showed that a method responsible for GaN and silicon LDMOS efficiency records performed even better with HV-HBT devices. TriQuint's products provided record average power-added efficiency above 58% at 42 W output power and 10.2 dB gain in a single-stage wideband CDMA base-station power amplifier (PA).

UCSD uses an approach called envelope tracking that dynamically controls supply voltage to minimize the power consumed by a PA. The actual output of a base-station PA varies with demand, but base stations often maintain a single constant supply voltage regardless.

In envelope tracking, the supply voltage is adjusted to levels closer to those needed at any time by the PA, reducing power loss from the system. To take advantage of this, an amplifier should be efficient across all of the supply voltages that the envelope tracking system varies through. "GaAs HV-HBTs are attractive options because they can provide high efficiency and gain over a wide dynamic range," said Kimball.

Envelope tracking is not exclusive to UCSD. It is under development at companies worldwide, although it is not yet being commercially deployed. "We've been talking HV-HBT technology to all of the major base-station manufacturers," explained Slansky. "Most of them are looking at envelope tracking as a next-generation technology, or maybe one and a half generations from now." In the interim, the company will offer discrete HV-HBT products that it has also tested in a Doherty configuration – another efficiency-boosting approach.



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...Mitsubishi sets SiC agenda

Japanese conglomerate Mitsubishi says that it will accelerate research into SiC modules as a key part of its global-warming-related business. It plans to exploit the low-power-loss technology before March 31, 2011. The company says that it "is considering the most suitable places of use for these modules, such as in air conditioners, photovoltaic inverters and elevators."

...Russia pumps \$63 m into LEDs

The state-funded Russian Corporation of Nanotechnologies has taken a minority stake in a GaN LED-lighting collaboration with Onexim Group Ltd and the Ural Optical

and Mechanical Plant for 1.77 billion rubles (\$63 million). The venture has purchased the German-Finnish LED epiwafer maker OptoGaN, whose founders Vladislav Bougrov and Maxim Odnoblyudov studied with Nobel Prize winner Zhores Alferov and at Russia's Ioffe Institute.

...Nichia and Sharp license LEDs and lasers

Nichia Corporation and Sharp Corporation have entered into a patent cross-licensing agreement covering LEDs and laser diodes. The Japanese giants have granted each other the right to use inventions in these areas covered by the vast number of patents that they say they own.

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WIRELESS COMMUNICATIONS

2009 will be 'make or break' for WiMAX

WiMAX, the high-speed connectivity technology that is competing with cellular and fixed broadband, is expected to have only 103 million subscribers worldwide by 2013.

That's according to a report entitled "WiMAX – the best and the worst of times" from telecommunications analyst company Informa. Author Mike Roberts says that close to 80 million WiMAX-enabled devices – such as handsets, high-end notebook PCs and USB dongles – should ship in 2013, as the technology finds its feet.

Many of these devices would be likely to feature III-V semiconductors in their power-amplifier stages, but the overall number is tiny compared with the billion-plus cell phone handsets that ship each year.

For 2008, Roberts believes that device volumes stood at approximately 2 million, following early WiMAX deployments in Korea. "WiMAX has had a hard time in Korea," Roberts told *Compound Semiconductor*. This is a result of the tough competition, as the vast majority of the Korean population already has access to either a fixed or mobile broadband connection.

Two years after its mid-2006 launch, Korea Telecom's WiMAX service had only 200,000 subscribers. In comparison, the same company's cellular wing had added 4.8 million subscribers to its high-speed HSDPA service over the same period.

In the short term, WiMAX should receive a major boost with the roll-out of a nationwide network by New Clearwire in the US. Backed by communications giant Sprint, cable companies Time Warner and Comcast, not to mention Google, New Clearwire received clearance for the network deployment from the Federal Communications Commission at the end of 2008.

With the \$3.2 billion project now also approved by shareholders and, in principle, by lenders, New Clearwire is all set to move ahead with widespread WiMAX deployment across Sprint's existing base-station infrastructure in the US.

Because mobile broadband is still a relatively expensive commodity in the US, WiMAX should have a better chance of success than in Korea. However, with the full extent of the credit crisis only now emerging, early adopters of WiMAX may be thin on the ground for some time yet.

Where Roberts sees a more compelling market opportunity for WiMAX, particularly in the longer term, is in developing countries where there is little or no broad-

band infrastructure – countries like India.

"Our forecasts show that WiMAX will account for 24% of India's total broadband subscribers by 2013, up from 7% in 2008," Roberts said.

Following in India's path could be Russia, Pakistan and various African nations, where the focus will be on providing a broadband service for business users in the first instance. By 2013, it is expected that about one-third of all WiMAX subscribers will be located in developing countries, although that proportion is very likely to grow in the long term, as most developed countries will prove harder to crack.

One exception to that rule might be Japan, where telecom operator KDDI is backing a major WiMAX deployment by UQ Communications, which is scheduled to launch by August. Combined with the US New Clearwire project, the success or otherwise of the Japanese network should give a clear indication of the technology's prospects.

"In 2009 we will find out whether they go ahead with the full deployments as planned," concluded Roberts. "It will be the make-or-break year."

DISPLAYS

Notebook LED display sales surge ahead



Leading the charge towards LED-backlit notebook PC panels is TMDisplay, a joint venture between Japanese electronics giants Toshiba and Matsushita.

Sales of notebook PCs featuring LED backlights reached a new high of 2.1 million panels in the third quarter of 2008, says a report from Austin, TX, analysts DisplaySearch.

This figure represents a jump of 63% from the 1.3 million units sold in the second quarter of 2008, as market penetration moved from 3.4 to 5.4%. The good news for LED makers is that this momentum is set to grow further. DisplaySearch expects the market share of LED-based notebook PCs to more than double in the latest quarter.



SemiLEDs Corporation has been selected as a 2009 Technology Pioneer by the World Economic Forum. The award recognizes the US-headquartered company's Taiwan-based mass production of high-power LEDs on flexible copper-alloy bases. The prize heralds SemiLEDs' 100 lm/W-plus, low-cost, products as "life-changing technology" that has "potential for long-term impact on business and society".

"With adoption triggered by the low cost and new LED backlight structures, estimates from notebook panel makers suggest 12.2% penetration in the fourth quarter of 2008," said industry analysts at the firm. It doesn't stop there, either. By the middle of 2009, this market-share figure is expected to surpass 25%, meaning that some 10 million notebook PCs featuring LED illumination will be sold in each quarter.

With dozens of LED chips needed in each backlight, the number of compound semiconductor devices required for notebook PCs will approach 1 billion per quarter.

Leading the industry shift away from traditional fluorescent lamps and towards the energy-efficient solid-state technology is Toshiba Matsushita Display Technology (TMDisplay), which grabbed a 39% share of the emerging market for LED-backlit panels in the third quarter.

DisplaySearch notes that leading brands like Acer, HP and Dell are planning to launch new LED notebook PCs in early 2009, propelling the technology from a high-end option into mainstream use.

"New 16:9 panels will largely adopt LED backlights in 2009," it predicted. "TMDisplay, which is mainly shipping 12.1 inch and 13.3 inch panels with LED backlights, is the leader, followed by AU Optronics and LG Display."



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A6 ☐ Applications engineering

A7 ☐ Science/engineering/technology management

A8 ☐ Corporate management

A9 ☐ Financial/market analysis

A11 ☐ Other (please specify) _____

3. Which of the following most closely describes the place where you work?

(tick one box only)

B1 ☐ Semiconductor fab or foundry

B2 ☐ Corporate semiconductor research center

B3 ☐ Academic/government semiconductor research center

B4 ☐ Epiwafer supplier

B5 ☐ Manufacturer of systems/components using compound semiconductor devices

B6 ☐ Semiconductor equipment or semiconductor materials company

B7 ☐ Finance or investment firm or market research/analysis

B10 ☐ Fabless chip supplier/developer

B9 ☐ Other (please specify) _____

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

C1 ☐ III-Vs: arsenides

C2 ☐ III-Vs: phosphides

C3 ☐ III-Vs: nitrides

C4 ☐ III-Vs: antimonides

C5 ☐ II-VIs

C6 ☐ SiC

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

C8 ☐ Other (please specify) _____

5. What types of semiconductor device are manufactured or developed at the place where you work? (tick all that apply)

D1 ☐ GaAs ICs or discretes

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

D10 ☐ Detectors

D12 ☐ GaN laser diodes

D14 ☐ Power semiconductor devices

D11 ☐ Other (please specify) _____

6. Please tick other relevant publications you receive/read. (tick all that apply)

E2 ☐ Semiconductor International

E3 ☐ Solid State Technology

E4 ☐ Laser Focus World

E5 ☐ Photonics Spectra

E7 ☐ EuroAsia Semiconductor

E8 ☐ Semiconductor Today

E6 ☐ Other (please specify) _____

7. How many employees are there at your site? (tick one box only)

F1 ☐ 0-19

F2 ☐ 20-49

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F5 ☐ 500-999

F6 ☐ More than 1000

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LASERS

Nichia claims GaN VCSEL breakthrough

Nichia has produced the first electrically pumped GaN VCSEL to emit continuous-wave (CW) light at room temperature.

The 410 nm laser improves on existing low-temperature operation GaN VCSELs thanks to better orientation of its electrodes and removal of its sapphire substrate. Researchers from the Japanese GaN pioneer reported the approximately 13.9 kA/cm² threshold current density device in *Applied Physics Express* in December 2008.

The best previous CW GaN VCSEL, deposited on a sapphire substrate with contacts located next to each other, only operated at temperatures up to 77 K. Nichia says that this device was limited by the fact that sapphire is a poor thermal conductor and the close proximity of the contacts.

"In side-by-side configuration for the n-type and p-type contacts, current crowding occurs near the edge of the p-type mesa," Yu Higuchi wrote. "Current crowding induces an increase in operating voltage and heat generation, especially in VCSELs, which require a high current density."

Higuchi grew an InGaN/GaN region by MOCVD on a sapphire wafer, starting with n-type GaN. Above this was deposited an active region consisting of multiple quantum wells made from alternating 9 nm thick InGaN and 13 nm thick GaN layers.

The Nichia team grew a p-type GaN layer above the active region, followed by a SiO₂ layer, into which they patterned an 8 μm diameter current aperture. Depositing 50 nm of indium tin oxide (ITO) provided a p-type ohmic contact and current-spreading layer.

Above this the team used niobium oxide as the basis of a layer that performed the

combined role of electrode and backside mirror. The lack of suitable distributed Bragg reflector (DBR) mirrors with suitable reflectivity and conductivity has been one of the key challenges for GaN VCSELs.

In addressing this, Nichia deposited a niobium dioxide electrode onto the ITO layer around the current aperture. Above the aperture, 11.5 pairs of alternating SiO₂ and niobium dioxide layers were grown as a DBR.

The researchers then bonded a silicon substrate on top of this structure, inverted it and removed the sapphire substrate by laser-induced lift off. They also polished back the n-type GaN layer so that the optical cavity was 1.1 μm thick, before making a seven-pair SiO₂/niobium dioxide DBR and n-type contact on top of it.

Although the device's threshold current density is higher than the 77 K VCSEL, at 4.3 V its threshold voltage is lower. Higuchi says that this is "probably due to vertical current injection without current crowding".

The GaN VCSEL's final output power was 0.14 mW at 12 mA injection current. The team concedes that so far "the VCSEL was easily degraded under CW operation".

UV LEDs

AlN growth start-up targets \$3 m injection

A spin-out from the University of California, Santa Barbara, wants cash to help AlN UV LEDs to match the performance of GaN blue emitters. Troy Baker, chief technology officer of Aurora UV, has designed a hydride vapor phase epitaxy (HVPE) reactor based on his work with GaN LED pioneer Shuji Nakamura. Baker helped to develop high-quality AlN substrates that can be used to produce UV LEDs.

"Mid- and deep-UV LEDs are extremely



Aurora UV won the Most Fundable Idea prize in UCSB's new-venture competition in May 2008.

poor efficiency, around 1%," Baker explained to *Compound Semiconductor*. "I think that with the proper substrates UV LEDs can be as efficient as blue LEDs."

Aurora UV, formerly known as Nitride Solutions, has a top epitaxy equipment maker poised to produce a commercial-volume system based on Baker's patented design. The start-up has identified investors who can help to provide the \$3 million needed to go ahead. These investors are hoping to be joined by counterparts with LED industry knowledge. "We think the best way would be to partner with an LED company that uses our substrates to make the UV LEDs," Baker explained.

UV-LED makers think that their products could perform UV sterilization more economically and reliably than mercury-based fluorescents. However, Baker points out that AlGaIn active regions with typical dislocation densities around 10⁹ cm⁻² are limiting efficiency of shorter-wavelength UV LEDs, which have higher AlN contents.

HVPE techniques developed at UCSB lower bulk AlN dislocation levels to 10⁶. "I've grown films up to 360 μm thick at rates of 180 μm an hour," Baker said, yet reactor design has limited further progress.

● Would your company be interested in working with Aurora UV? E-mail troy.baker@aurorauv.com.



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...Optium deal drives \$187 m Finisar loss

Finisar took \$179 million in charges over its acquisition of Optium for the three months ended November 2008, reflecting the slump in market value of its new purchase. The optical communications company was also hit by a \$10.5 million charge for Optium's ongoing R&D. Although the latest results were otherwise within expectations, the Sunnyvale, CA, firm sees revenues falling sequentially. "However, thanks to new product qualifications, we see the potential

for a return to sequential growth in the April quarter," said executive chairman Jerry Rawls.

...HRL demos first graphene FETs

Los Angeles, CA, research lab HRL has made the first radio-frequency field effect transistors fabricated from monolayer carbon sheets. The 2 μm gate length FETs are made from epitaxially grown graphene materials with on-state current density of 1180 μA/μm at a drain bias of 1 V. Their current gain cut-off frequency (f_T) is 4 GHz and maximum

oscillation frequency (f_{MAX}) is 14 GHz.

...Showa Denko takes over ESICAT

Having founded epiwafer foundry ESICAT in 2005 with six industrial partners, based on its own technology and that of Japanese research centers CRIEPI and AIST, Showa Denko took complete control at the beginning of 2009. The industrial giant will expand ESICAT's business and "encourage the growth of the SiC epitaxial wafer market for power device applications".

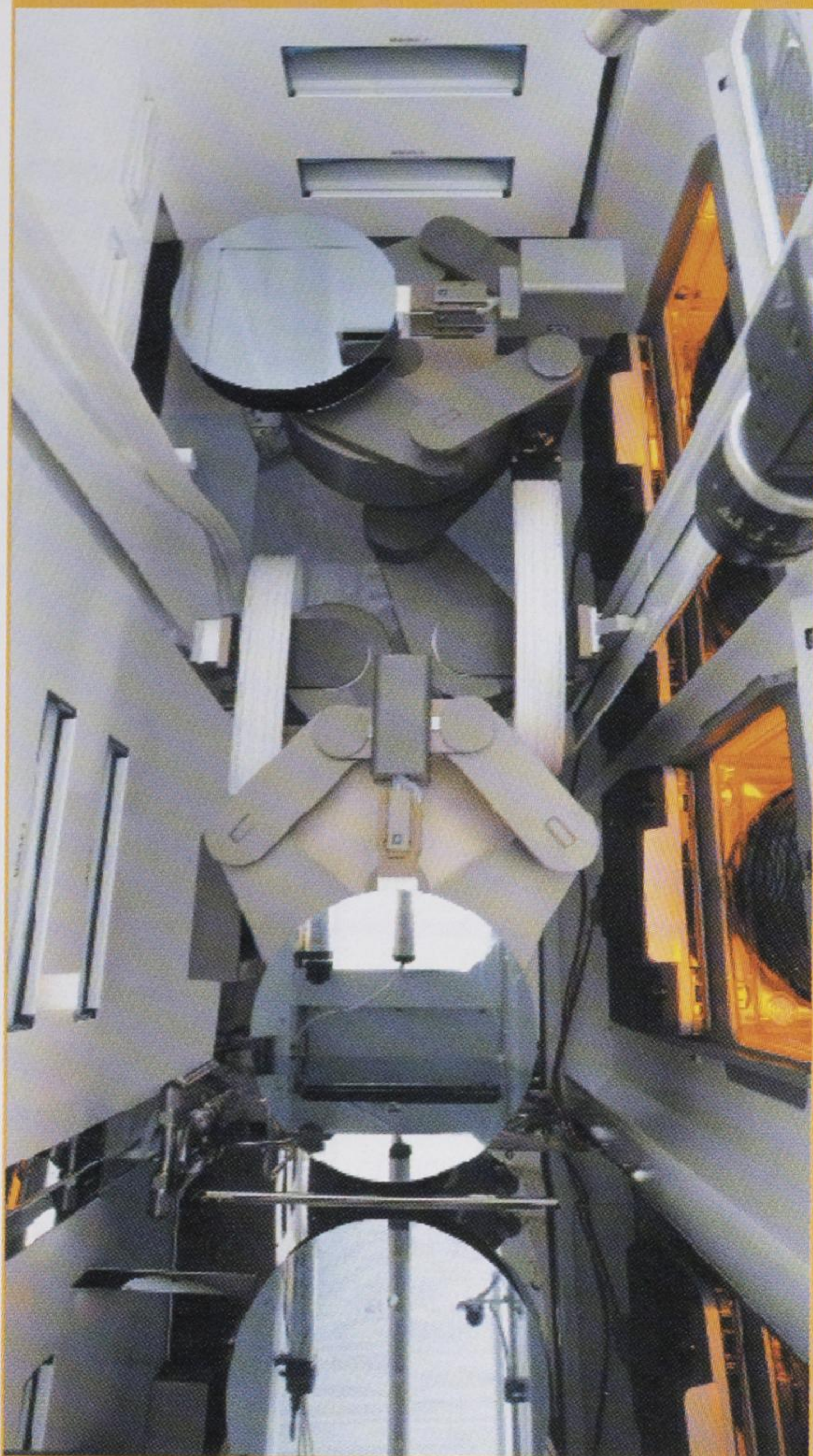
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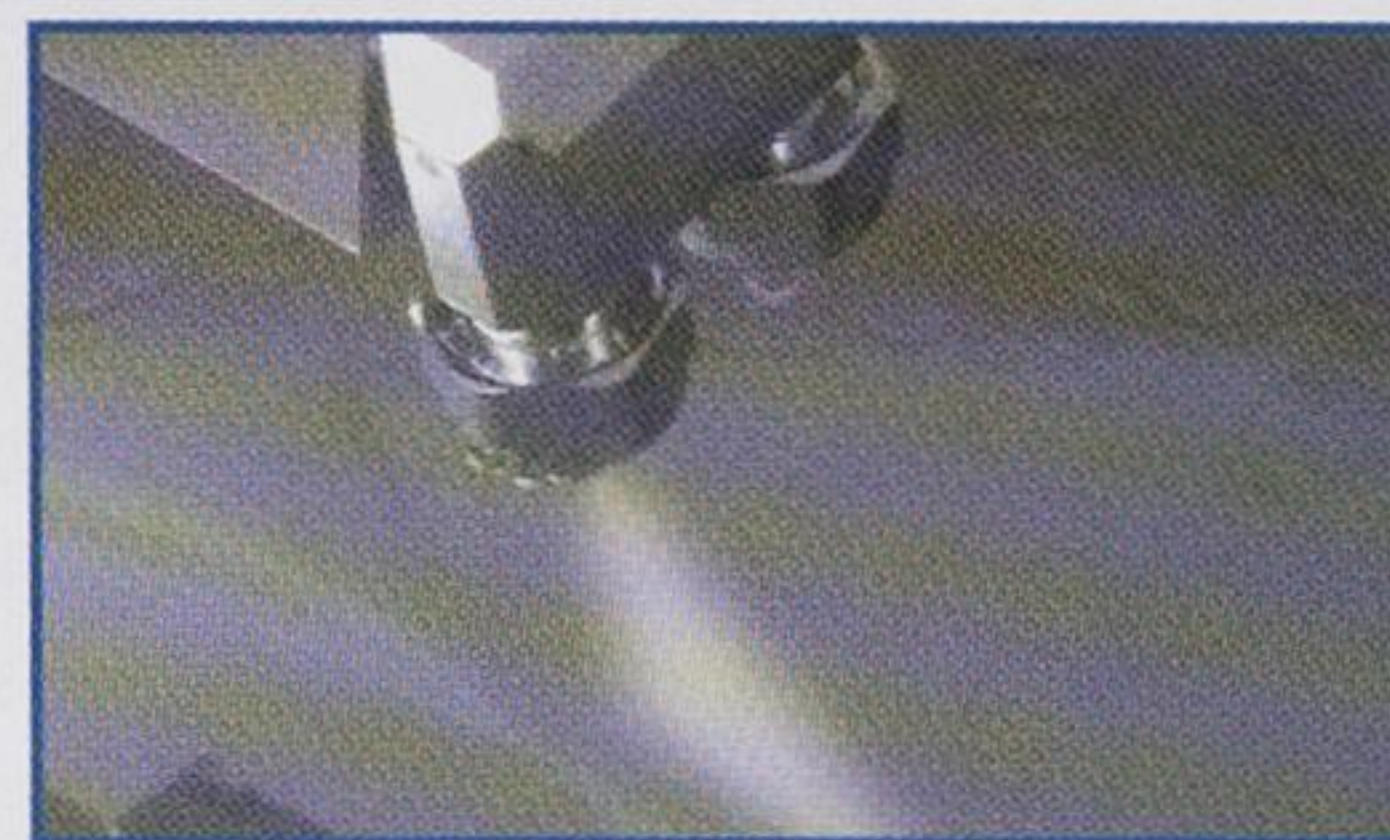


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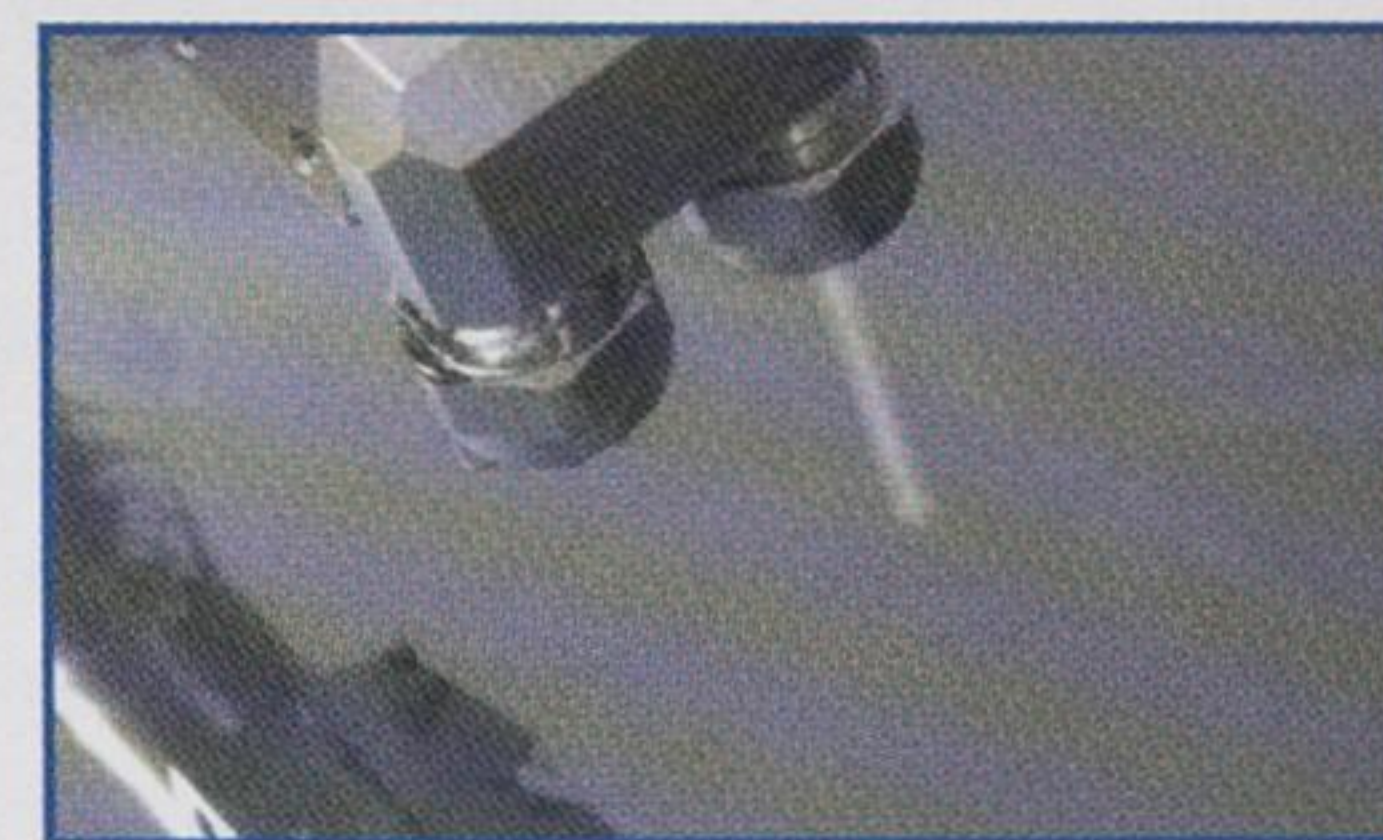
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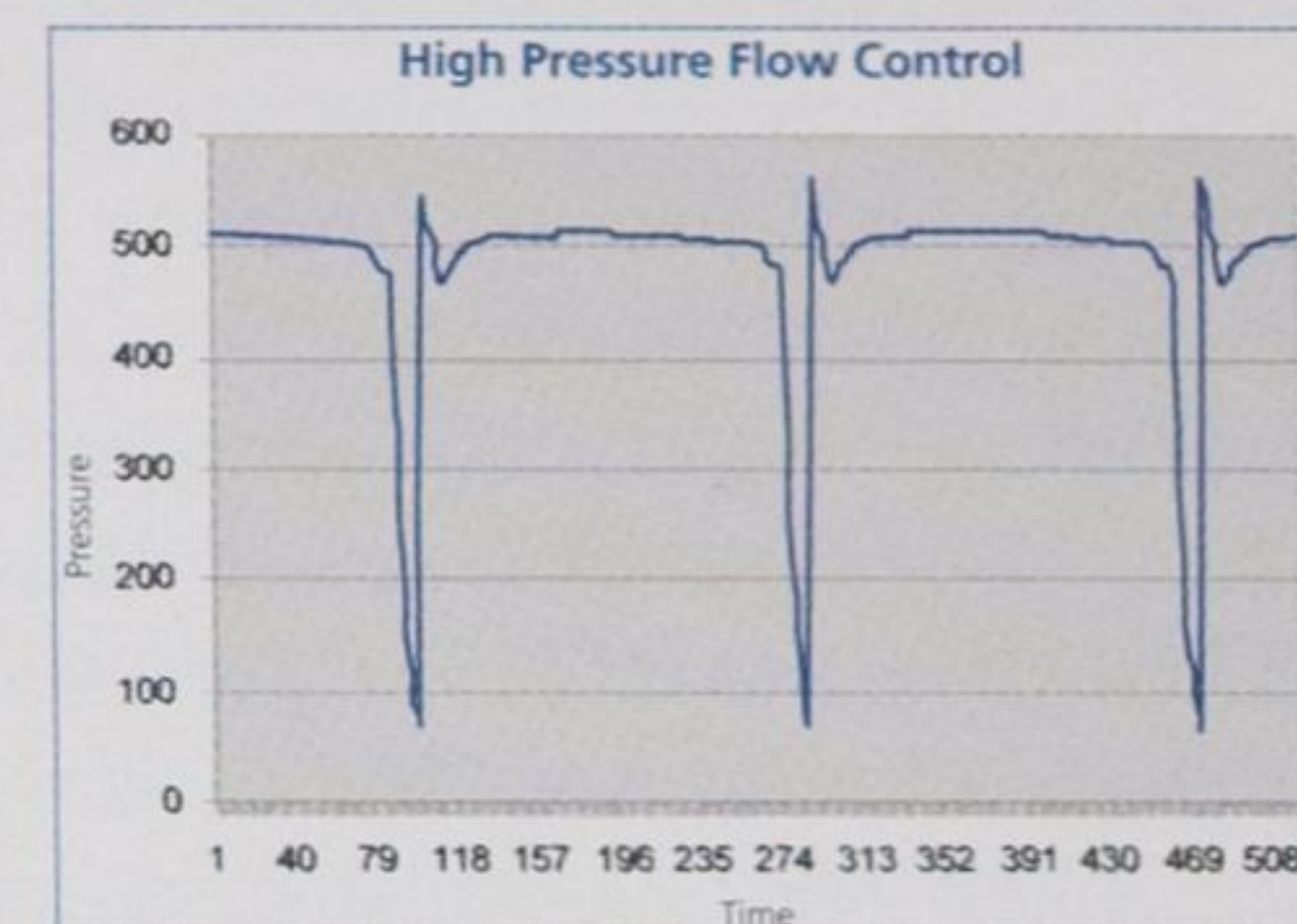
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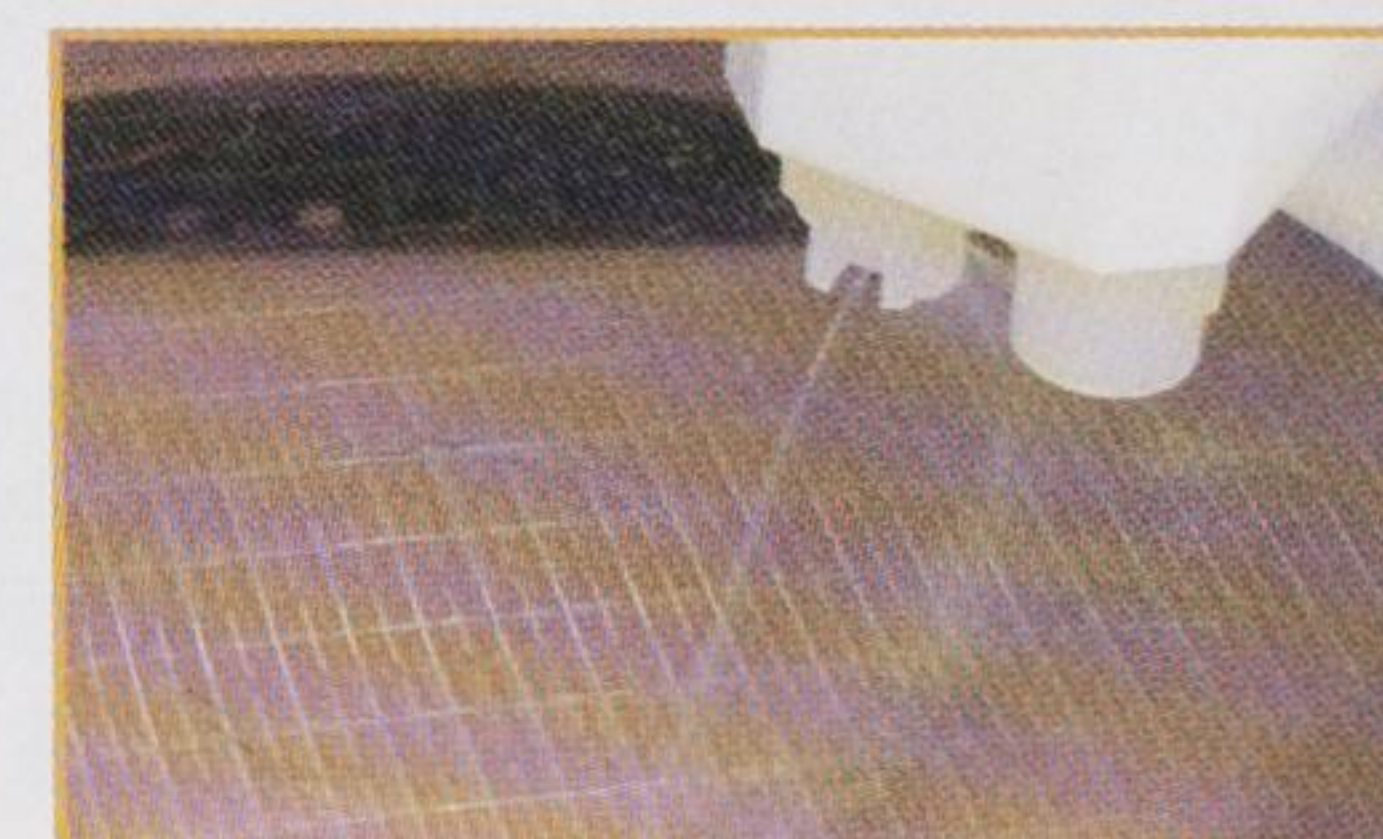
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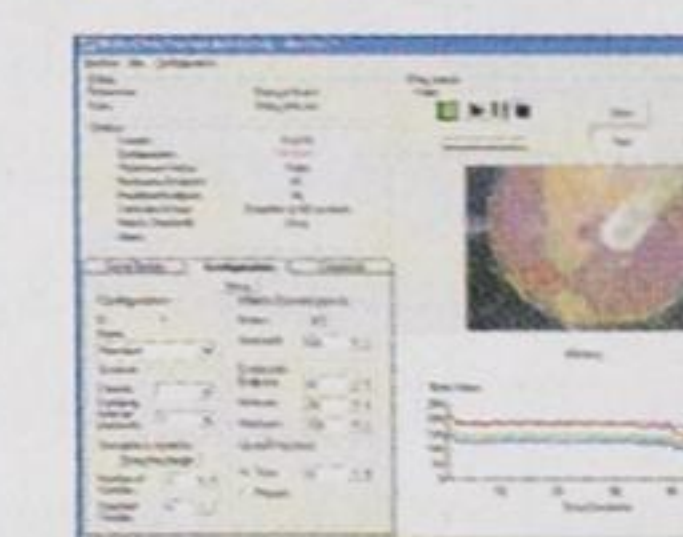
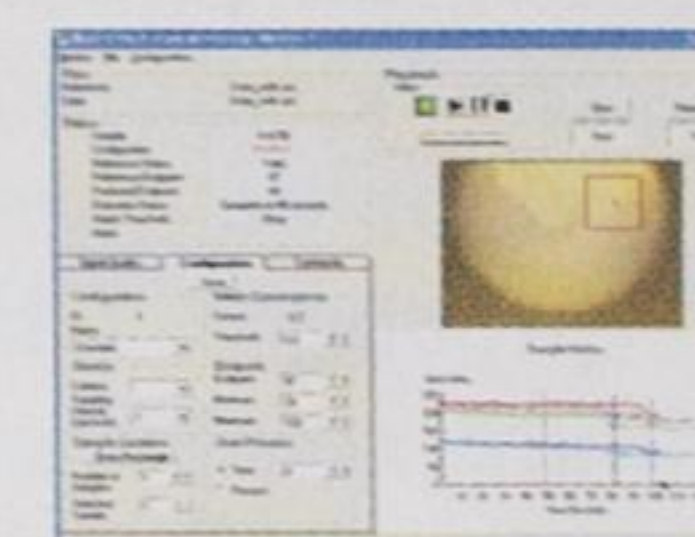
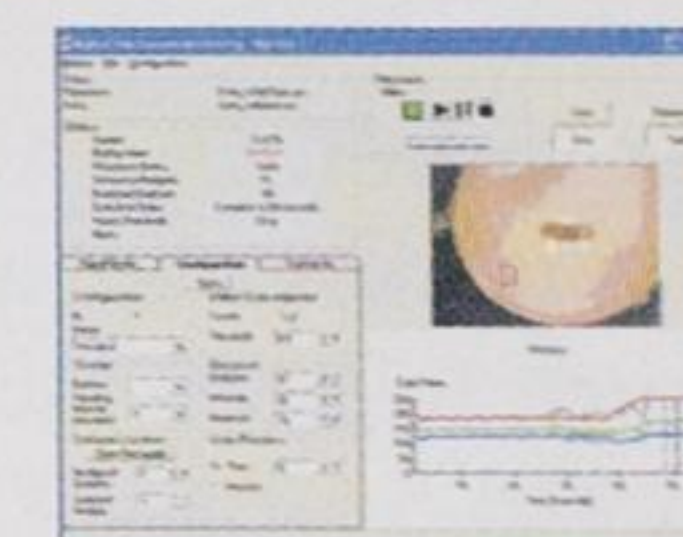
Backside/Bevel Cleaning



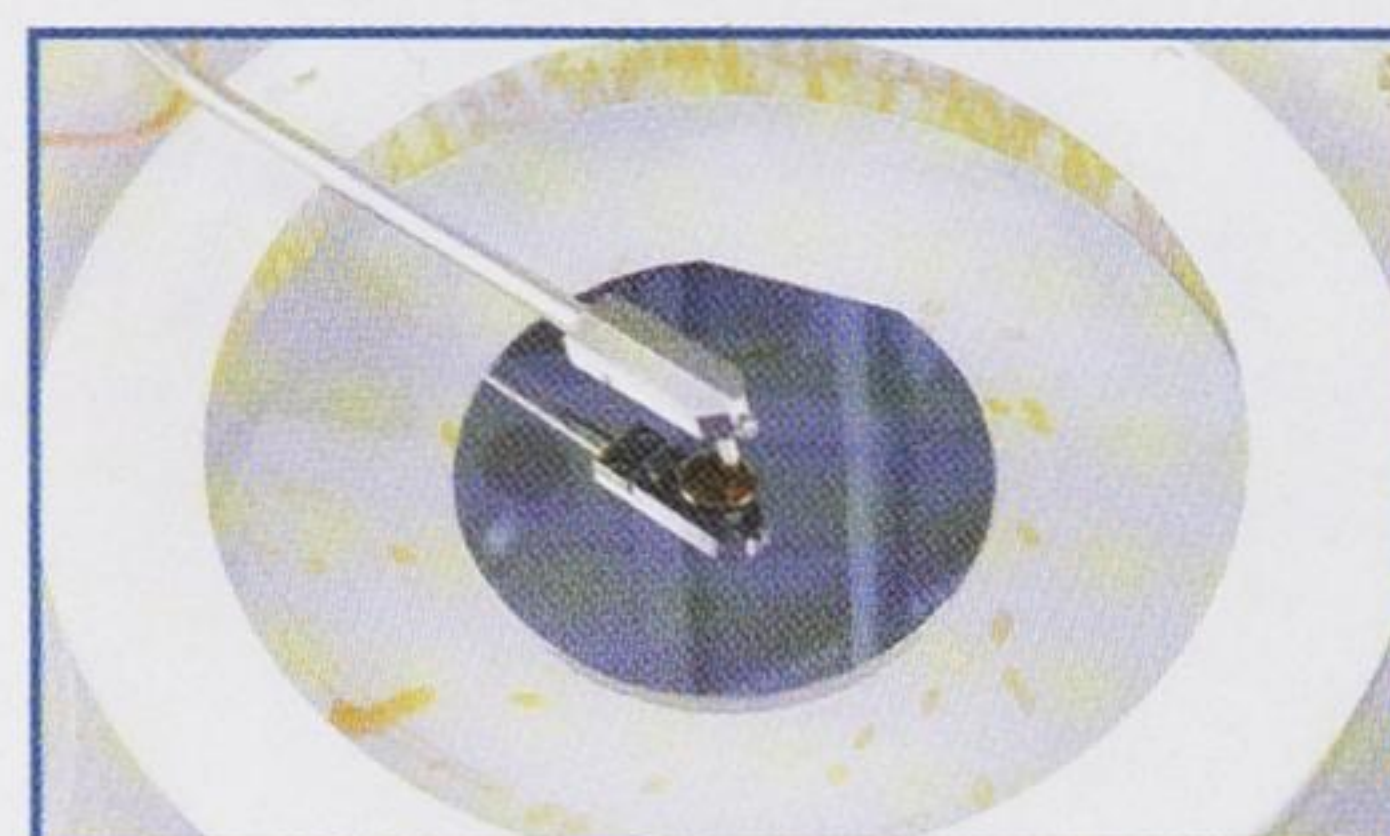
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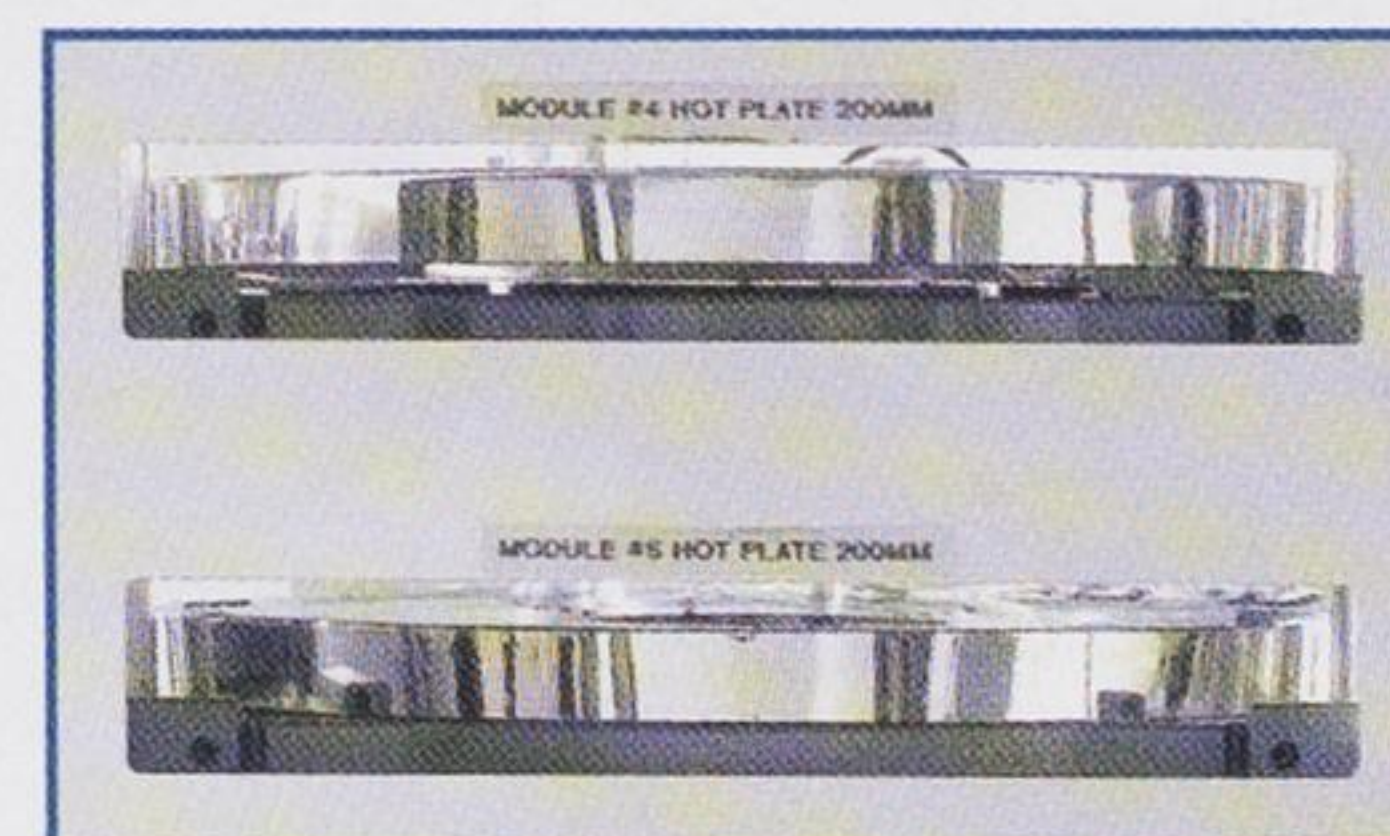
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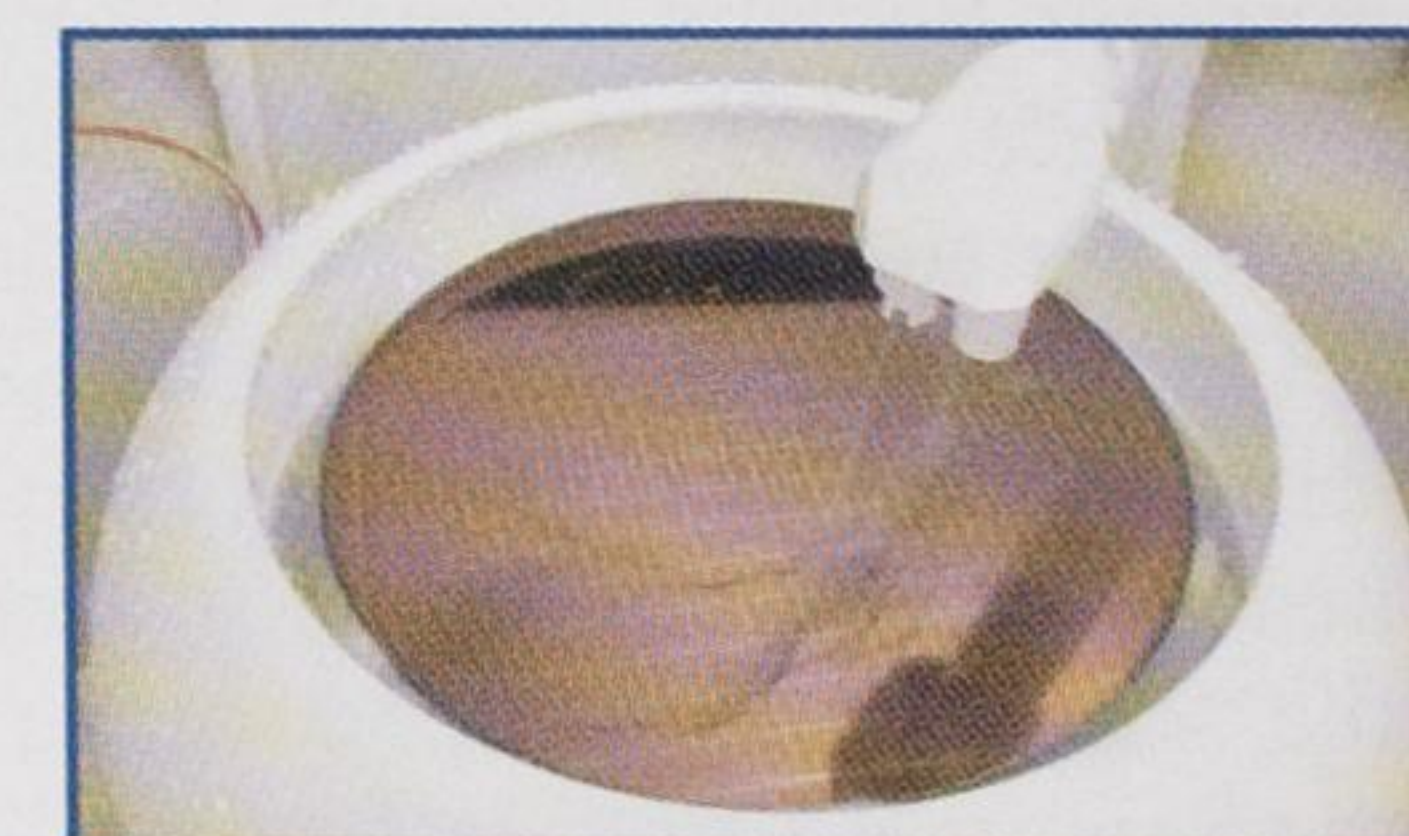
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OPTOELECTRONICS

Demand 'drops off a cliff' at Emcore

Emcore has cut 100 jobs after its results for the September quarter were hit by \$5 million worth of order cancellations at the very end of the period.

The shortfall in its core fiber optics business contributed to a \$19.7 million loss that surprised market analysts covering the diverse compound semiconductor company. Emcore lost a third of its market value on releasing these results, falling from \$1.54 at close of trading on December 10, 2008, to \$1.02 at close the following day.

"During the September quarter we were tracking well for our revenue plan, but the demand seemed to drop off a cliff after September 15," explained Hong Hou, Emcore's CEO. "The optical revenue decreased from \$53.6 million to \$46.1 million sequentially."

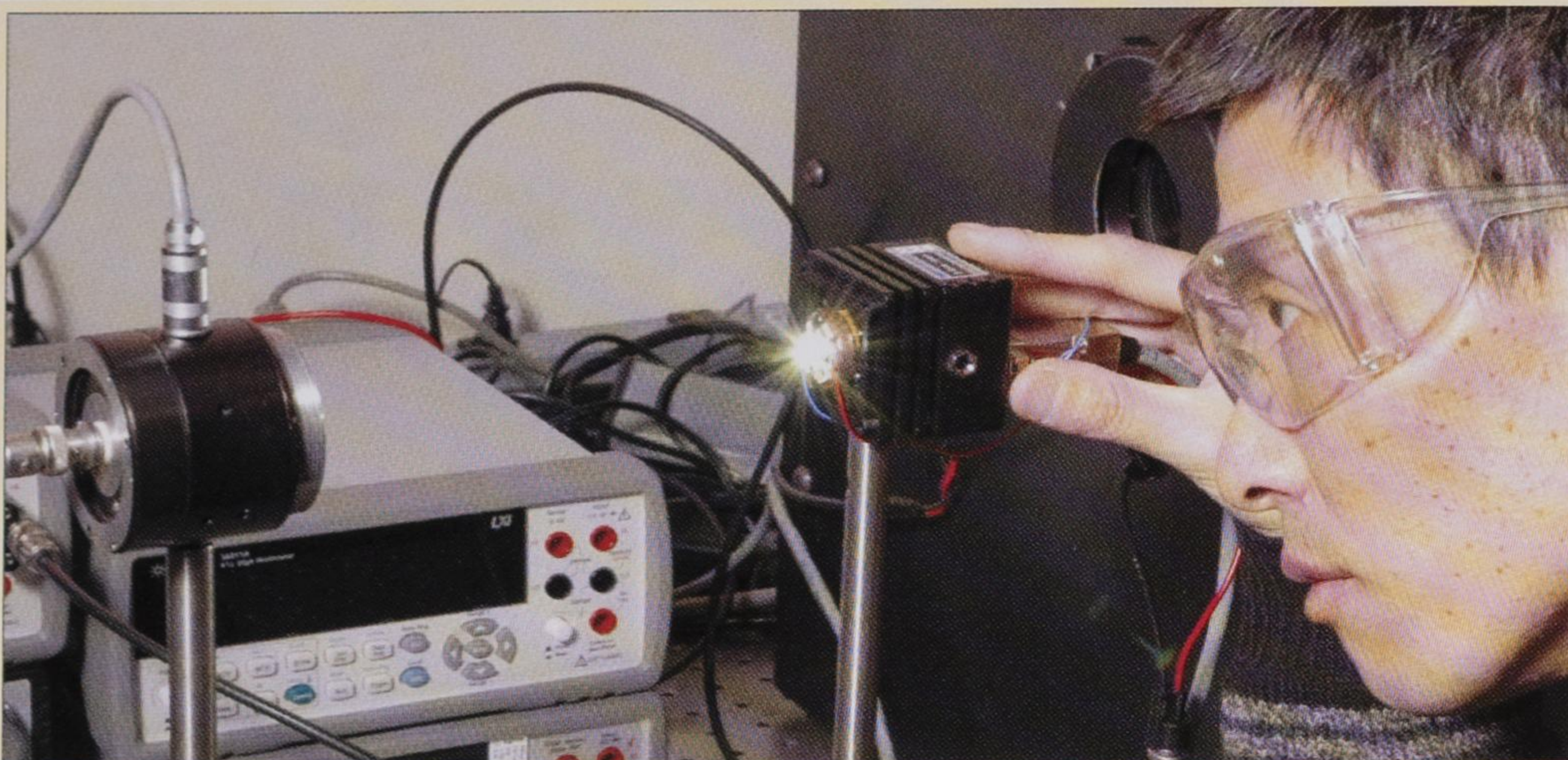
The company's concentrating photovoltaic (CPV) business failed to ship against some orders because the customers concerned were too great a credit risk. Emcore also saw delays in more concrete orders, as companies reacted to uncertainty over the future of solar-power incentives in the US and Spain.

Although Hou didn't say exactly how overall photovoltaic revenue was earned, the headline figure fell 8% from the previous quarter to \$14.5 million. Despite its problems, CPV actually boosted this figure, compensating for a \$5.3 million fall in revenue from the US government for GaAs-based solar cells to be used on satellites.

A further blow to the company's profitability came in the three months ended September as it took a \$4.5 million charge for CPV system inventory that has now become obsolete. The stock will be offered for sale to small projects, but the charge brought the quarter's photovoltaic gross profit margin crashing to -31.6%. These systems and modules became obsolete because Emcore has upgraded from its second-generation to third-generation CPV technology.

On the basis of the potential for these systems Emcore is cautiously optimistic, with nearly 150 MW of orders in negotiation in the south-west US alone. Since the end of the September quarter the solar business has been boosted by the US congress passing an eight-year extension of the solar investment tax credit incentive, Hou points out.

Despite this the company is taking measures to reduce costs and boost profitability. This includes cutting staff bonuses in 2008, while eliminating them and merit increases in salary for this year.



The commercialization of solid-state lighting based on LEDs could be aided by a new test procedure developed at the US National Institute for Standards and Technology (NIST) in Gaithersburg, MD. NIST scientists Yuqin Zong and Yoshi Ohno say that their method will help to close the gap between LED manufacturers and the lighting industry, by providing a test for LED brightness and color that is comparable to conventional lamp measurements.

Light produced by an LED depends on its operating temperature and, more specifically, the junction temperature in the semiconductor. To help ensure speedy device production, LED manufacturers use a test based on high-speed optical pulses to check the color and brightness of their devices. However, these 20 ms pulses do not give sufficient time for the chips to warm up to normal operation, where junction temperatures might reach 60°C.

In contrast, the wider lighting industry tends to use a steady-state DC approach to lamp metrology. "There has been a strong need for a standardized method for high-power LED measurements," Ohno told *Compound Semiconductor*. "This method has been accepted by most major LED and lighting companies as well as many instrument manufacturers."

Ohno and Zong use a temperature-controlled heat sink, which sets the LED chip to any specified junction temperature prior to DC testing of device output. These heat sinks are cheap and widely available, and the team says that its method is compatible with all types of high-power LEDs, including arrays of emitters connected in series.

ADVANCED DEVICES

Intel closes in on compound logic

III-V MOSFET developers have devoted many years to the search for a suitable p-channel material for their transistors, which promise high-speed, low-power logic devices. But their pursuit may now be over, with Intel and QinetiQ saying that they have found a strong candidate in InSb.

The US silicon chip maker and UK defense company presented a paper at the IEEE Electron Devices Meeting in San Francisco, CA, on December 17, 2008, where they detailed the structure of a III-V quantum-well FET with a record p-channel cut-off frequency (f_T). This 40 nm gate length transistor, which features a compressively strained 5 nm thick InSb quantum well, delivers an f_T of 140 GHz at a supply voltage of 0.5 V.

The work compliments earlier research by the partnership, which developed n-channel transistors on silicon and InSb substrates

with cut-off frequencies up to 300 GHz. CMOS logic needs both types of devices.

The p-channel FET's high cut-off frequency stems from a high hole mobility in InSb, which has been maximized through strain optimization. At 1.9% compressive strain, hole mobility hits $1230 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$.

Marko Radosavljevic and co-workers created strain in InSb by sandwiching it between two $\text{Al}_{0.35}\text{In}_{0.65}\text{Sb}$ barriers. All of the transistor's layers were grown by MBE on (100) GaAs and a wet etch produced the gate recess, which created a 10 nm gate-to-channel separation. Ti/Al metallization formed the gate, source and drain contacts. The researchers claim that their transistor also delivers a record transconductance for III-V p-channel FETs of $510 \mu\text{S}/\mu\text{m}$.

In addition, they say that their device's performance is superior to that of silicon equivalents. "Compared with silicon p-MOSFETs, the InSb p-channel QWFETs show a reduction in gate delay and a significant improvement in energy-delay product, which represents the energy-efficiency of the device," said Radosavljevic and colleagues. At identical speeds, the InSb

MOSFET uses one-tenth of the power of a silicon equivalent and delivers a two-fold speed advantage at the same power.

III-V/SILICON INTEGRATION

HRL Labs marries InP and CMOS wafers

Scientists at HRL Laboratories in Malibu, CA, have combined InP and CMOS in a breakthrough that could allow rapid adoption of more-advanced integrated technology.

At the IEEE Electron Devices Meeting in December 2008 the researchers presented 300 GHz InP double HBTs (DHBTS) married with 130 nm RF-CMOS technology at the wafer level. This allows the superior performance of InP transistors to be united with a silicon manufacturing technology that can produce ICs exploiting more than 1 billion transistors in high volume.

The technology developed by HRL can join 3 inch or 100 mm InP DHBT wafers to 200 or 300 mm CMOS wafers created by IBM's CMRF8SF process. The InP transistors featured $0.25 \times 4 \mu\text{m}$ emitters. "No electrical impact to the CMOS devices has yet been observed and the InP DHBTs suf-

fer minimal performance degradation," said James Li and his co-authors in their paper.

Li and colleagues say that this is the first demonstration of unperturbed CMOS performance after heterogeneous integration with an InP HBT. The DHBT's cut-off frequency (f_T) is more than 300 GHz, but the maximum oscillation frequency (f_{MAX}) is below 150 GHz, which they describe as modest.

The team says that the low f_{MAX} is caused by additional parasitic loading of a thermal via. The epitaxial material is also to blame because it causes higher base resistance and capacitance between the base and collector.

The data produced by HRL came from the combination of a 3 inch InP DHBT wafer and a 200 mm CMOS wafer. Heterogeneous integration began by bonding the episurface of the InP wafer, which features an additional 160 nm InGaAsP/InP composite etch stop below the sub-collector, to a handle wafer.

The InP substrate and etch-stop layers were removed and a $0.5 \mu\text{m}$ thick aluminum heat spreading layer was added to bond this to the CMOS wafer. A laser trimmed the CMOS wafer to a 3 inch diameter before the handle was removed. Standard processing techniques were used to fabricate the InP DHBTs and the heterogeneous interconnects.



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...Cree claims highest-output LED

LED manufacturer Cree has claimed record efficiency of 161 lm/W for a $1 \times 1 \text{ mm}$ white power device. The Durham, NC, company says that it will be moving into manufacturing with the advances that have been seen in its record LED.

...Santur's tunable ramp hits 200,000

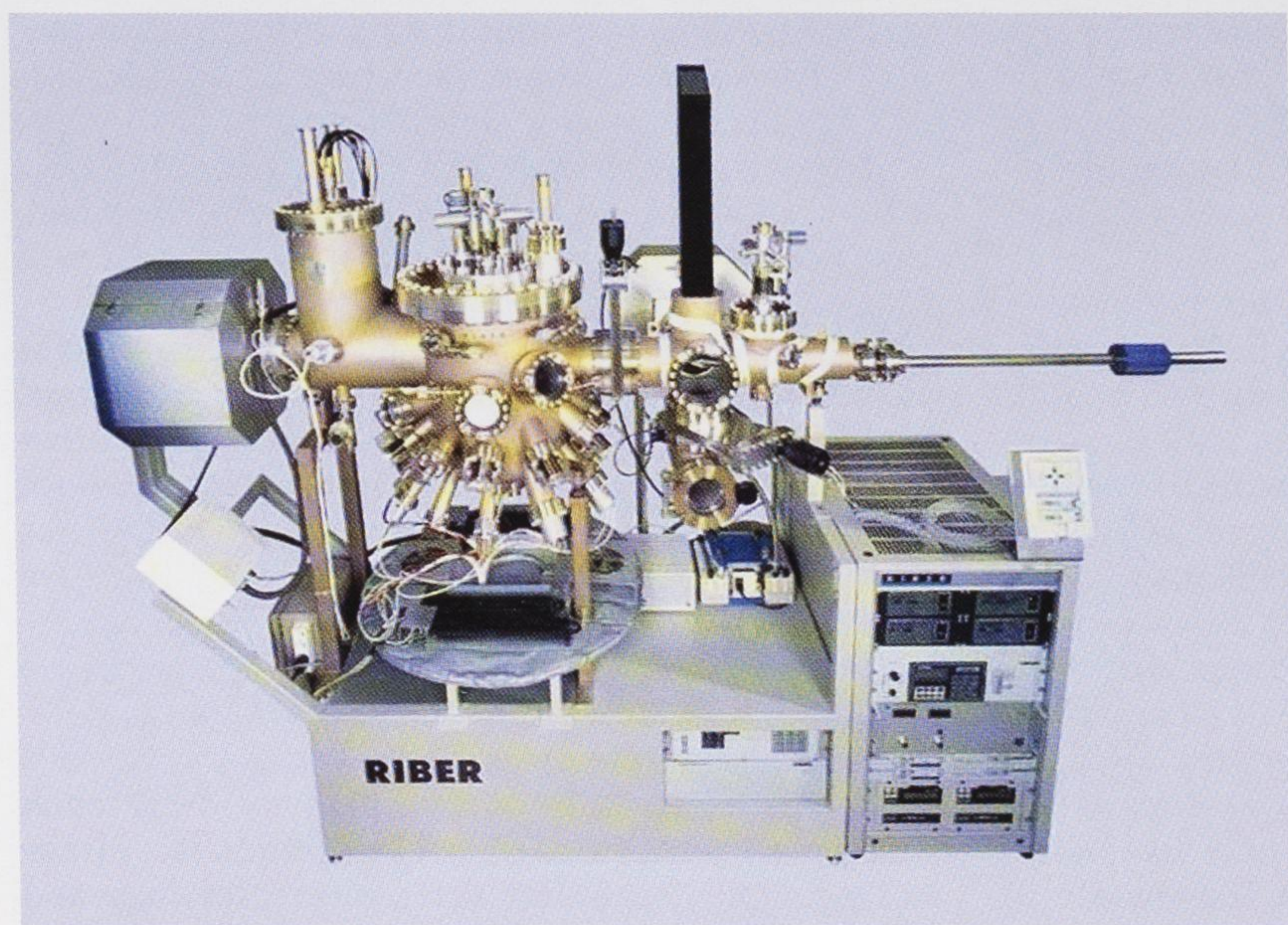
Fremont, CA, based Santur Corporation has shipped its 200,000th InP tunable laser. Santur took about seven years to ship the first 100,000 devices but only one additional year to ship the next 100,000.

...Compound photovoltaics market to soar

According to data from US market analysts Strategy Analytics, III-V solar will outgrow the 23% annual growth rate expected for the solar industry. "High cell conversion and lower material usage will translate to compound annual average growth rate of 133% through 2012," said Asif Anwar, author of the report.

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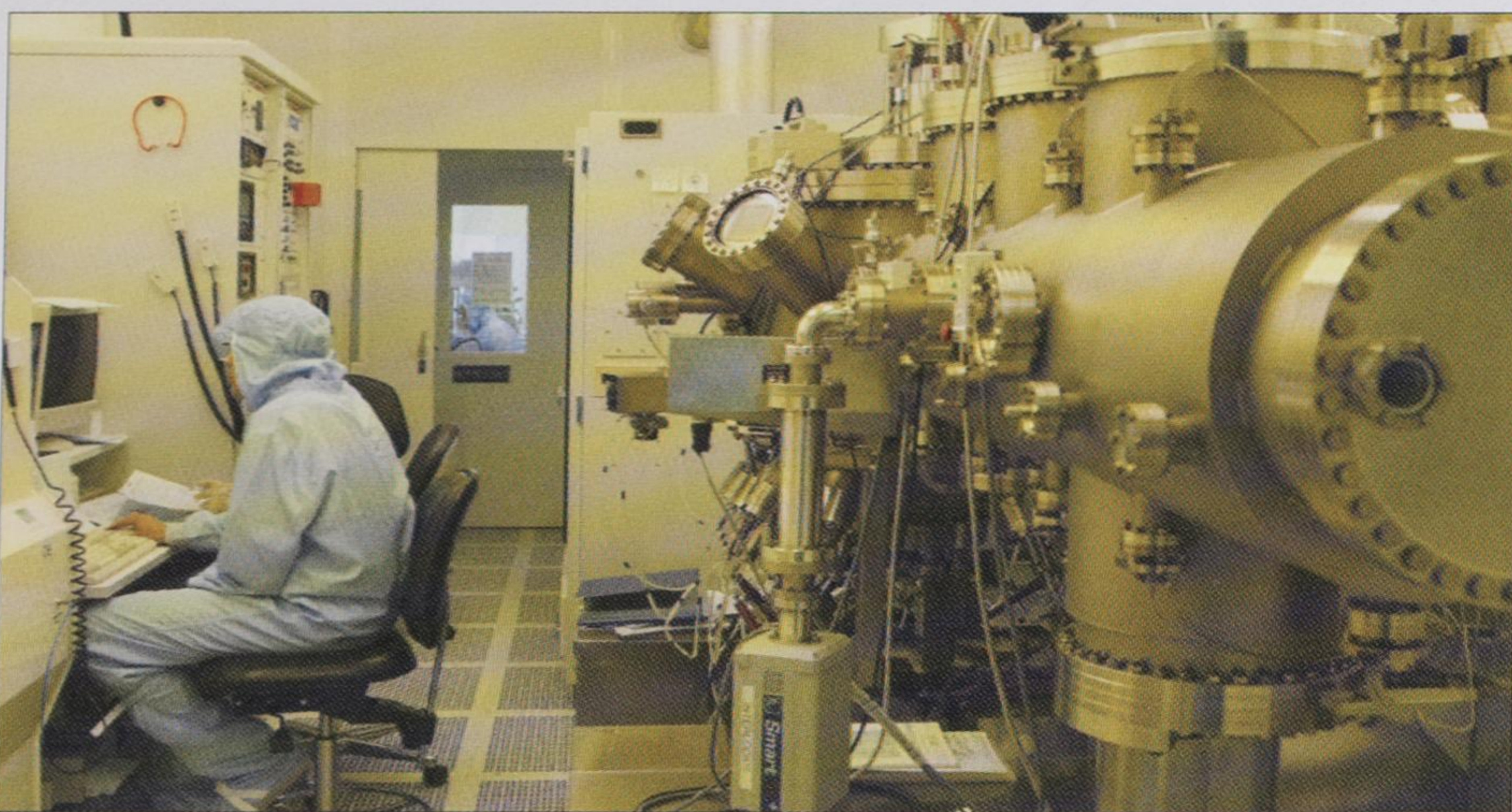
RIBER



980 nm PUMP LASERS

GaAs diode firms pump up competition

As 3S Photonics seeks to wrest 980 nm pump-laser market share from Bookham and JDSU, **Andy Extance** hears how all three will contest the leadership in the terrestrial and submarine optical communications component sector.



3S PHOTONICS

3S Photonics is now targeting terrestrial optical communication applications with the 980 nm emitting diodes made in its GaAs fab.

Changes are afoot in the world of GaAs 980 nm pump laser diodes. One company says that its sales have grown so much that it has advanced to the top spot, while an upstart says that it is set to cut into this lead in 2009. Yet the overall market value is growing only modestly, and the world is experiencing the second recession in a decade. The first one had a catastrophic effect on the optoelectronics industry, so how can the sector host such grand ambitions?

One factor is that the major players in this market – Bookham, JDSU and Furukawa Electric – are now vying with a very vocal competitor, 3S Photonics. The company, also known as 3SP, says that it is taking business from its vertically integrated rivals and is ramping up its output. Surprised by the level of interest in its InP transmission lasers, the French fab began offering GaAs-based 980 nm pump lasers for the terrestrial market in mid 2008. Production is accelerating and is destined to be a key part of 3SP's plan to expand its revenue by 20% in 2009.

"JDSU and Bookham are also manufacturing optical amplifiers," explained 3SP's director of marketing, Yannick Bailly. "That causes problems for some of the customers." He believes that his company's ability to avoid such a conflict of interest provides it with a strong competitive opportunity. "The market is demanding alternative supply solutions," he said.

This marks the next stage in the ex-Alcatel and Avanex III-V fab's strategy. It is now expanding from the product lines that it started business with in June 2007, when 3SP was divested from Avanex. Then, its original aim was returning to profitability from its submarine pumps and transmission lasers.

Much of the company's revenue still comes from

pump lasers for the submarine optical communication market, targeting major undersea backbone links. This comparatively stable sector is helping 3SP to weather the global economic storm. "We have very good visibility in the submarine market to the end of 2010," Bailly explained.

The high-reliability GaAs laser-diode technology that it uses in submarine pumps was crucial in developing its latest 980 nm products, and also enables 3SP to make uncooled terrestrial pumps. Although the French firm has recently entered this market, Bookham boasts that it still makes nearly all of the uncooled 980 nm pumps sold in the world today.

"That's been a really important product for us," explained Mark Ives, director of the line solution business that sells Bookham's pump lasers and amplifiers. "It's becoming increasingly important to amplifier designers. As more people deploy 40 and 100 Gbit/s communications there's a need for very small, low-cost, single-channel amplifiers."

Running without a thermoelectric cooler shrinks the package size of Bookham's products, and cuts energy consumption and running costs. The company's ridged-waveguide GaAs diode chips enable this advantage, ensuring that efficiency drops much less at higher temperatures than competing designs.

These chips, made in Bookham's Zurich, Switzerland, fab and packaged in Shenzhen, China, are set to reach new highs in power during 2009. By continuously improving its manufacturing processes, Ives says that the company will be able to change its diode binning strategy to include a record output product line. "The highest power today is 275 mW," Ives said, "and our intention is to launch a product that will offer rather more power than that."

Now, whereas 3S Photonics is moving from submarine pump lasers to uncooled terrestrial pumps, Bookham is making good a move in the other direction. It qualified production of its OceanBright 980 nm submarine pumps late in 2007 and has secured a long-term supply deal with key undersea amplifier maker Tyco. Ives says that strategic agreements are now in place with another major submarine player that will grow its market share in the sector.

As Bookham steps up its own expansion into 3SP's staple market, Ives is unperturbed by the French company's claims that vertical integration is a disadvantage. "Our customers value our technology and are compelled to work with us," he said. "Pumps are viewed as being such critical items in the amplifier that very often the customer that the manufacturer sells to will dictate which pump should be used."

"3S Photonics isn't even on our radar."

Toby Strite
JDSU

Outside of the niche submarine and uncooled markets, Ives says that Bookham claimed several key terrestrial 980 nm pump design wins in 2008. The contribution of these extra sales and its uncooled products has helped pump revenue to increase by 30% year-on-year. "We believe that has positioned us as the market leader in terms of revenue for terrestrial pumps," Ives claimed.

This might surprise Milpitas, CA, pump laser manufacturer JDSU. "We continue to ship twice as much as our nearest competitor and four times as much as the next competitor," said Toby Strite, director of high-power laser marketing at the company. "3S Photonics isn't even on our radar." He also claims that JDSU leads the way in submarine pump sales, thanks to technology bought from TriQuint. This market was one of the most badly affected by the technology crash at the turn of the century, and when sales began to flow again as recently as 2006, JDSU had a qualified pump laser ready to go.

He points out that, as important as Bookham considers uncooled diodes to be, JDSU believes that they only represent 5% of the total market for pump lasers. "We determined that this platform cannot compete on cost," Strite said. "The few dollars saved on the cooler are gobbled up by much larger costs of poor production yields and added testing requirements."

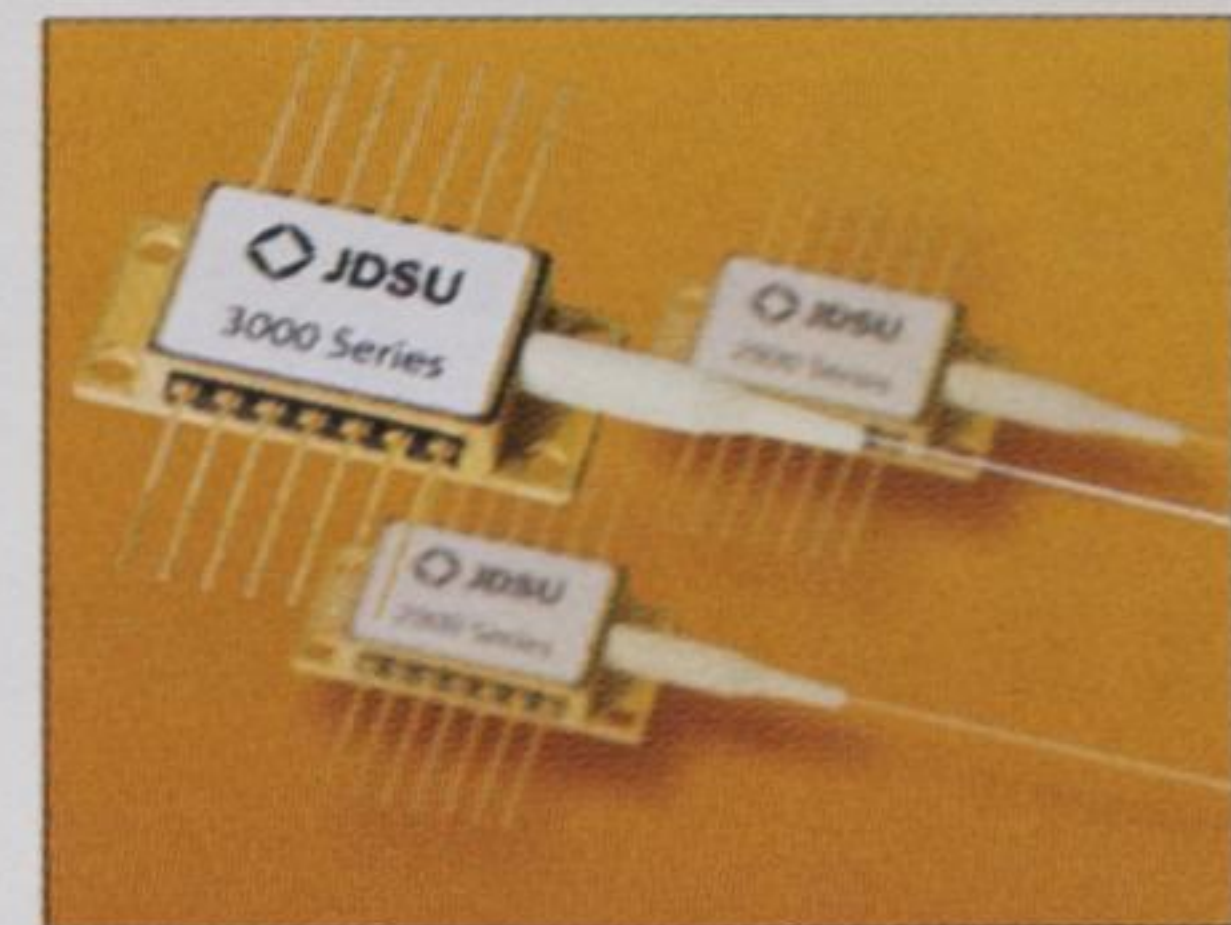
Instead of selling uncooled lasers, JDSU is producing pumps operating at 45°C that keep manufactur-

ing costs down. Strite says that maintaining a fixed but elevated temperature reduces testing and yield problems associated with uncooled diodes and allows the use of cheaper coolers. The firm will introduce 550 mW pumps from this line this year.

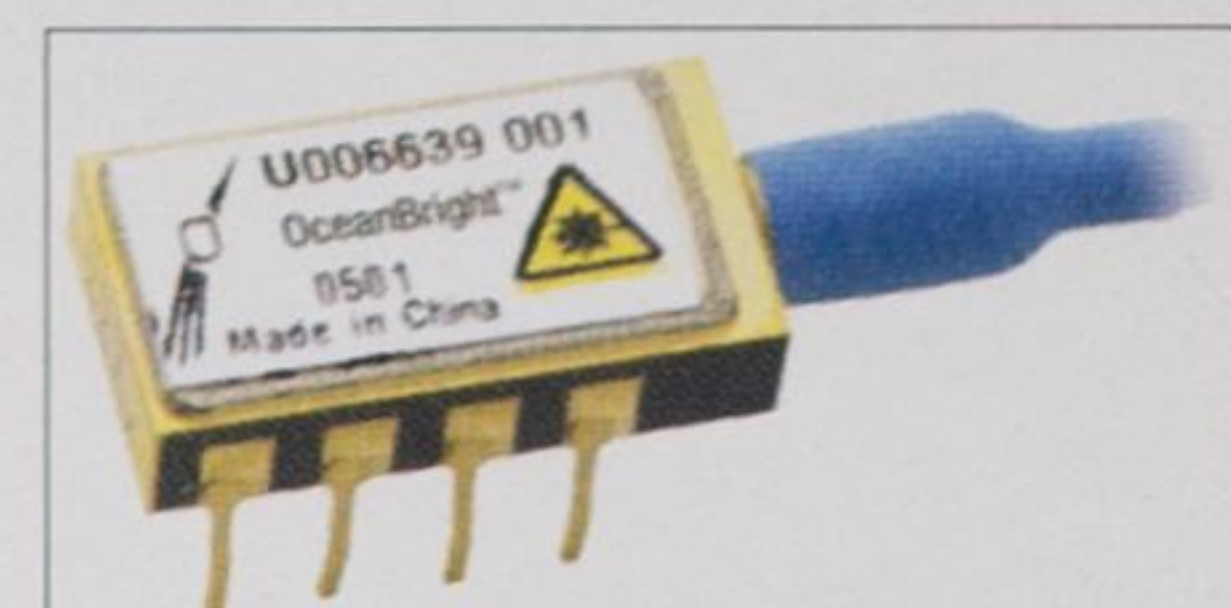
During 2009, JDSU will be continuing to lower the cost of packaging its 980 nm pumps, working to reduce the expense of manual processes like fiber alignment and soldering. "Optics for telecommunication, while a large market, is not large enough to automate," he pointed out. For this reason, JDSU's research in this market is now focused on packaging rather than chip development. "As long as 980 nm pump lasers have been around there's been an 80/20 split between the package and chip costs."

As for the French company seeking to cut into its market share, Strite's outlook is circumspect because 3S Photonics is also a supplier to JDSU. He points out that everybody is feeling the effects of the current economic climate and in the ultra-competitive optical communications market you need to take your advantages where you can.

"We are proud to have 3SP as one of our fiber-Bragg grating suppliers, despite their obvious desire to compete with our 980 nm product leadership," he said. "These are challenging times in which companies only succeed by partnering with the best available vendors. We don't have the luxury of considering whether our vendors covet our market position."



JDSU says that its 500 mW output 2900 series 980 nm pumps are powerful enough for 95% of all required applications.



Bookham's OceanBright submarine laser is set to be deployed by an additional undersea amplifier manufacturer.



MOCVD

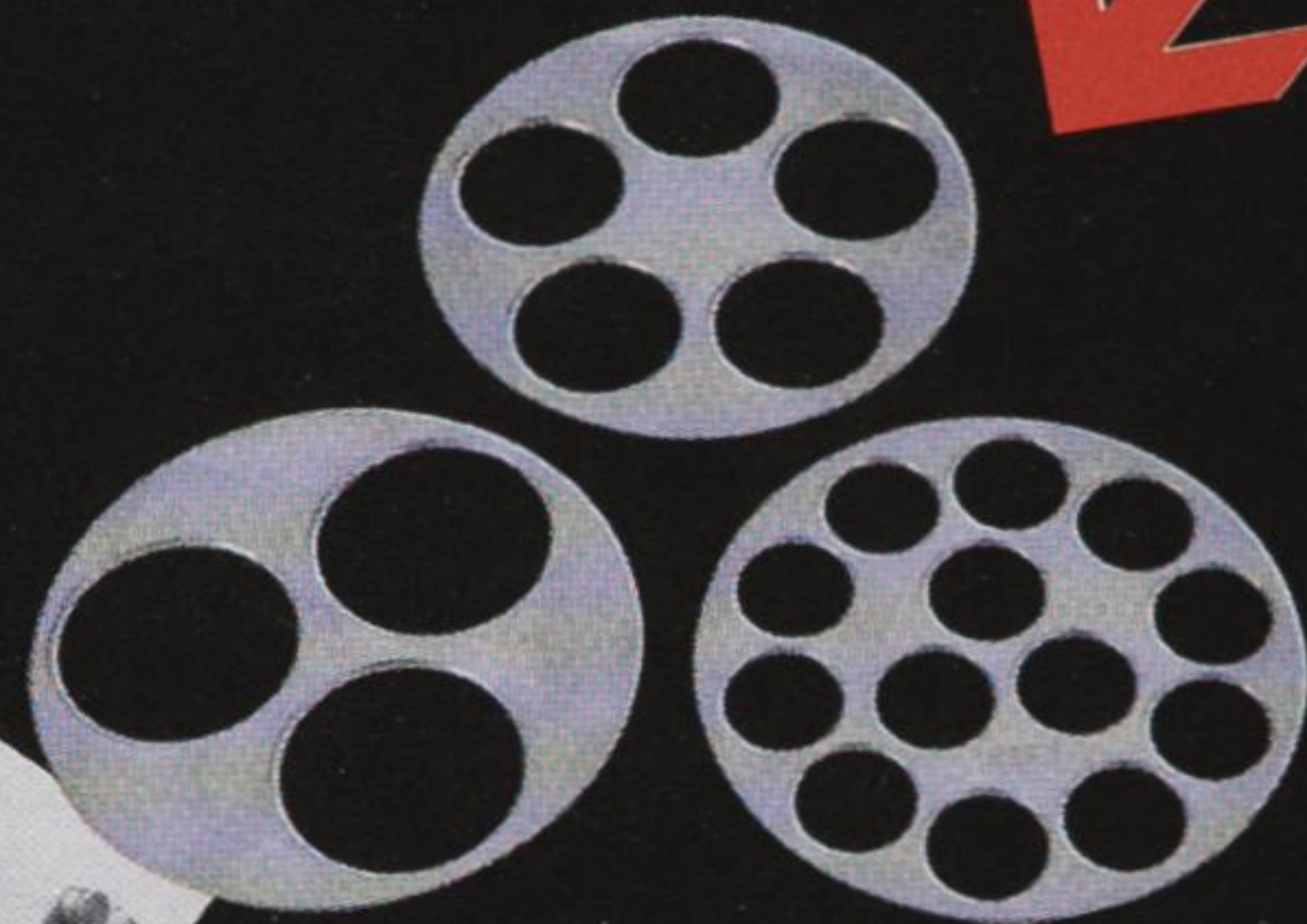
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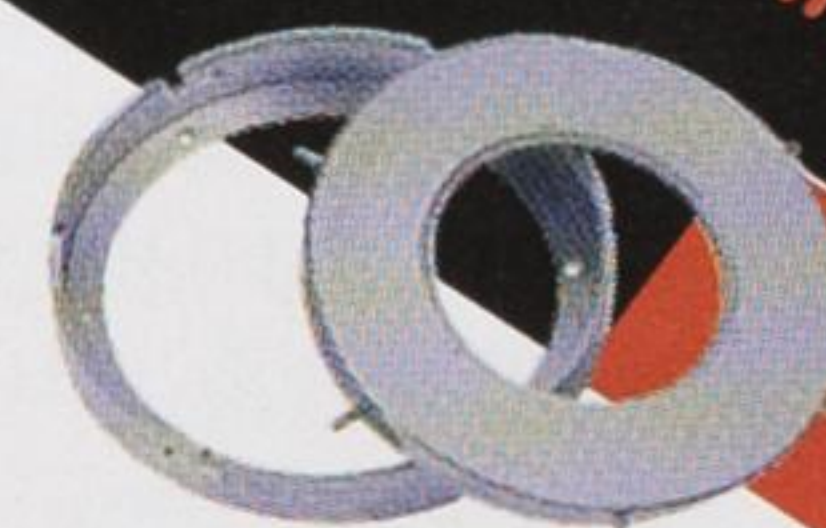
GaN
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SiGe
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EPITAXY EQUIPMENT

MBE stalwarts concentrate

Riber has set its sights on nitride component production, new classes of solar cells and organic semiconductors.

Michael Hatcher visited the Parisian equipment company to find out more about its new strategic focus.

In a forgotten corner of Paris, tucked away at the end of a one-way street and close to the river Seine, there stands an unprepossessing building. But venture inside and you can witness the very cutting edge of advanced semiconductor production technology.

Here stands Riber, the company that has arguably done more than any other to propel molecular beam epitaxy (MBE) into the production environment. Behind the iron gates guarding its parking lot, in a cleanroom at the heart of the building, nearly a dozen MBE reactors are being prepared for shipment.

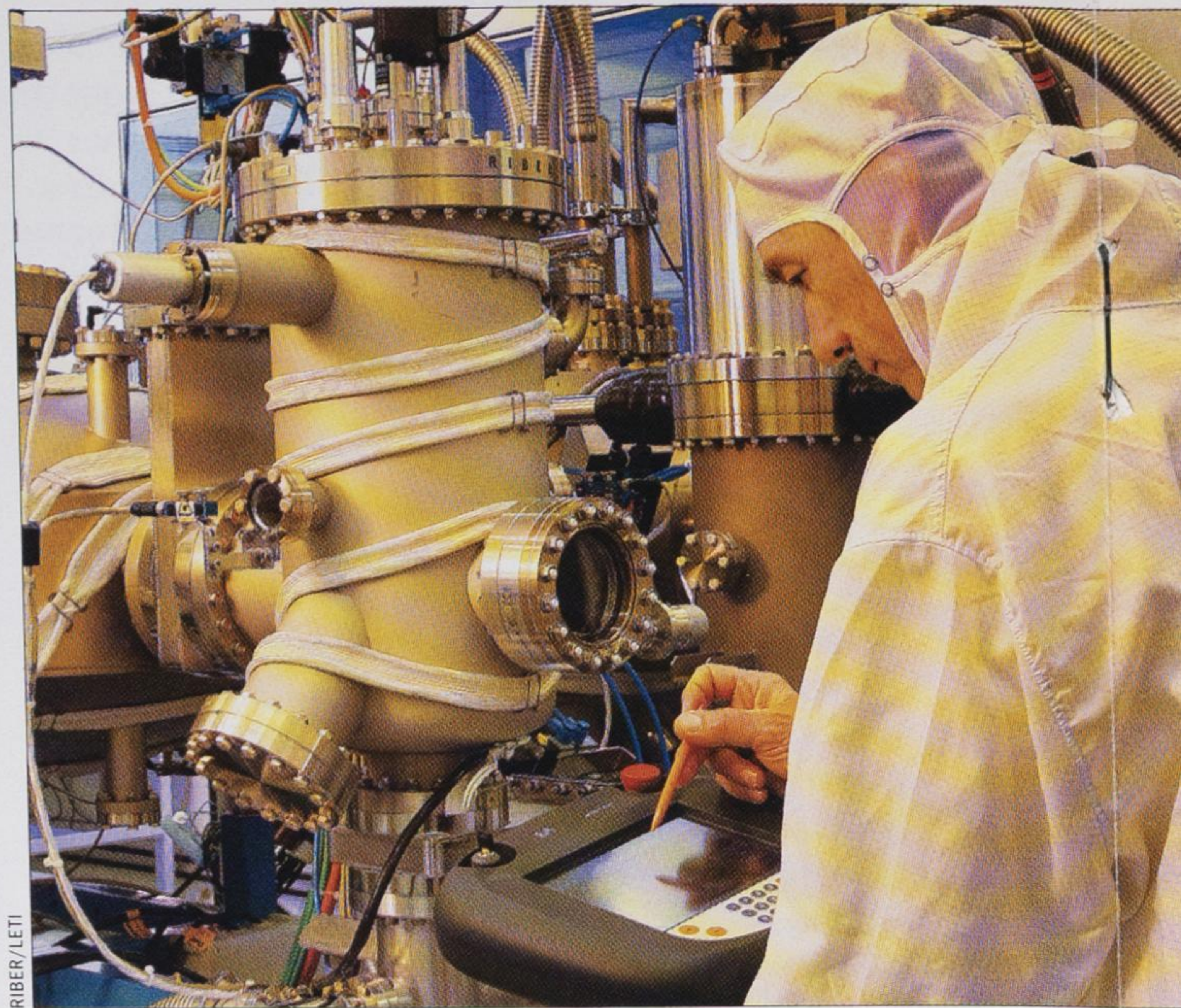
It is these new machines that will produce some of the first GaN HEMT epiwafers for high-power RFIC fabrication, organic LED technology for the coolest of displays and solar cells that will become a cornerstone of energy production.

But the MBE equipment business has been no easy ride. With sales of production reactors slowing to a near standstill, Riber's finances have been under pressure. Disappointing financial results were the inevitable outcome, before a new supervisory and executive board began to take shape.

Noël Goutard might not be a familiar name in semiconductor circles. But as the former CEO of automotive equipment multinational Valeo, a company that once cornered the market in clutch systems for cars, he has business experience to burn. In December 2007, Goutard increased his investment in Riber. He then brought in Jean-Pierre Regner, a seasoned executive with 30 years of experience at Philips Semiconductors France as an external consultant – including a stint as wafer fab manager.

Regner's analysis was stark – Riber needed to change. It was not placing enough focus on service and should be integrated much more closely with Addon, its MBE component parts subsidiary. Within a few months, Regner became president of Riber's executive board, with Michel Picault moving to head up the company's systems division, and Addon was fully assimilated under Riber's control.

"We are now focused on three key activities," said Regner. "Systems, sources and service." Systems has long been Riber's core strength – the company has been selling MBE equipment for more than 30 years. Central to the renewed focus on sources was the 2008 fusion with Addon. Spun out of Riber under the direction of Pierre Bouchaib, the man



One of Riber's cluster molecular beam epitaxy reactors, installed at CEA Leti. The Parisian firm also has machines producing multi-junction solar cells (under the European project "IBPOWER") and is developing III-V MOSFET structures at IMEC in Belgium.

who spearheaded Riber's early MBE activity in the 1970s and 1980s, this part of the business is going to be instrumental in Riber's future. New sources are crucial for the deposition of materials like copper and selenium for thin-film solar, and of more complex chemistries needed for organic transistors and organic LEDs.

Under construction

Bouchaib, now back in the sales director role at Riber, strolls the company corridors, a familiar face to every employee. With a friendly greeting and a pack of Gauloises always at the ready, here is the "godfather" of MBE. Peering into the Class 100 cleanroom where 10 MBE machines are under construction, Bouchaib confidently predicts that all of them will be completed and shipped within a few short weeks. Inside the cleanroom sit reactors large and small, destined for production facilities and research labs, where they will make quantum-dot lasers, organic transistors and more.

Having designed and sold MBE equipment for the past 35 years, Bouchaib is probably as well placed as anybody to predict the future. "Solar cells," is his definitive response. And not just the complex, high-efficiency III-V cells – where the rival MOCVD technology has so far cornered the market – Bouchaib is talking about CdTe and copper indium gallium selenide (CIGS) technologies.

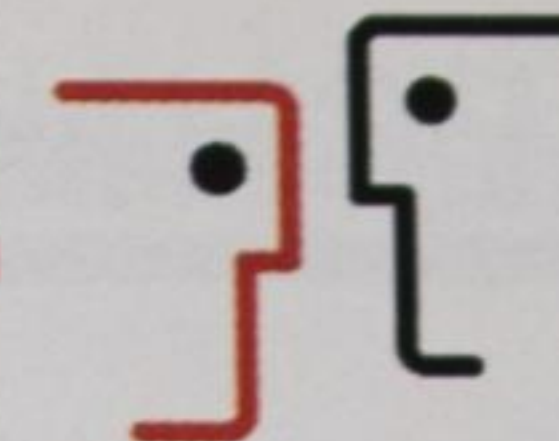
GaN transistors grown by MBE

HEMT structure growth on 4 inch silicon

Low reverse bias current leakage: <2 nA
High breakdown voltage: >150 V
Residual capacitance on CV: ~10 pF
High current

HEMT structure growth on 3 inch SiC

Very low reverse bias current leakage: ~1 nA
Residual capacitance on CV: <3 pF
High current



e on emerging markets

MBE production of nitride components – dealing with the challenge

One of the key trends that Riber is hoping to benefit from is the proliferation of nitride semiconductors for power electronics and high-power RF systems. The company began developing a production MBE reactor for nitride deposition in 2002, but only very recently has that work come to fruition.

The production system is based on an ammonia injector design and has demanded some crucial development work to withstand the corrosive nature of this chemical.

One advantage of MBE over MOCVD for nitride epiwafer production had always been the possibility of using simple nitrogen gas, rather than ammonia, as the source of nitrogen atoms. But the problem, explains Bouchaib, is that a plasma source is needed to deliver atomic nitrogen. And maintaining a plasma that is sufficiently stable for high-precision deposition has so far proved impossible, despite Riber's best efforts.



The lesser of the two evils was to deal with ammonia – which Riber has done by developing a more resilient thermal element, and by pumping and cycling the ammonia using a dedicated cryopanel to deliver a low-temperature process.

That work now appears to have paid off. After installing the nitride production

machine in October 2008, the first GaN HEMT epiwafers and transistors made using Riber's MBE 49 platform (pictured) rolled off of its customer's production line just a month later.

So far, the results look good. GaN films produced on both 4 inch silicon and 3 inch SiC wafers have shown less than a 1% variation in thickness, composition and sheet resistance. Wafer-to-wafer reproducibility on one platen, in either a 3 × 4 inch or 5 × 3 inch configuration, has shown the same consistency, while run-to-run variations are within 2%.

Now qualified and showing 95% yields, that first industrial nitride MBE reactor could produce up to 4800 GaN HEMT epiwafers per year. It has also been used to fabricate state-of-the-art devices on a 6 inch SopSiC (silicon-on-polycrystalline SiC) material platform and Riber is now looking to apply the expertise gained in similar systems for power electronic devices and even LEDs.

Despite stacks of venture capital funding and its emergence as a high-speed, low-cost production technology (a 750 kW system from Global Solar has just been deployed in Tucson, AZ), there remains a problem with CIGS – specifically in the uniform deposition of the elements required to form $\text{CuIn}_x\text{Ga}_{1-x}\text{Se}_2$ heterojunctions. While there is no requirement for the precision that a typical MBE reactor brings, uniform deposition is needed to produce the cells reliably at good, economic yields.

Indium and gallium can be deposited relatively easily, with good uniformity. However, copper and selenium pose a challenge. If makers of CIGS cells are to solve this problem, which Bouchaib believes will seriously hamper volume CIGS cell production, his name should be at the top of their contacts list.

Riber's engineers, in close collaboration with the expertise developed at Addon, are now adapting the company's MBE sources to provide the kind of deposition speeds that are demanded. So far, they have come up with specially designed crucibles called Muso cells that are compatible with each of the CIGS elements. MC crucibles deliver sulphur and selenium, PG crucibles suit indium and gallium, while the HT version is designed for copper.

Bouchaib's components should be up to the task, so far as film deposition quality is concerned. As ever though, speed is key. CIGS developers want at least 10 $\mu\text{m}/\text{h}$. "I'm not sure that we can deliver huge

volumes at the moment, and we certainly need to do more development to get to higher volumes, but we think that we can adapt," Bouchaib said. At the moment uniformity is quoted as $\pm 5\%$, with a material yield of 75% and a flux stability of 1.45%. CIGS companies will want more than this, but the approach is looking promising and Bouchaib believes that the sources are suited to low-cost deposition.

The third plank of Riber's strategy – service – is what precipitated its take over of Oxford Instruments Plasma Technology's (OIPT's) MBE division last year. Although OIPT had sold barely any MBE reactors in recent years, it did have an enormous number still in service, under either its own brand or that of the old VG Semicon group. In a single swipe, this acquisition increased Riber's footprint dramatically. Of the 800 or so MBE machines around the world, some 500 are now serviced by Riber and former OIPT customers will benefit from improvements to their kit, such as software upgrades.

The MBE systems market is now largely the preserve of two vendors – Riber and US rival Veeco Instruments. But in the history of the III-V sector, it is difficult to overstate the importance of Riber's pioneers. Having reinvigorated itself over the past year, it looks set to take on the challenges posed by new applications, customers and materials. Once upon a time, GaAs was that new application. Now Riber is ready to spread its wings beyond III-Vs.

SemiSouth's transistors boost photovoltaic system efficiencies

Solar power is still too expensive to compete in free market economies. However, improvements in inverter efficiency, which could be driven by an uptake of SiC JFETs with lower conduction and switching losses than incumbent silicon IGBTs, could change that, says SemiSouth's **Jeff Casady**.



FIRST SOLAR

First Solar's CdTe panels have enjoyed substantial deployment in the German solar farms that receive generous financial subsidies. One of the company's goals is to reduce the cost of its CdTe panels so that they can compete in free markets within five years. This goal will be aided by improvements in solar-inverter efficiencies.

The credit crunch is unlikely to thwart growth of the solar-cell market. Although the financial crisis has led The Information Network to downgrade its growth forecast for this year's installed capacity of solar panels by 23%, this market analyst still expects global photovoltaic deployment to rise by 26% in 2009. And next year should be even better, with installations soaring by 48% to hit 10.5 GW.

Although this figure sounds large, it is only equivalent to the output of a handful of nuclear reactors. The reality is that the vast majority of today's electricity is generated through the burning of fossil fuels, and solar-power's success has predominantly come from subsidized markets, such as those in Germany, Spain and Japan. However, if photovoltaic energy is to move on and become a serious contender in global energy markets, then electrical generation costs must fall so that this technology can compete in free market economies.

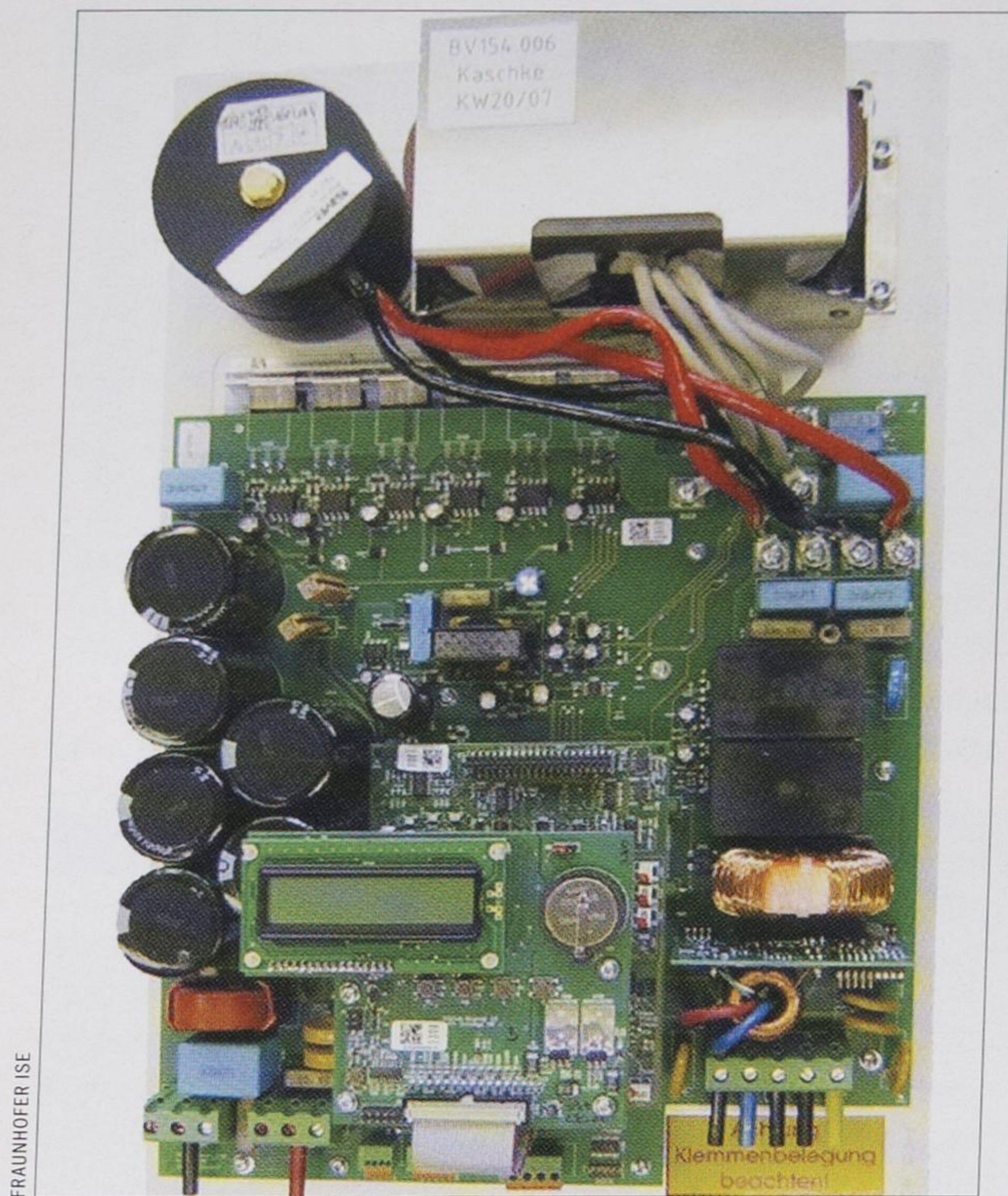
There are many ways to cut the costs of solar sys-

tems. One obvious route is to decrease the cell's cost per watt, which can be done by improving device efficiencies, reducing material consumption and streamlining manufacturing processes. However, savings can also result from reductions in installation costs, which typically account for half of the total cost of the build, and improvements to the efficiency of the inverter that converts the DC output from the cells into the AC form that is needed by individual customers and national grids.

The leading manufacturers of solar inverters, such as SMA Solar Technology, Fronius and Xantrex, use silicon MOSFETs or insulated gate bipolar transistors (IGBTs) in their circuits, alongside silicon or SiC diodes. These inverters deliver typical conversion efficiencies of 94–97%, but a switch from silicon to SiC transistors could lead to even smaller losses. At SemiSouth in Starkville, MS, we are developing a SiC FET for this purpose, which has delivered excellent results in solar-inverter trials by the Fraunhofer Institute of Technology, Germany.

We selected SiC because it has the potential to produce efficient transistors that operate at high voltages and currents. These strengths stem from the excellent intrinsic properties of this wide-bandgap semiconductor, which has an electric field strength 10 times that of silicon and a thermal conductivity that is three times higher. Power devices built with SiC have switching losses that are 1000 times lower than silicon equivalents and feature an on-resistance per unit area that is 100 times smaller than the incumbent technology.

Many of today's inverters are designed to operate at input voltages of more than 600 V and are based on the silicon IGBT. One of the major weaknesses of this bipolar device is its slow switching speed, which is limited by the time that it takes for the stored minority charge to be swept out of the drift region. Improving the IGBT's switching speed is a significant challenge, which explains why inverters typically operate at just 16–20 kHz – a frequency that minimizes switching losses, but requires deployment of expensive and bulky inductors and



The Fraunhofer Institute for Solar Energy has demonstrated that the efficiency of advanced solar inverters can be improved by replacing Infineon's silicon IGBT with SemiSouth's JFET.

capacitors. SiC transistors deliver far higher switching speeds and they should allow the use of smaller, lower-cost passive components.

IGBTs also suffer from power losses during conduction, which impact inverter efficiency. Moving to larger devices can increase the conduction efficiency, but this comes at the expense of a lower switching efficiency. SiC JFETs avoid this compromise because they operate without a constant voltage drop across the device – the root cause of IGBT conduction inefficiencies.

If higher inverter efficiencies are realized, the benefits are not just restricted to a lower cost per watt. Greater efficiencies also lead to less heating, which increases component reliability and reduces thermal management demands.

The inverter's input voltage is governed by the photovoltaic panels, which each produce an output of tens of volts. The US silicon solar-cell manufacturer SunPower, for example, produces 1.6 by 1.0 m panels with a 55 V output and smaller 40 V versions, while the clear-cut leader of CdTe photovoltaics, First Solar, makes 1.2 by 0.6 m panels with 62–71 V output. These panels can be linked together in parallel and deliver outputs of several hundred volts.

The high field strength of SiC makes it ideal for producing high-voltage devices for inverters. These can operate at higher voltages, which leads to cuts in the solar-system costs and efficiency improvements. These gains are a result of a reduction in ohmic losses in panel wiring, which is cheaper to install because it carries less current. Up to 1000 V DC

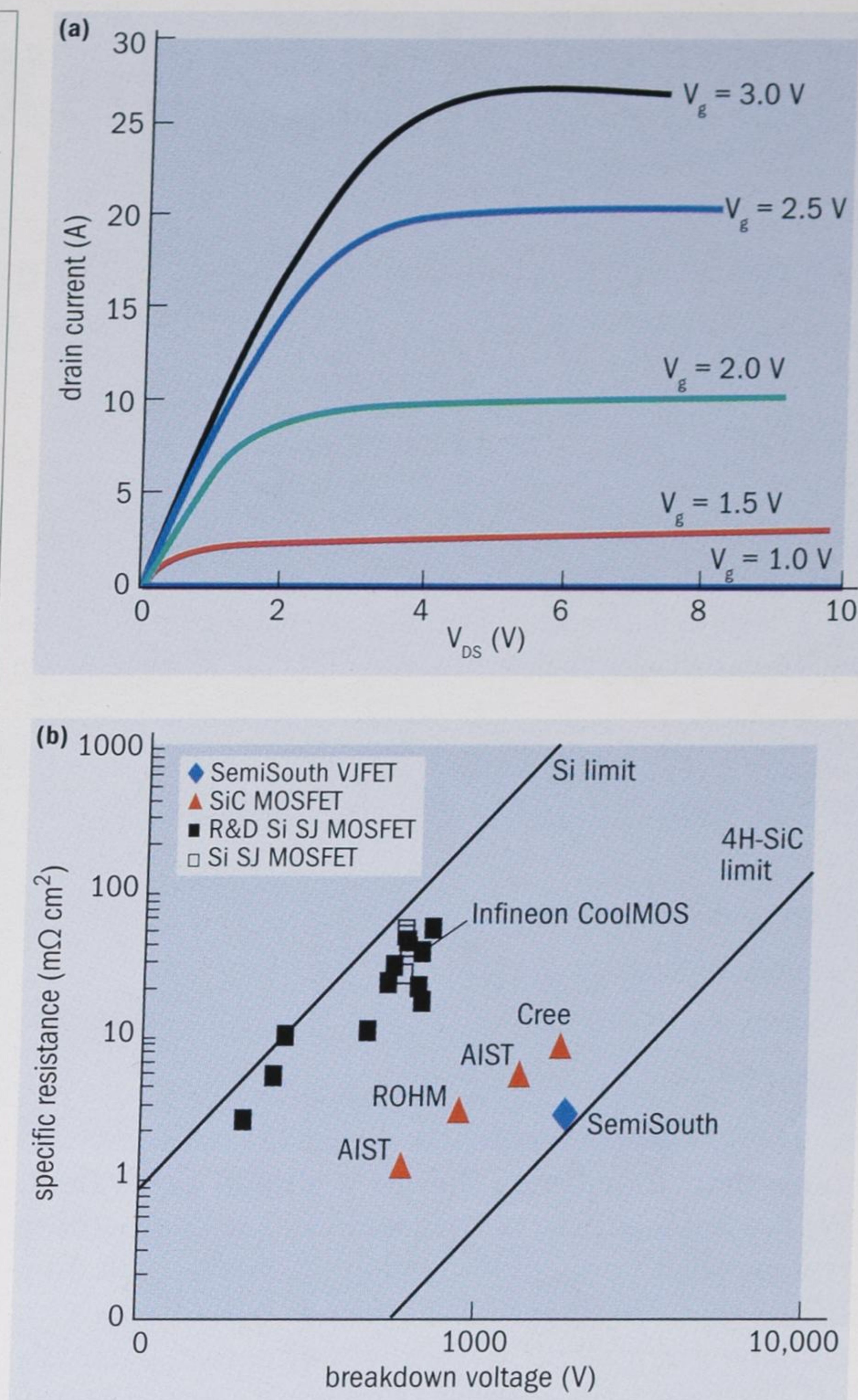


Fig. 1. SemiSouth's normally off SiC JFET, which was released in June 2008, has a threshold voltage of 1.0 V and can block 1200 V with no gate voltage (a). It has a saturation current of more than 25 A. The set of DC curves were taken at room temperature, with the gate voltage (V_g) decreased from a 3.0 V maximum in 0.5 V increments. SemiSouth's JFET operates at very close to the limit for 4H-SiC (b).

input inverters are currently under development and revisions to electrical code legislation could lead to even higher input voltages.

Realizing the potential of SiC

The merits of SiC have been appreciated for many years, but fabricating reliable devices that fulfill the semiconductor's potential has not been easy. A great deal of effort has been channeled at the development of a high-quality substrate and substantial progress has been made during the last two decades. The first commercial SiC substrates were launched in 1991 and today it is possible to obtain 100 mm material with a very low defect density, no micropipes, and few particles, basal plane defects and dislocations. The extremely low density of all of these types of defects is important for delivering a high yield with power devices, which typically have large chip sizes.

Another milestone for SiC came in 2001, thanks to Infineon's launch of the first SiC Schottky diodes. Since then other companies, including ourselves, have unveiled similar products with 600 and 1200 V ratings. But the market is eagerly awaiting the release of a SiC power transistor.

If this device is to enjoy commercial success, it will have to be reliable, normally off and cost no

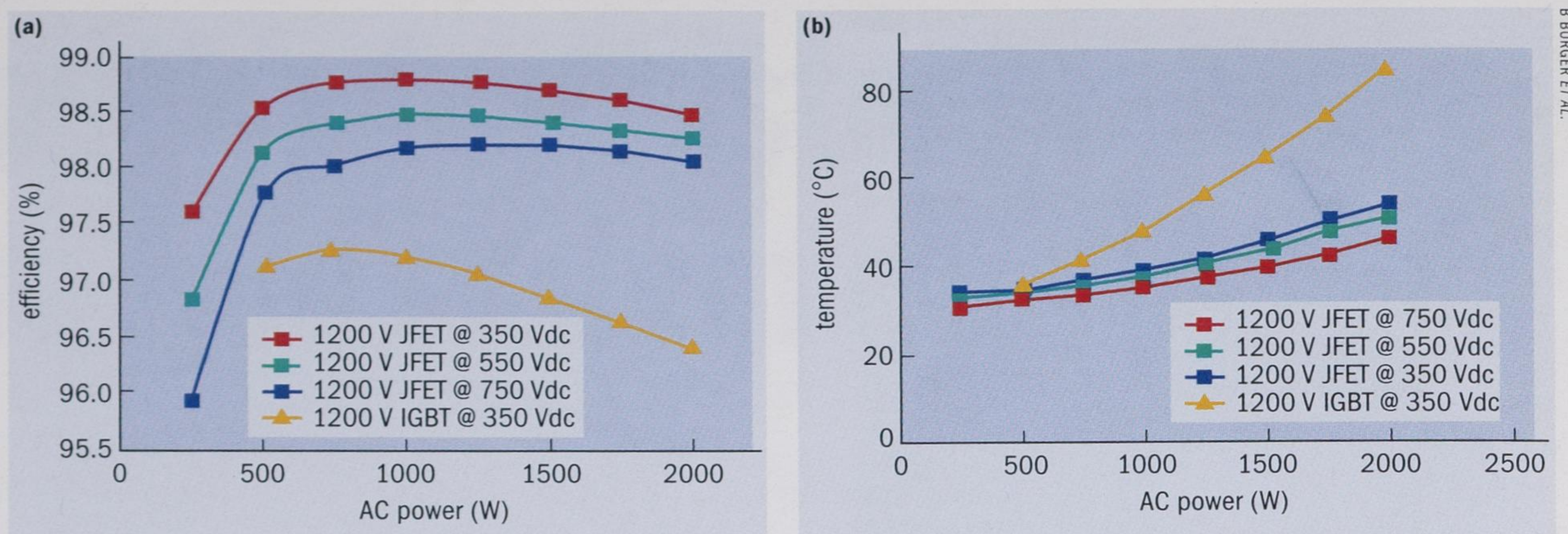


Fig. 2. Tests by the Fraunhofer Institute for Solar Energy reveal the higher efficiencies (a) and lower device temperature (b) that result from replacing Infineon's fourth-generation silicon IGBT with a SemiSouth 63 mΩ, normally off SiC JFET.

Table 1. Material properties

Material property	Silicon	4H-SiC	GaN
Bandgap (eV)	1.12	3.25	3.4
Breakdown field (MV/cm)	0.25	~3	~3
Thermal conductivity (W/cm K)	1.5	4.9	1.3
Electron mobility (cm ² /Vs)	1200	800	900
Dielectric constant	11.7	9.7	9.0

more than four times that of a silicon equivalent. We are hitting these targets and we face competition from several companies around the globe, including Infineon, Cree, TranSiC, Rohm and Microsemi. Our contender is a SiC JFET – a cost-effective, normally off device, which we have shipped to a limited number of customers since June 2008.

Our initial products are 1200 V JFETs with 125 and 63 mΩ resistance, which are offered as bare die or as a TO-247 package. These transistors have saturation currents exceeding 25 A and threshold voltages of 1 V (figure 1, p19).

Our JFET's performance is unrivaled, thanks to its combination of a high breakdown voltage and low on-resistance (figure 1, p19). Device operation is very close to the 4H-SiC limit, a target that leads to SiC power transistors that are highly cost-effective and capable of delivering high performance.

Outperforming other silicon and SiC transistors can't guarantee long-term success for our JFET. This device will have to see off the threat posed by another wide-bandgap semiconductor – GaN. However, this rival is a more immature technology for power device manufacture and we believe that the production costs for these transistors will be higher than those for our SiC JFETs. Nitride devices are also hampered by poor thermal conductivity, high defect densities that impact reliability and yield, and the need for relatively large die sizes compared with SiC.

The contribution that our SiC JFETs can make on a state-of-the-art solar-inverter system has been assessed by the Fraunhofer Institute for Solar Energy Systems. The Fraunhofer team replaced a fourth-generation Infineon silicon IGBT with

our JFET and observed a 1.6% increase in DC to AC conversion efficiency at an input of 350 V DC (figure 2). Higher inputs of up to 750 V DC led to a slight decline in efficiency from the peak of 98.8%, but this SiC-based inverter always delivers a superior performance to the silicon-based version. The higher efficiencies lowered the inverter's operating temperature, and at a 5 kW output up to 80% of the heat sink could be removed.

We believe that SiC devices can target a \$2 billion slice of the power-semiconductor market, which is worth \$14 billion according to market analyst IMS Research. The sales opportunities for SiC devices should increase over the next few years because the power semiconductor market is expected to increase at a compound annual growth rate of 15%.

Potential sales of SiC devices for solar inverters are a small fraction of that market, but success promises to highlight the benefits of wide-bandgap electronics and bring down the costs of solar energy. We believe that SiC will play a key part in generating new efficiency and cost records, which will help to drive up solar-system deployment.

In the past it has not been possible to enjoy all of the benefits of SiC because devices have been unreliable, expensive and unavailable in high volumes. However, our release of the normally off JFET will address all of these weaknesses. Solar inverters will benefit first, followed by power supplies and electric drive markets.

Further reading

B Burger *et al.* (2008) *23rd Annual Photovoltaic Conference*.



About the author

Jeff Casady is SemiSouth's chief technology officer, vice-president of business development and a co-founder of the company. He has previously held a faculty position at Mississippi State University, working in SiC power transistor development, and prior to that he was employed by Northrop Grumman.

RPI starts to extinguish the green gap

Banishing V-defects and switching to non-polar growth could close the green gap and create efficient, high-quality white-light sources, say RPI's **Christian Wetzel** and **Theeradetch Detchprohm**.

Who would not want to go green these days? Not the green of the dollars that were lost on Wall Street, more the green of ecological responsibility.

Among LED developers, green is a goal in terms of efficiency and color. Bright-red tail lights adorn today's automobiles and electronic gadgets are covered with blue LEDs. But it's much trickier to make a true green that efficiently emits at 550 nm – the wavelength to which our eyes are most sensitive.

A fascination with green might seem misplaced. Doesn't the future lie with white LEDs – well touted replacements for inefficient incandescents and ugly fluorescent lamps? Yes and no. These white-emitting chips are highly efficient, as anybody with a battery-powered LED flashlight will testify. But skin tones produced by flashlight photography look awful because they are skewed by the light source – a mixture of a blue LED and yellow phosphor.

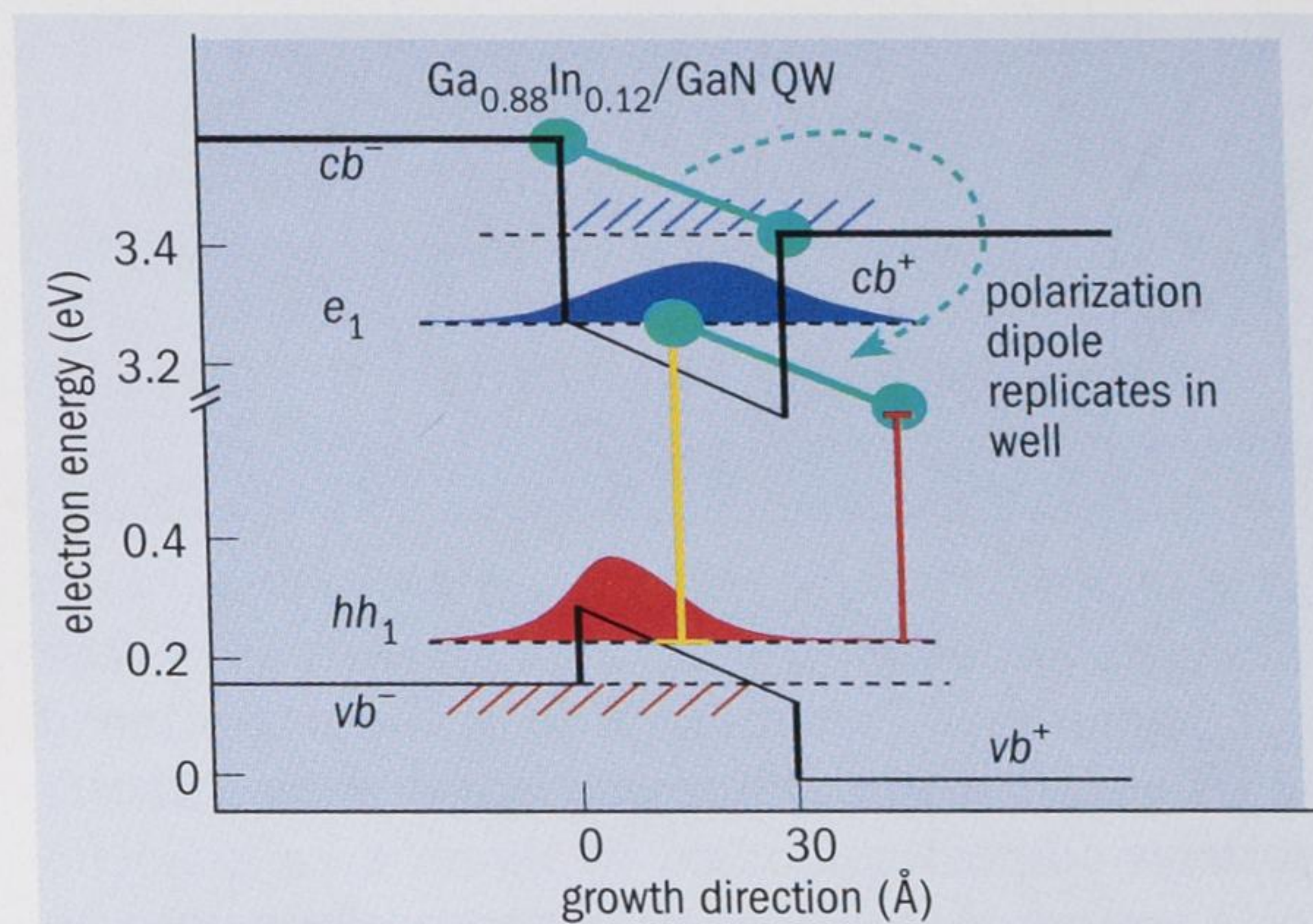
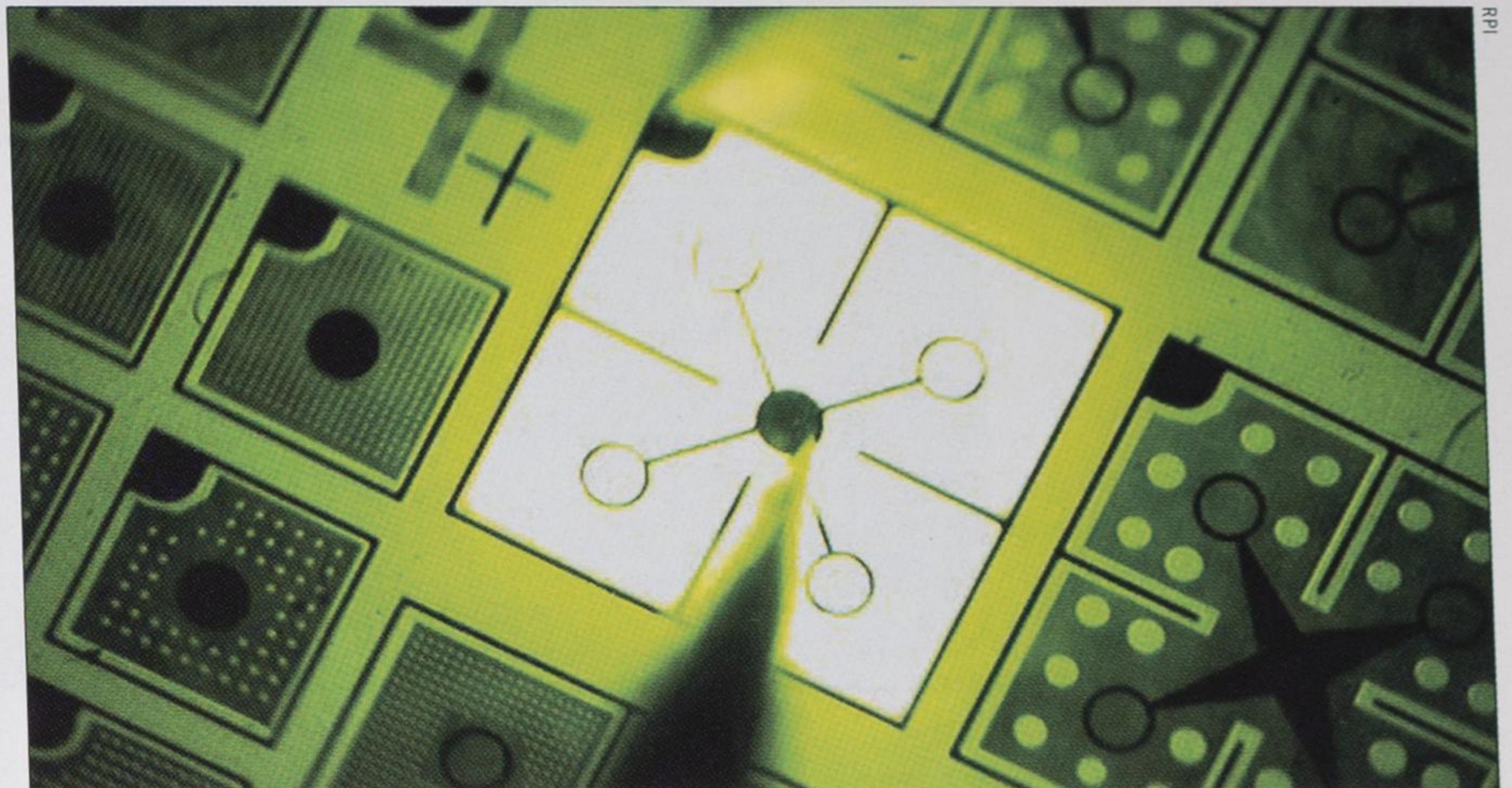
Switch to a red-green-blue source, such as that used for display backlighting, and color reproduction improves. But even this has its limitations. If you illuminate food or jewelry, such as diffracting diamonds and mother of pearl, some colors will still be missing. That's because colors cannot be seen unless they are already in the light source. What's needed is a full color spectrum that includes efficient greens, which requires a solution to the green gap.

At Rensselaer Polytechnic Institute (RPI) in Troy, NY, we have embarked on this quest and made significant progress with growth techniques that produce the smooth quantum well and barrier layers required for efficient greens. LEDs that are built on non-polar crystal faces are also showing promise.

We decided to avoid the combination of green-emitting phosphors and blue LED chips because down-conversion reduces efficiency by at least 20%. Instead, we have looked to extend the spectral coverage of conventional nitride devices.

In one sense, it's obvious how to increase the wavelength of a nitride LED – add more indium to the quantum wells. However, $\text{Ga}_{1-x}\text{In}_x\text{N}$ layers with more than 20% InN can suffer from strain that leads to defects and low radiative efficiency.

In addition, III-nitride crystals have a hexagonal crystal structure, and heteroepitaxial growth on conventional sapphire leads to a complementary pair of static two-dimensional sheet charges at every interface. Large internal electric fields result from these, which are equivalent to $\pm 10^{14} \text{ cm}^{-2}$ electrons. They pull apart the electrons and holes



RPI's on-die electroluminescence spectra

(top) demonstrate that 530 nm LEDs can hit 40% internal quantum efficiency.

Fig. 1. (left) Internal electric fields alter the band structure in c-plane GaN LEDs. Researchers at RPI claim that a polarization dipole can be seen in the band offset across the well, which translates into a Stokes shift in the quantum well between the absorption edge (yellow line) and peak emission (red line).

in the quantum wells, causing wavelengths to shift with drive current and cutting the electron-hole recombination rate.

We have extracted a value for the electric field strength from spectroscopic features seen in measurements on nitride structures with 3 nm thick quantum wells. However, this value for electric field strength cannot explain other experimental results on these structures, such as the large variation in radiative recombination rates and the large Stokes shift between the absorption edge and emission band.

But we can make sense of everything when we describe the electric field as a "Stark ladder" with step sizes equal to the polarization dipole (figure 1). The Stokes shift accurately tracks this dipole energy (the product of electric field strength, well width and electron charge) in ultraviolet, blue and green nitride quantum-well structures. It also accounts for

Fig. 2. Uncoated, on-wafer die that are grown on *c*-plane sapphire and have dimensions of $350\text{ }\mu\text{m} \times 350\text{ }\mu\text{m}$ and $700\text{ }\mu\text{m} \times 700\text{ }\mu\text{m}$ can deliver promising output powers and high external quantum efficiencies. This is according to measurements that employ $50\text{ }\mu\text{s}$ pulses and 1% duty cycles.

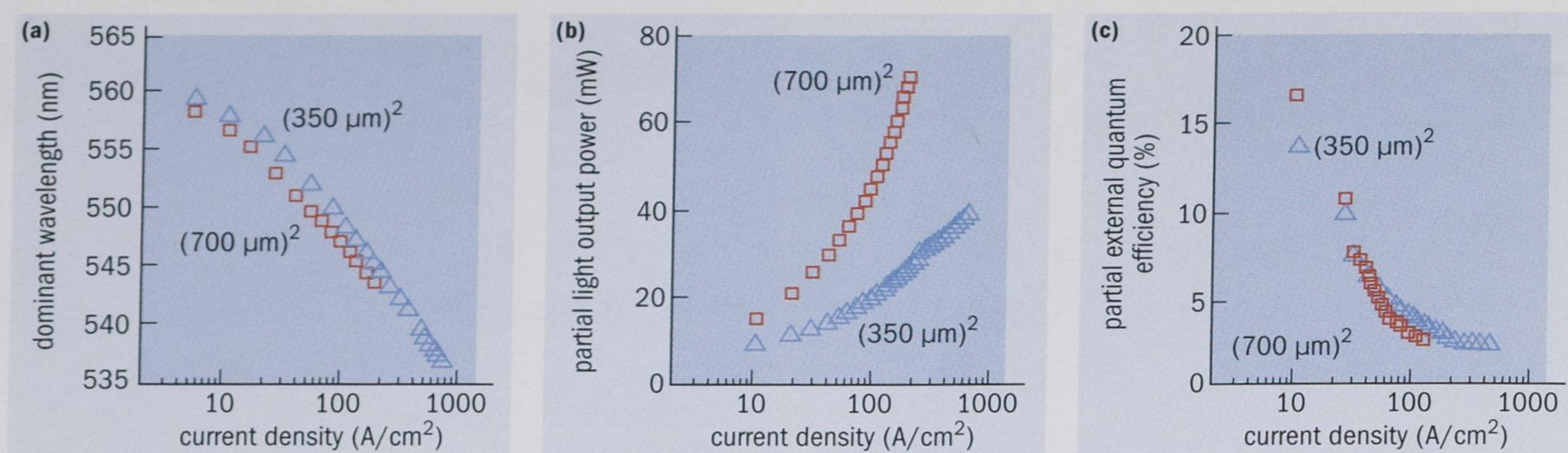


Fig. 3. Transmission electron micrographs show that RPI researchers can produce a variety of high-quality, dislocation-free material on bulk GaN. This includes blue-emitting *c*-plane structures **(a)**, a non-polar *a*-plane green-emitting structure **(b)** and a non-polar *m*-plane blue-emitting structure **(c)**.

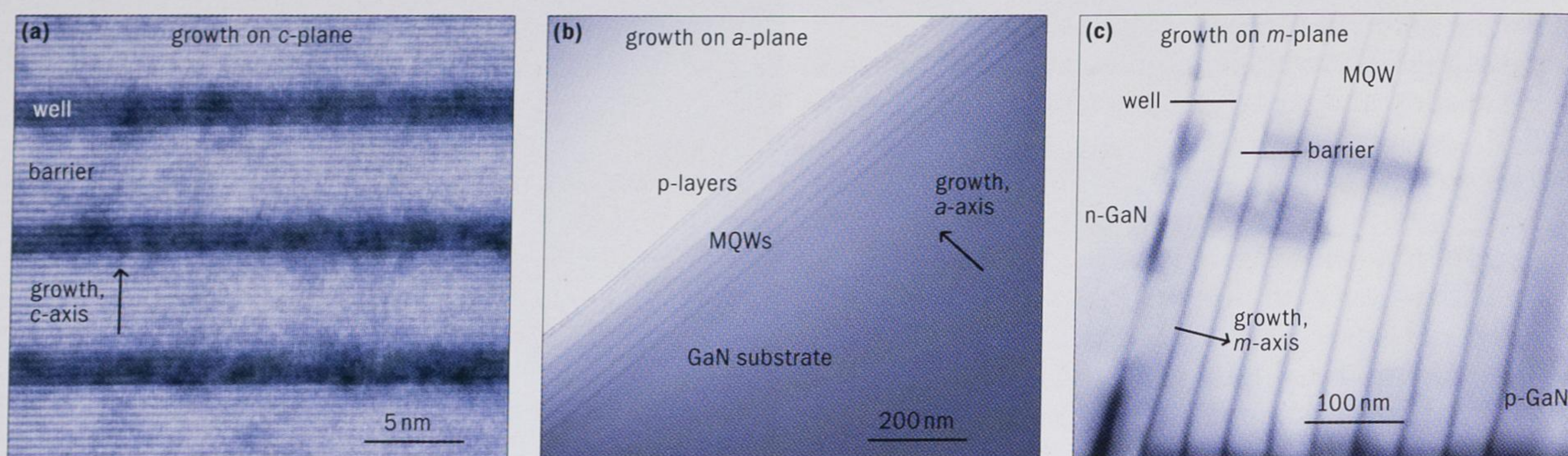
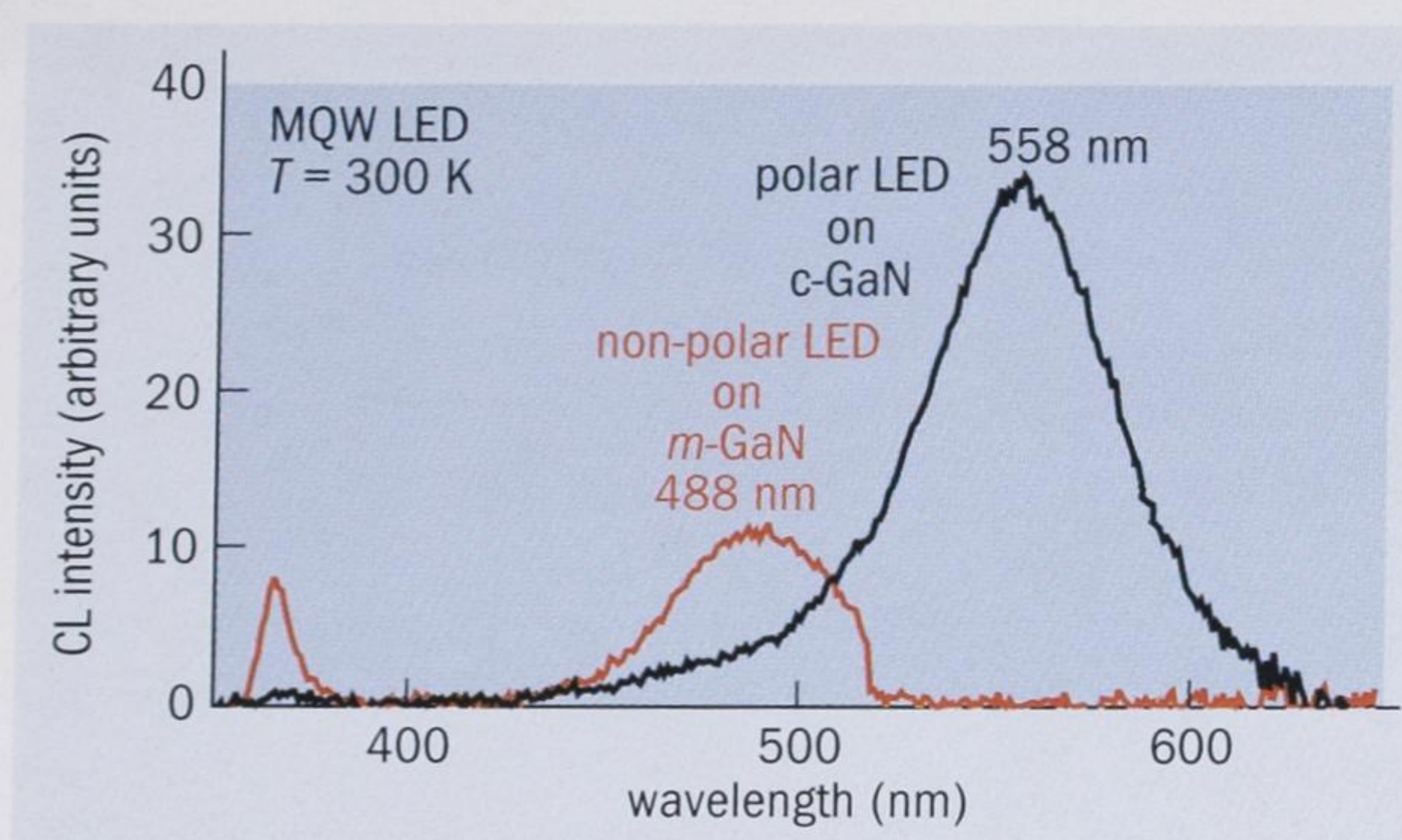


Fig. 4. The emission of non-polar LEDs on *m*-plane GaN is blue shifted by 70 nm compared with polar *c*-plane devices that are produced with the same growth process. RPI attributes the *c*-plane structure's longer emission wavelength to its large polarization dipole.



the blue shift in emission wavelength with increasing drive current.

We are not the only team of researchers with an explanation for wavelength variations in these structures. Other groups have put forward qualitative theories based on fluctuations, separation and ordering in GaInN wells, which are based on observations from X-ray diffraction and high-energy electron-beam experiments. We don't dispute their claims that GaInN can show compositional variations, because spinodal decomposition of GaInN is to be expected under thermodynamic equilibrium. However, MOCVD processes can take place away from equilibrium conditions. Horst Strunk's group at the University of Erlangen, for example, has identified material with high and low alloy uniformities.

Our studies have involved the fabrication of a range of LEDs on *c*-plane sapphire that emit at various wavelengths. We have found that device output and efficiency fall at wavelengths beyond 500 nm, due to an increase in quantum-well roughness. This results from V-defects that decorate threading dis-

locations, which are far more detrimental to green LEDs than to blue ones.

Over the course of a couple of thousand epitaxial growths we have learned to reduce the active region's roughness. Progress has been assessed through measurements of the smoothness of the barrier layer with an atomic force microscope. We have established a growth regime that eliminates the decoration of threading dislocations with V-defects.

X-ray measurements reveal the excellent thickness uniformity of improved barrier and well structures. This has allowed us to double the number of quantum wells in the active region, resulting in an even greater gain in the light output of our green and dark-green LEDs. Pulsed measurements reveal that $350\text{ }\mu\text{m} \times 350\text{ }\mu\text{m}$ bare die, which don't have the benefits of light-extraction technologies, produce 45 mW output at 537 nm and 700 mA (figure 2). And $700\text{ }\mu\text{m} \times 700\text{ }\mu\text{m}$ die can deliver 70 mW at 545 nm under the same driving conditions.

Using the same production process, 530 nm structures can hit a peak electroluminescence internal quantum efficiency of 40% and have an efficiency of 20% at 35 A/cm^2 – the typical current density for 1 W lamps. We believe that these are the best values ever reported for deep-green LEDs.

Substantial additional gains should result from improvements in crystalline quality, and in particular a reduction in threading dislocations. HVPE can deposit thick GaN layers with dislocation densities of $5 \times 10^6\text{ cm}^{-2}$. Companies such as Kyma Technologies are producing polished, epi-ready bulk GaN substrates with this technology in sizes of up to 2 inches in diameter.

This material is a great starting point, but its use

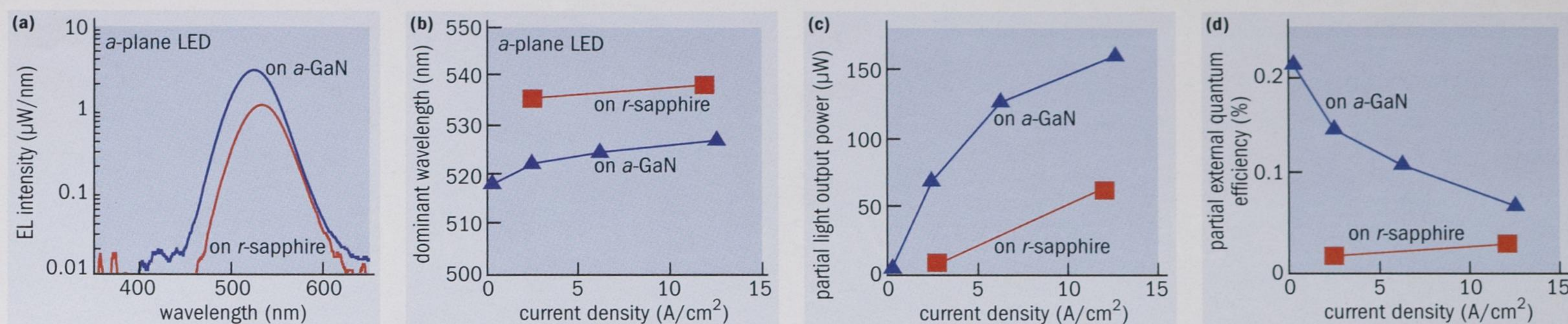


Fig. 5. Non-polar LEDs on *a*-plane GaN and *r*-plane sapphire emit at 527 and 539 nm, respectively, and produce a small red shift in wavelength as current increases.

can only be justified when its high quality is carried through to the epitaxial structure. Polishing damage, even below the surface, can cancel out the benefits.

Armed with this material, we have studied the effects of piezoelectric polarization on the LED's efficiency, its performance droop and, in particular, its role in the green gap. By slicing along different crystallographic orientations of thick GaN layers grown in the *c*-direction, we have prepared 5 mm stripes of *a*- and *m*-plane material and used them for the growth of non-polar devices.

The LEDs that we have grown on the *a*- and *m*-planes are not hampered by polarization fields that are associated with strained layers. They are also free from the threading and misfit dislocations that plague nitride heterostructures grown on cheaper platforms, such as *r*-plane sapphire and *m*-plane SiC. Defects are very scarce, with cross-sectional transmission electron micrographs (TEMs) showing an upper defect density limit of 10^7 – 10^8 cm^{-2} for our LED structures grown along the *c*-, *a*- and *m*-axes (figure 3). This compares favorably to non-polar structures produced by other groups.

Identical process conditions for these three types of LED are no guarantee for identical layer structures and optimal performance in every case, due to alloy composition and layer thickness variations. However, TEM and X-ray diffraction spectra reveal well width and alloy composition variations of less than 10%. This level of uniformity is not actually that surprising – first principles calculations by John Northrup from Palo Alto Research Center, CA, suggest that at an atomic level the growth mechanism is the same for GaInN grown on the *c*- and *m*-planes.

The differences in polarization fields in the *c*-, *a*- and *m*-plane devices have a big impact on emission wavelength. Our *c*-plane is red shifted by 70 nm compared with its non-polar *m*-plane equivalent (figure 4). However, this is to be expected – our calculations indicate that the polarization dipole in the polar LED is 250 meV, and if the fields could be turned off it would be blue shifted by 58 nm.

Red shifting of LED emission by polarization fields aids the development of polar LEDs spanning the shades of green. Non-polar structures don't share this benefit, so they need much higher indium content in the wells, or a larger well width. We have now adopted these approaches and started to pro-

duce green *a*-plane LEDs on *r*-plane sapphire and on the *a*-plane side wall of bulk GaN (figure 5). As expected, threading dislocations plague the former structure, but are almost absent from the latter.

LED powers from these non-polar, green-emitting structures are currently less than 1 mW, but we expect substantial improvements through better p-type doping and optimized junction placement. One encouraging sign is that these devices deliver the predicted wavelength stability with drive current. Unlike with polar structures, there's no blue shift in emission – in fact, there's just a tiny red shift as the current is cranked up.

At the University of California, Santa Barbara (UCSB), researchers have reached even longer wavelengths with semi-polar GaN LEDs. The polarization dipole in their device is weaker than that in a *c*-plane LED, but it still pushes the emission to longer wavelengths and causes a significant blue shift with drive current – UCSB's $600 \times 450 \mu\text{m}$ chip emits at 579 nm at 1 mA, and 550 nm at 100 mA.

The recent availability of polar and non-polar LEDs will help us to unravel the role of piezoelectric polarization in the green gap. Questions that we can start to address include: does light output efficiency benefit from the improved wave-function overlap in the non-polar structure, and are blue LEDs highly efficient as a result of piezoelectric polarization? The roles of electron overflow into the p-type layers and non-radiative Auger processes – popular theories for the cause of droop in blue LEDs – also have to be established in relation to the green gap.

Although there are fundamental issues still to be resolved, it is clear that reduced threading dislocations and improved polarization control will play a huge role in bridging the green gap. This could lead to the manufacture of a product with green credentials in all aspects – a white LED lamp with a great color balance and unprecedented efficiency.

Further reading

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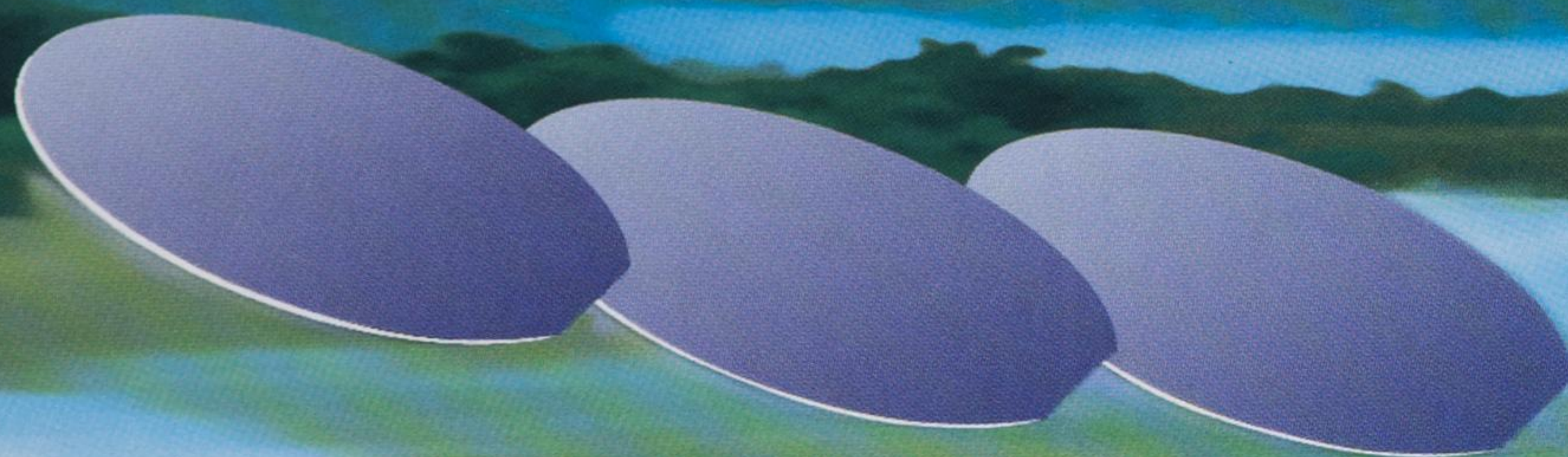
About the authors

Christian Wetzel (left) is a future chips constellation professor and associate professor of physics at Rensselaer Polytechnic Institute. He previously held the roles of senior epi scientist and green project manager at Uniroyal Optoelectronics. **Theeradetch Detchprohm** (right) is a research associate professor in the same group. Recent aspects of this work have been supported by a DOE/NETL Solid-State Lighting Contract of Directed Research under DE-FC26-06NT42860.

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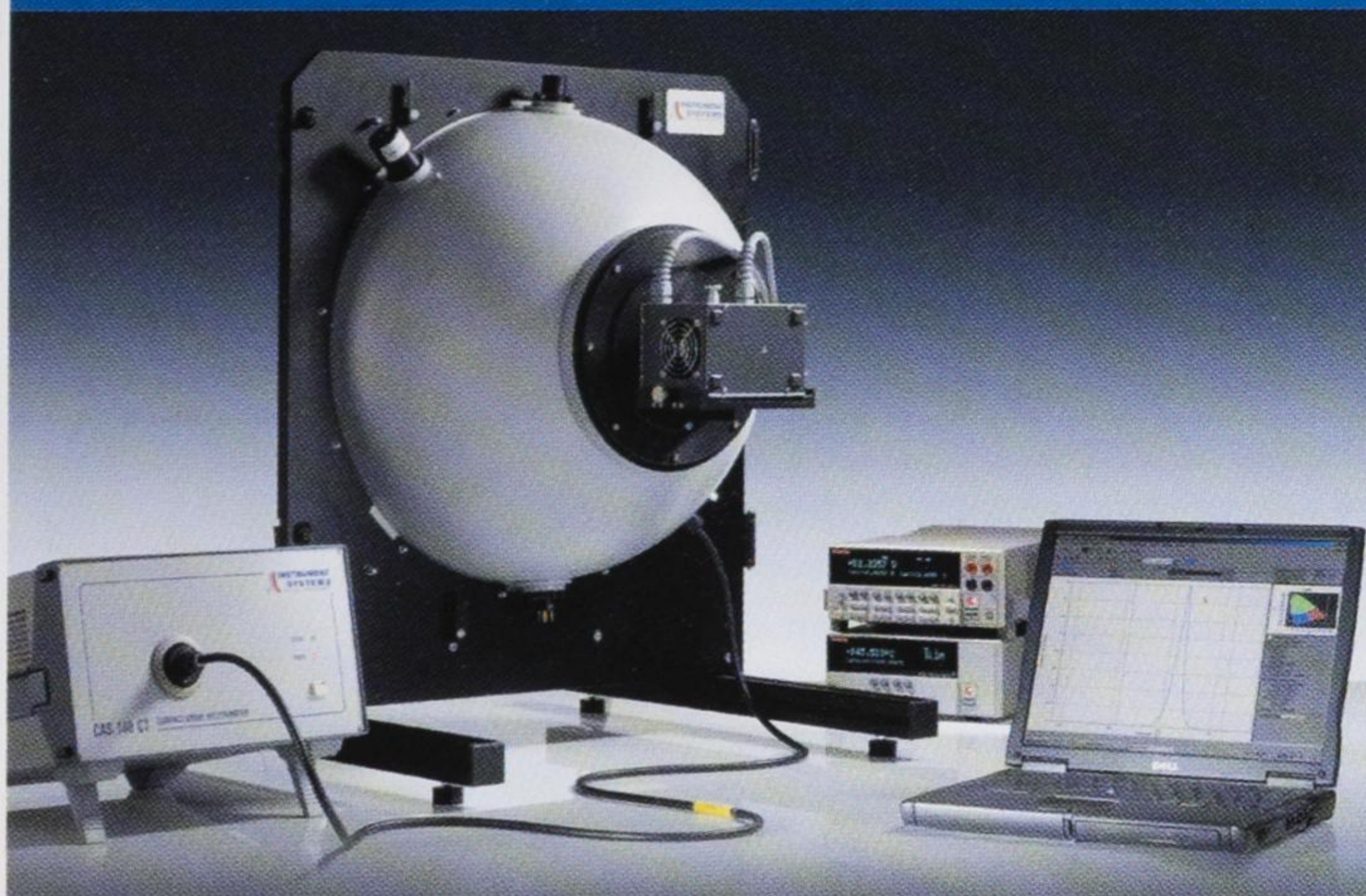
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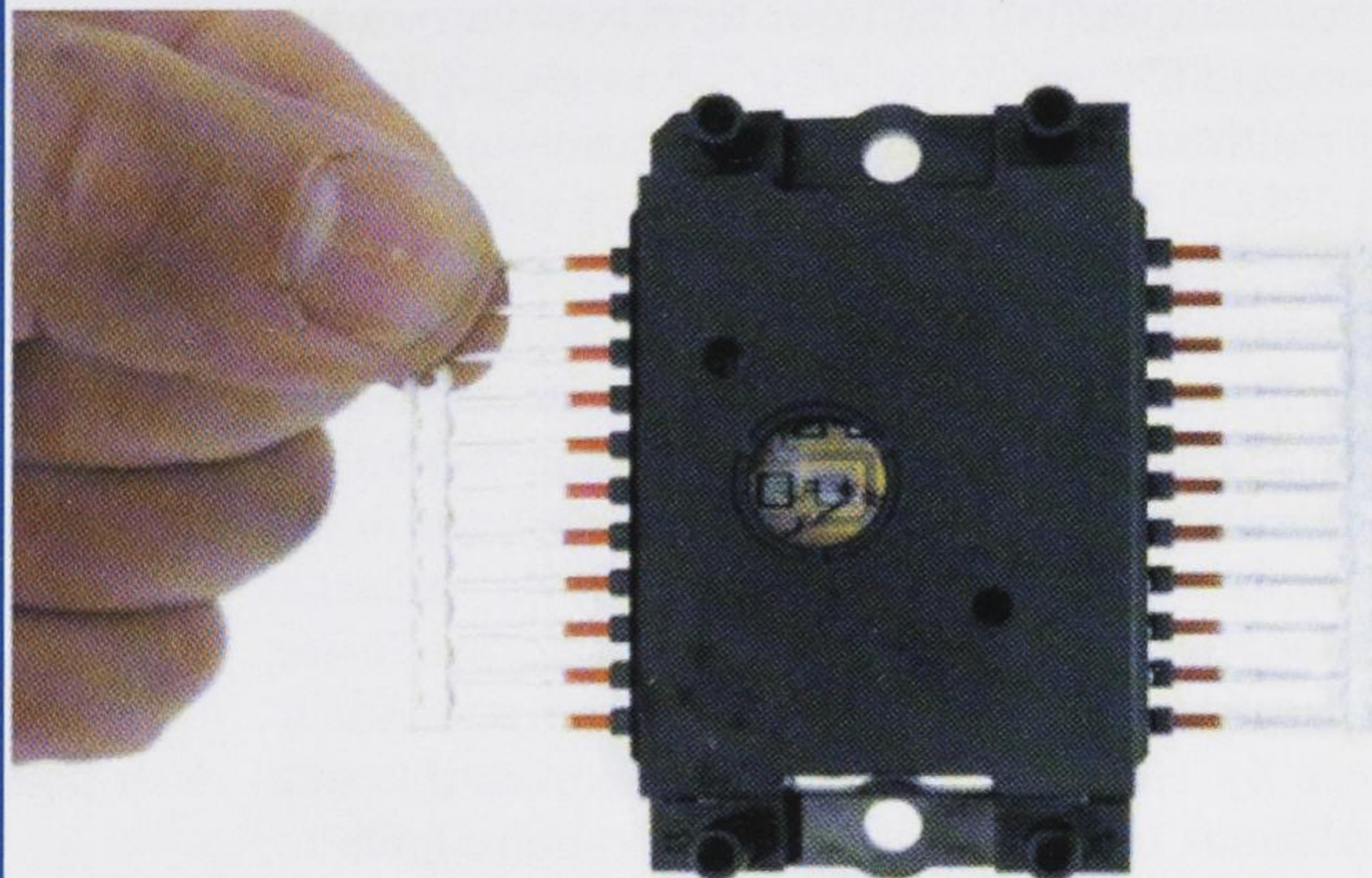
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Cree gets set for MOSFET launch

Armed with a reliable gate oxide, the SiC MOSFET is a great asset in power modules. The result is higher efficiencies and operating temperatures, which can cut solar inverter losses in half and increase the range of operation for military aircraft, explains **Jim Richmond** from Cree.

More-efficient power devices deliver many benefits. Some of these are obvious, such as a reduction in the carbon footprint. However, others, which are application specific, are more subtle and can easily be overlooked.

Hybrid electric vehicles using more-efficient power electronics have the obvious benefit of improving the efficiency of conversion from the DC battery to the AC source that powers the engine, leading to reduced gasoline consumption. However, improved electronics also generate less heat and consequently reduce the size, weight and complexity of the cooling system. This cuts production costs, frees up space under the bonnet and leads to a further increase in the miles-per-gallon figure through a reduction in the vehicle's weight.

Improvements in device efficiency also provide a variety of benefits for military aircraft and alternative energy systems. Power electronics are used to control the flight path of military aircraft and efficiency gains can save weight through a reduction in cooling requirements, leading to a greater flying range. In another example, more-efficient electronics can increase the output of fuel cells, wind turbines and solar panels, by providing more-efficient conversion of their electrical output into a form that is suitable for grid connection.

These benefits are driving substantial efforts to create more-efficient power modules. The workhorse of today's power systems is the insulated gate bipolar transistor (IGBT), a mature silicon device that has little headroom for improvement. But efficiency gains will come from the deployment of SiC transistors, which are undergoing a transition from development to commercial release.

SiC devices outperform silicon equivalents on many fronts, because of their superior intrinsic properties. A wider bandgap produces devices that can perform at high voltages and temperatures, handle current density spikes, and deliver low conduction and switching losses. These attributes allow systems that employ SiC power electronics to deliver high efficiencies, and be lighter and smaller, due to reduced cooling requirements. In addition, systems can operate at high frequencies, which cuts the passive component count.

SiC JFETs, BJTs and MOSFETs are all under development at Cree, which is headquartered in



US AIR FORCE

The US Air Force Research Lab is funding research to investigate the performance of SiC power modules for use in inverters that drive the flight-control actuators on combat aircraft, such as the F-35 Lightning II. This war plane is under development and introduction is planned for 2011.

Durham, NC. Currently our main focus is on the MOSFET because it is likely that the SiC market will evolve along a similar path to that of silicon. Initially, silicon JFETs and BJTs dominated the power-switching market, but sales plummeted when a viable MOSFET was launched and its rivals were reduced to serving niche applications. This shift in market share was spurred by the ease of operation offered by the MOSFET, a normally off, voltage-controlled device. In comparison, JFETs are normally on and BJTs are current-controlled devices.

High-voltage devices

Our SiC MOSFET, which is now being targeted for commercial release, will provide customers with a versatile power electronics device. Silicon MOSFETs only serve applications employing voltages below 600 V, because higher voltages produce unacceptably high device resistances, so IGBTs are used beyond 600 V. SiC MOSFETs, however, can operate at up to 6–10 kV.

Our SiC MOSFETs will also have to compete with an emerging technology – GaN transistors. These two devices share many attributes that result from a wide bandgap. However, SiC is a more mature technology and devices can be built on native substrates

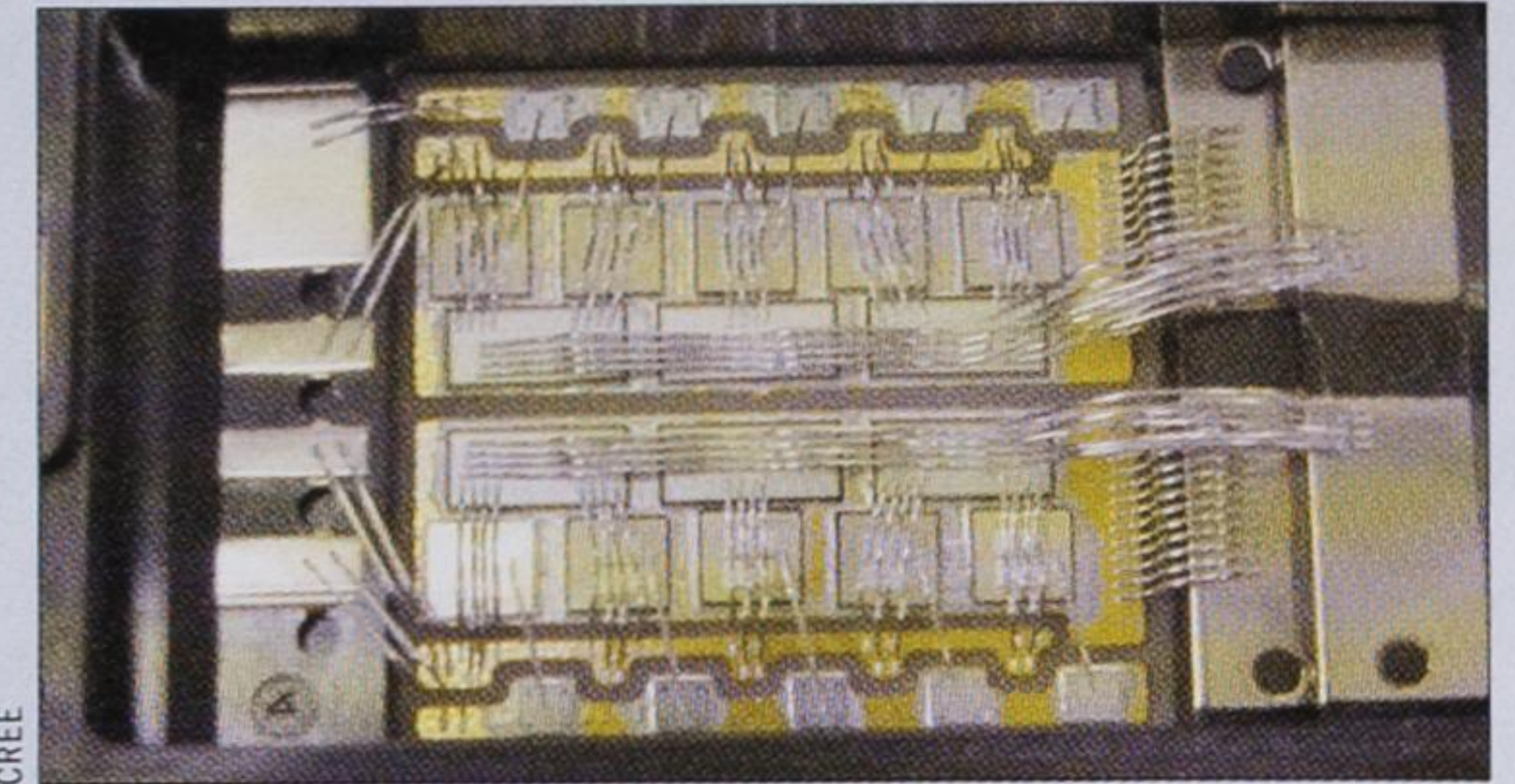
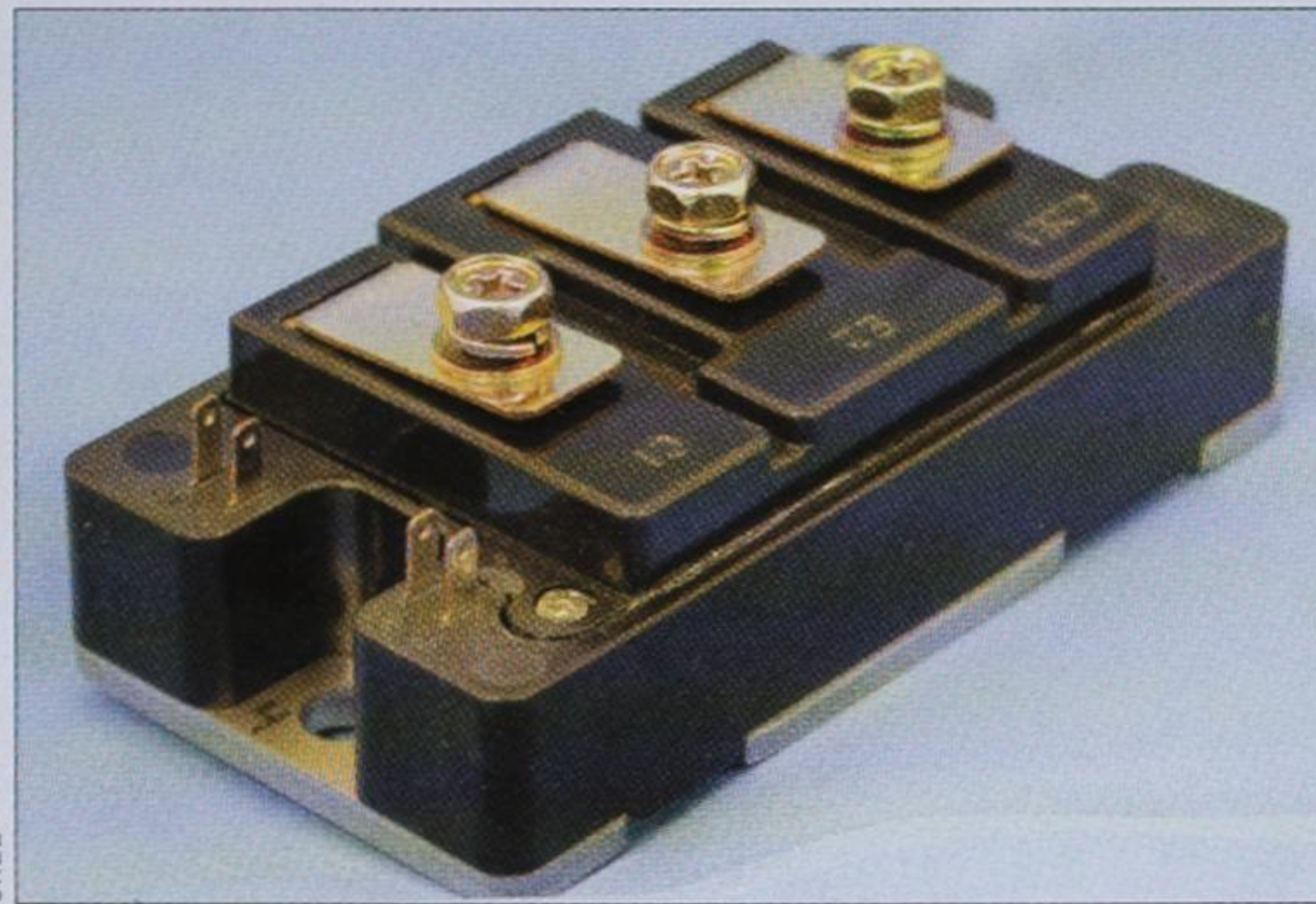
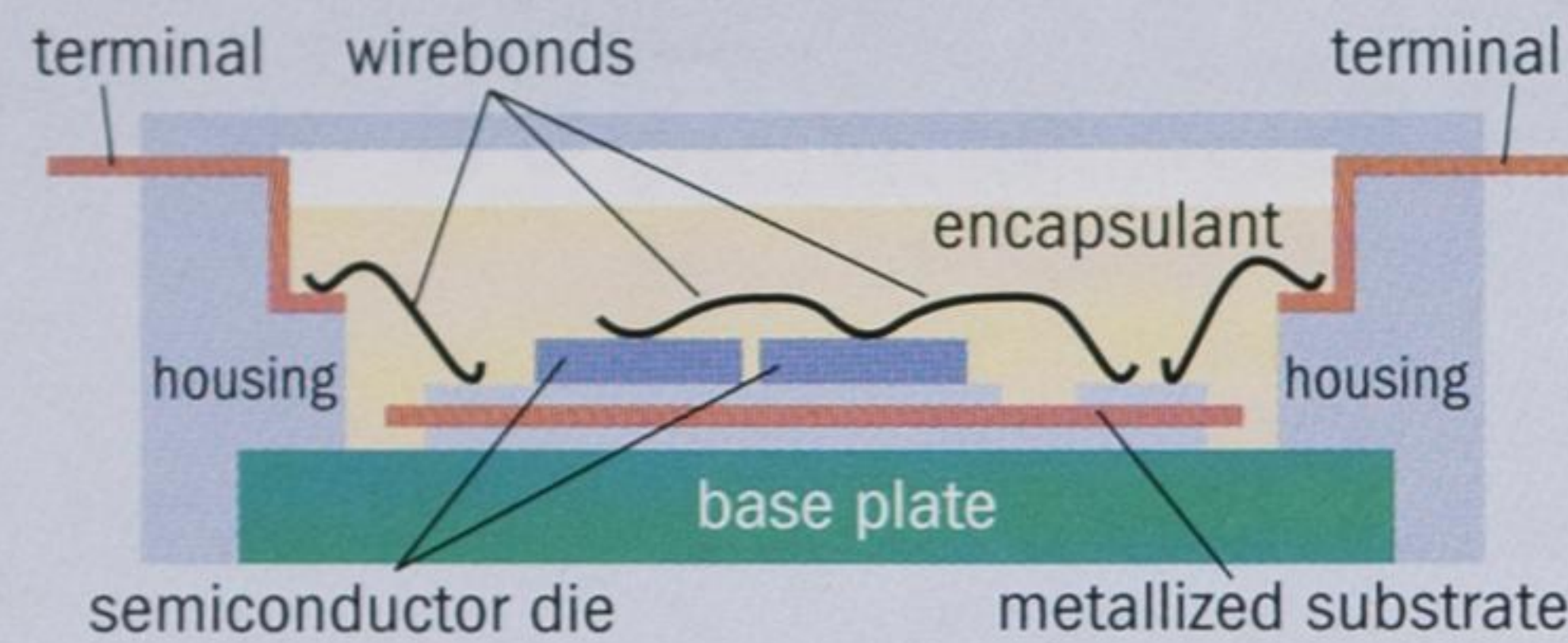
Modules for the US Air Force

Cree has built power modules for the US Air Force Research Lab for use in inverters that drive the flight-control actuators on combat aircraft. These modules are 1200V, 100 A designs with a dual-switch configuration that can operate at 200 °C, which is 50 °C higher than silicon-based equivalents. Cree's partner in this effort was US-based power-module manufacturer Powerex, which performed the design and assembly of the modules.

The packages are built along similar lines to conventional power modules used for switching, which share the current load between several transistors connected in parallel. The transistors are mounted on a high thermal conductivity base plate and cooled by a heat sink or heat exchanger, which is connected to the plate. The power chips are soldered to the base plate if they do not require electrical isolation from the heat exchanger. If electrical isolation is needed, the chip can be mounted on a metallized ceramic substrate that is soldered to the base plate.

Terminals on the module provide external electrical connections and wirebonds link the internal side of the terminals to the chips and substrates. The die are protected from moisture and contamination with an encapsulant that also reduces vibration-induced mechanical stress in the wirebonds. Plastic housing and a cover hold everything together and protect the internal components.

Cree produced two versions of its power module – version A used five 20 A MOSFETs in parallel to deliver the 100 A rating; and version B employed two 50 A MOSFETs in parallel. Both versions used a common base



Power modules feature several semiconductor die that are housed in an encapsulated package (top left). Cree's dual power module for the Air Force Research Lab (bottom left) can either employ five 20 A MOSFET die per switch (top right) or two 50 A MOSFET die per switch (bottom right) to deliver 100 A.

plate, terminal and housing design.

It is essential to minimize the weight of any equipment installed in an aircraft. To this end, a 98 g graphite-fiber-reinforced, copper-alloy-metal matrix was used in place of standard copper. This made the base plate 32% lighter and cut the total mass of the module by 14%.

The thermal performance of Cree's module has been improved with copper-bonded AlN substrates. The AlN substrates have a conductivity of $210 \text{ W m}^{-1} \text{ K}^{-1}$, which is 10 times higher than the more commonly used alumina substrates.

The B design produces a lower parasitic

inductance and package parasitic resistance than A and has a smaller on-resistance between the drain and source contacts because of a simplified chip and wirebond layout. This leads to an impressive set of electrical performance characteristics, including conduction and switching losses that are 38 and 60% lower than a silicon IGBT module with equal rating, for a junction operating temperature of 150 °C. At a 20 kHz switching frequency this translates to a 54% reduction in power loss. Version B has the same DC characteristics as A, while switching measurements on version B are ongoing.

with high thermal conductivities that improve surge and avalanche ratings. In comparison, nitride transistors are grown on foreign substrates and have to employ a lateral device geometry that complicates packaging and module assembly.

SiC MOSFET performance hinges on the oxide quality of the gate in the transistor. Although SiC shares silicon's native oxide, techniques that silicon developers use to improve SiO_2 quality have not worked to date. Instead we have devoted many years of research to developing a thermally grown SiO_2 layer and improving its quality. We fabricated our first power MOSFET on the 6H form of SiC in 1993 and four years later we replicated this device on the 4H polytype that we use today. This produces transistors with lower on-resistance thanks to the substrate's higher vertical electron mobility.

More recently, we have added an annealing process in nitrogen oxide gases, which boosts channel mobility through a reduction in interface state

density by almost an order of magnitude. In 2002 we fabricated our first nitrided SiC MOSFET and further efforts over the last few years have enabled us to deliver a gate oxide with a mobility of more than $20 \text{ cm}^2/\text{Vs}$ on DMOS structures. This reliable and stable oxide is the key to the fabrication of a commercially viable MOSFET.

Our oxide's mobility is not the highest reported value – researchers at Chalmers University of Technology in Gothenburg, Sweden, have produced oxide mobilities of more than $100 \text{ cm}^2/\text{Vs}$ on low-doped, epitaxial-grown layers. However, this Swedish process is not compatible with vertical structures, making it unsuitable for MOSFET production.

We have assessed the reliability of our MOSFET's oxide with time-dependent dielectric breakdown testing, which revealed a projected life of more than 100 years at fields below 6 MV/cm (figure 2). This testing accelerates the failure rate by increasing the field on the oxide.

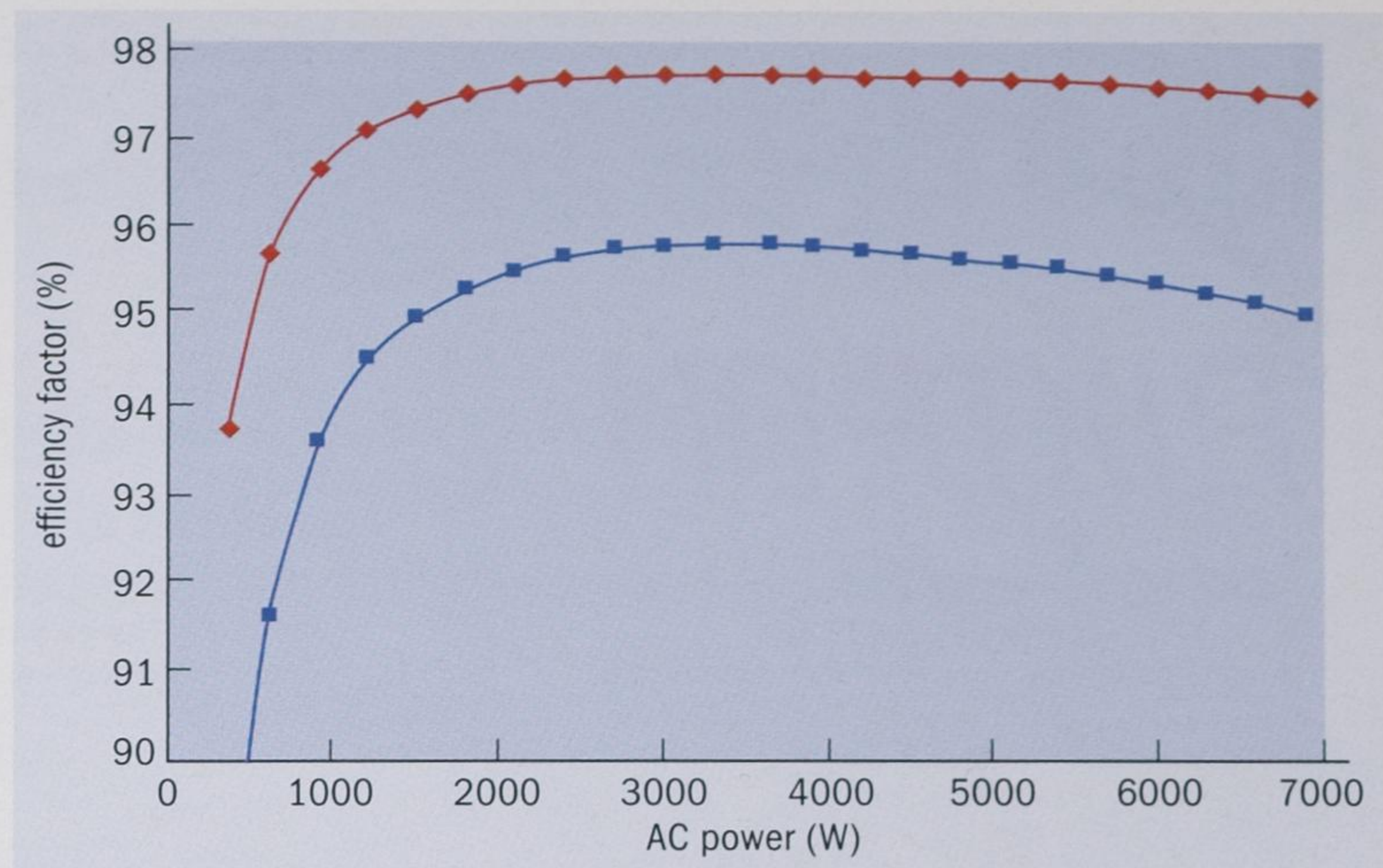
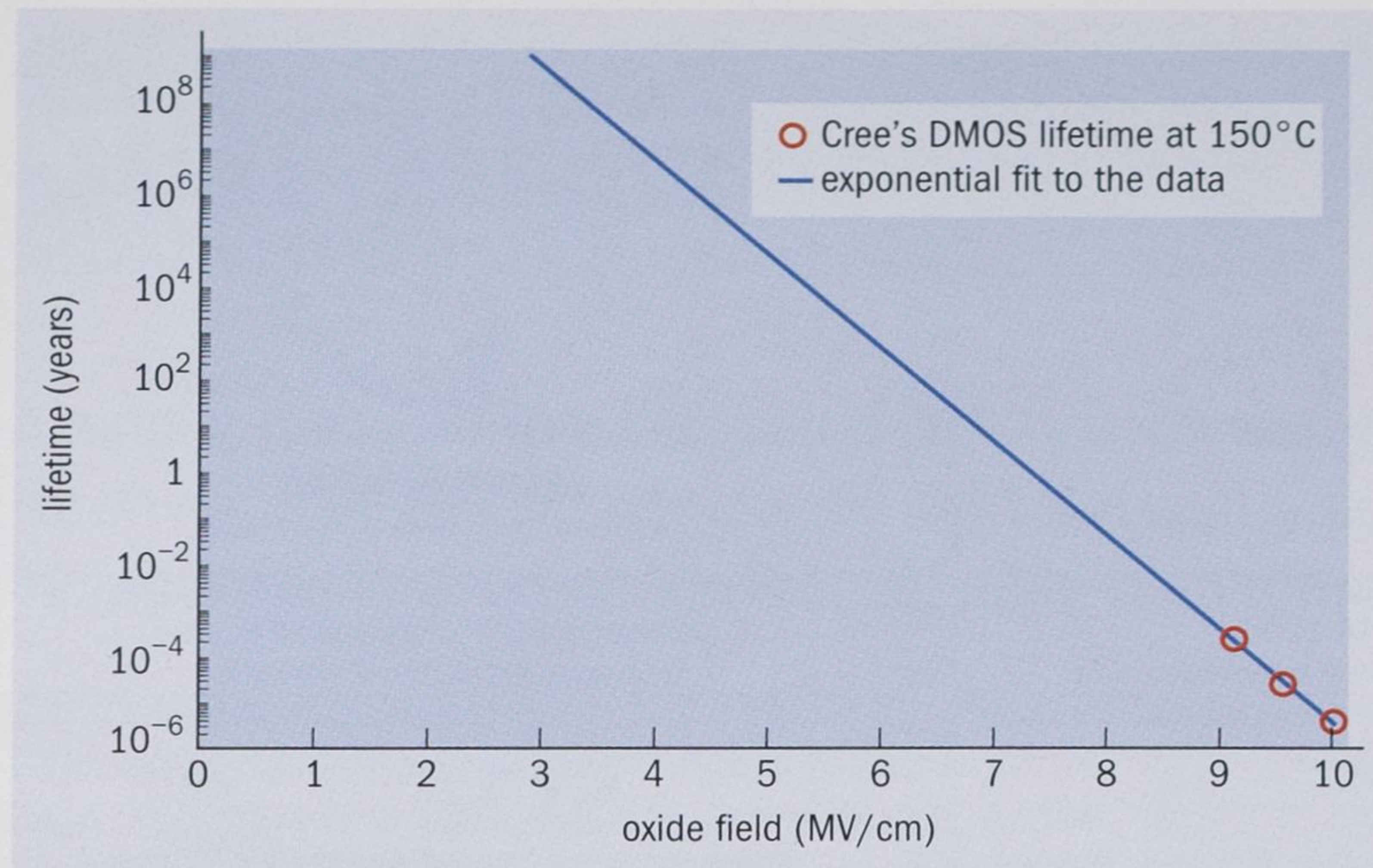


Fig. 1. (left) After many years of research, Cree has developed a reliable gate oxide that has an expected lifetime of more than 100 years. **Fig. 2.** (right) Replacing 1200V silicon insulated gate bipolar transistors with 1200V SiC MOSFETs delivers significant efficiency gains in solar inverters at various output powers.

The final hurdle for our MOSFET is gate oxide stability. This is being assessed by high-temperature gate bias tests, which heat the MOSFET to its maximum temperature while it is biased at its maximum gate voltage. To pass, the MOSFET characteristics must remain stable for 1000 hours. Data relating to these tests have not yet been published, but the initial results are encouraging.

Military backing

Many SiC developers have benefited from the backing of the US Army Research Lab and the US Air Force Research Lab. These institutions have managed programs focusing on improvements in gate oxides and those that investigate the potential of many types of SiC device. We have been involved in several of these, including a recent project to develop large SiC switch devices, which spurred our development of 1200V MOSFETs operating at 20 and 50 A.

It is possible to build MOSFETs capable of handling even higher currents by making bigger devices. However, production yields suffer because larger transistors are more difficult to process and the likelihood of a material defect in the device is higher. A better, well known approach to higher currents is to build circuits that share the current load between multiple transistors by connecting them in parallel. SiC MOSFETs exhibit ideal behavior for this – if one transistor has a slightly lower on-resistance than the others it will take more current and heat up, leading to an increase in its on-resistance that shifts current to other devices. We have used this approach to build power modules featuring several SiC MOSFETs for the Air Force Research Lab. These can be used in inverters that drive the flight-control actuators on combat aircraft (see box “Modules for the US Air Force”).

SiC MOSFETs can also improve the efficiency of inverters that connect the DC output from a solar-power system to the AC grid. The benefit of SiC MOSFETs in this application has been revealed by Bruno Burger’s team at Fraunhofer Institute for

Solar Energy Systems (ISE) in Germany, which compared the performance of inverters employing silicon IGBTs and our SiC MOSFETs.

Comparisons were made with a 7kW, 16.6kHz three-phase grid-connected solar inverter designed for 400V AC operation. Voltage peaks will be near 600V, so 1200V IGBTs are required in the inverter, which were swapped with our 1200V SiC MOSFETs during testing.

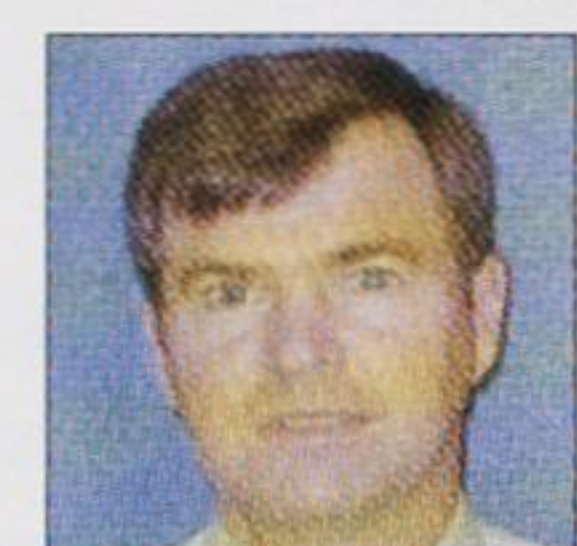
The wide-bandgap transistors increased the maximum efficiency by 1.9% to almost 98%, which equates to a halving of the inverter loss. SiC MOSFETs also cut the heat-sink temperature from 93 to 50°C, at an ambient temperature of 25°C.

Our SiC transistors can provide a significant financial benefit in European countries with feed-in tariffs for renewable energies. In Germany, 7kW photovoltaic systems are producing 7MWhr a year with a €0.49 (\$0.63)/kWh feed-in tariff. The tariff generates €3430 for the solar-system’s owner. A switch to SiC MOSFETs would produce an additional income of €81, assuming the efficiency gains calculated by Fraunhofer ISE. Greater financial benefits can be expected in sunnier climates, such as southern France and Spain, and here there is a stronger case for using SiC MOSFETs in inverters. This cash benefit is one of the less obvious advantages of SiC, but one that complements the reductions in greenhouse gas emissions that stem from greater device efficiencies.

It is clear that SiC MOSFETs are already delivering benefits over silicon IGBTs, even though these wide-bandgap devices are still to be optimized. Inevitably, improvements will follow that will deliver further increases in energy efficiency, which will carve out a bigger share of the overall power semiconductor market for the SiC MOSFET.

Further reading

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About the author

Jim Richmond is the power device R&D test manager at Cree Inc.

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Sofradir backs a two-tone approach

A single, narrow detection range holds back the effectiveness of all forms of infrared detector. However, this can be addressed with Sofradir's mercury cadmium telluride dual-band design that incorporates a production-friendly semi-planar architecture, says the company's **Philippe Tribolet**.

Choosing the correct infrared camera requires some care. Whether it is intended for surveillance, or for identifying a particular object, it is important to select the optimum spectral band to obtain the most informative images.

Unfortunately, the ideal waveband isn't fixed. It depends on factors such as humidity, air temperature and the size of the water droplets in the atmosphere. These all influence the transmission of infrared radiation and can have a significant impact on the quality of images generated by detectors operating over distances of several kilometers or more, such as those used for remote sensing of the earth from satellites and long-range surveillance. On top of this, single-band cameras can struggle in military applications, because flares and decoys can hamper the detection and identification of targets.

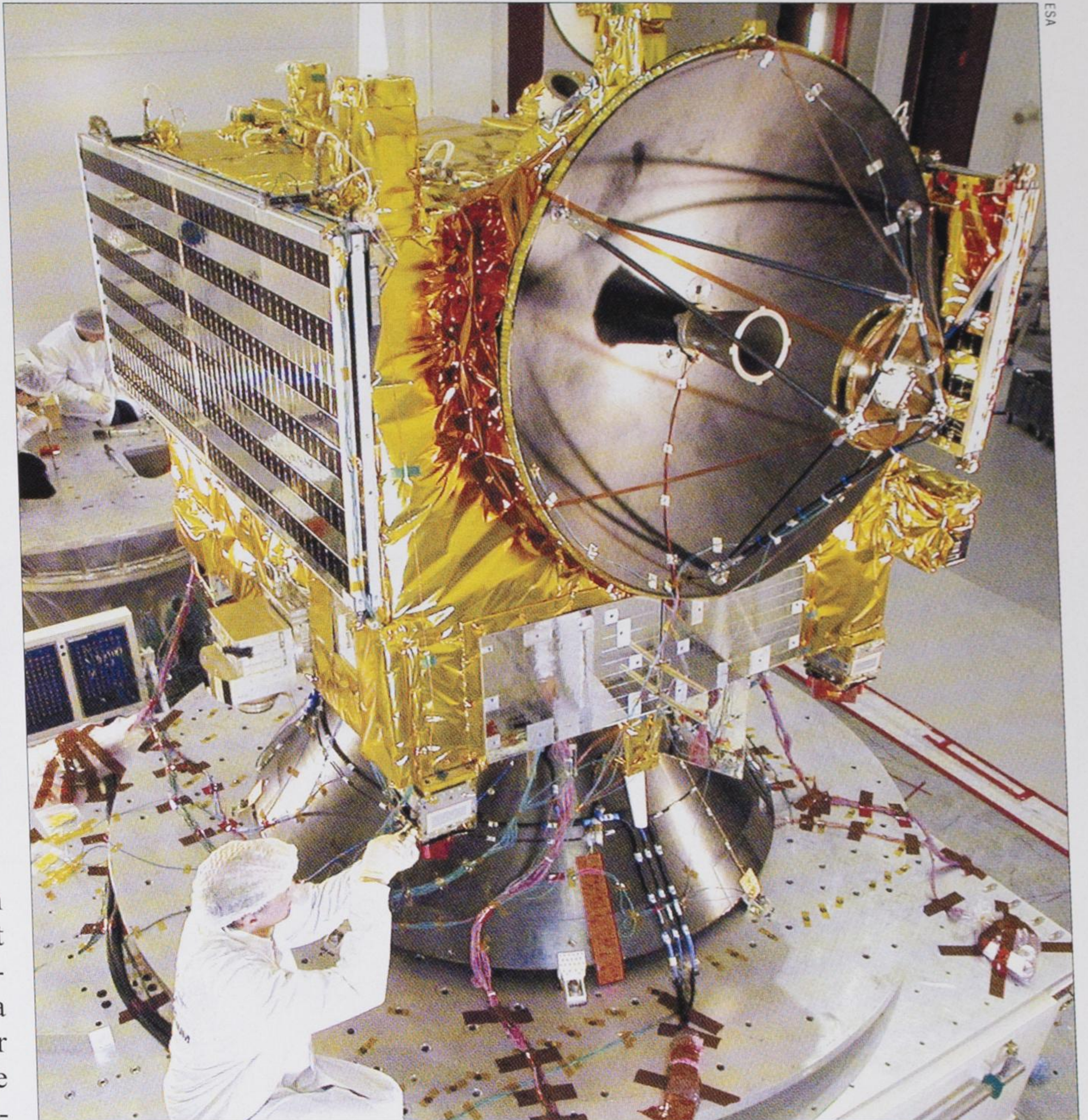
However, it's possible to address these issues by switching to infrared detectors and accompanying optics that can deliver high performance in multiple spectral bands. The penalty is greater complexity, as this multi-spectral detector requires pixels to deliver simultaneous detection in at least two wavebands.

Imaging options

Moving to just two bands equips the camera with several modes of operation. One option is to select the most appropriate band for a particular application, but two channels can also be used to provide a pair of images that convey different information. For example, a camera mounted on an orbiting satellite might provide one image that monitors cloud positions, and one that reveals pollution levels. The two images from a dual-band camera can then be merged to generate a single, more informative image.

For an all-weather camera, the best results come from pairing detection in the medium-wave infrared (MWIR) (3–5 μm) and long-wave infrared (LWIR) (8–12 μm). Cameras with this feature should make a big impact on the detector market, as long as the cost premium over a single-band detector is acceptable. However, meeting this criterion demands the deployment of a cost-effective technology that is applicable to high-volume manufacturing.

Today, it's only possible to get dual-band performance with cryogenically cooled designs based on a stack of compound semiconductor layers, which feature separate regions for the absorption



The European Space Agency launched the Venus Express satellite in 2005. It was equipped with a solar occultation infrared instrument, which featured a single-band 320×256 pixel detector for medium-wavelength infrared detection, for studying Venus' atmosphere. Since then, Sofradir has won contracts for supplying detectors for other space missions, and in November 2008 it signed a €6.7 million (\$9.2 million) deal with Astrium SAS – a supplier of satellites and space equipment. Sofradir will supply a custom-made three-band short-wave infrared detector for the multi-spectral instrument – an earth-observation tool that is used onboard the Sentinel-2 satellite.

of each spectral band. InAsGaSb type-II superlattice designs are one option, alongside quantum-well infrared photodetectors (QWIPs) that are based on layers of GaAlAs and GaAs, and detectors based on the HgCdTe family of compounds.

Although the type-II superlattice structure can in principle cover different wavebands, today's designs can only provide detection in the MWIR and SWIR

Growing HgCdTe detectors by MBE

CEA-Leti and Sofradir employ MBE growth to make their HgCdTe detectors, because this enables the growth of complex heterostructures containing very high-quality layers. The main challenge is to grow material with a sufficiently low surface defect density.

The dual-band detector structure contains layers with differing HgCdTe compositions. Unfortunately, the changes in cadmium composition favor non-ideal growth conditions and lead to an increase in surface defect density that is mainly caused by tellurium precipitates.

High-quality growth is possible by adjusting the temperature of the CdZnTe substrate, but this also alters layer composition. To overcome this problem the researchers at CEA-Leti and Sofradir have learned to control the HgCdTe composition over a range of growth temperatures, and they can now produce epiwafers with a surface defect density of less than 200 cm^{-2} . This density of defects is very similar to that for HgCdTe detector structures that operate over a



single spectral band.

The adjustments in cadmium composition needed for the dual-band structure would normally cause strain due to changes in lattice constant. However, this is avoided by adding tiny amounts of zinc to the barrier and cap, so that these layers have the same lattice constant as the absorbing layers.

With this approach the researchers at CEA-Leti and Sofradir have produced material with excellent crystal quality. High-resolution X-ray diffraction spectra show a single peak with a full-width half maximum of 25 arcsecs. Dislocation densities are in the very low 10^5 cm^{-2} .

(1–2.5 μm), while QWIPs are restricted to covering the MWIR and LWIR, or the LWIR and VLWIR (12–20 μm). But detectors based on HgCdTe can detect in all bands, while delivering superior performance to QWIPs.

The development of dual-band HgCdTe detectors has actually been underway for many years – the French national research and development center CEA-Leti started to develop this technology in the early 1990s, and it delivered the first proof-of-concept demonstration at the start of this decade. Since then it has been joined by a domestic partner, our research team at Sofradir, which is headquartered in Chatenay-Malabry and has production and development facilities in Veurey-Voroize.

Multiple architectures

Our partnership has developed and demonstrated two different types of architectures for SW/MW, MW/MW and MW/LW focal plane arrays (FPAs). The first is a conventional “n-p-n” mesa structure that features two back-to-back photodiodes, with one connection per pixel. Commercial FPAs down to 24 μm pitches are available with 640×512 pixel arrays operating at a frame rate of 60 Hz, while larger format FPAs are under development.

This approach gives the detector excellent spatial coherence because every pixel detects both bands. However, because the read-out from these two bands is sequential rather than simultaneous, the design reduces temporal coherence.

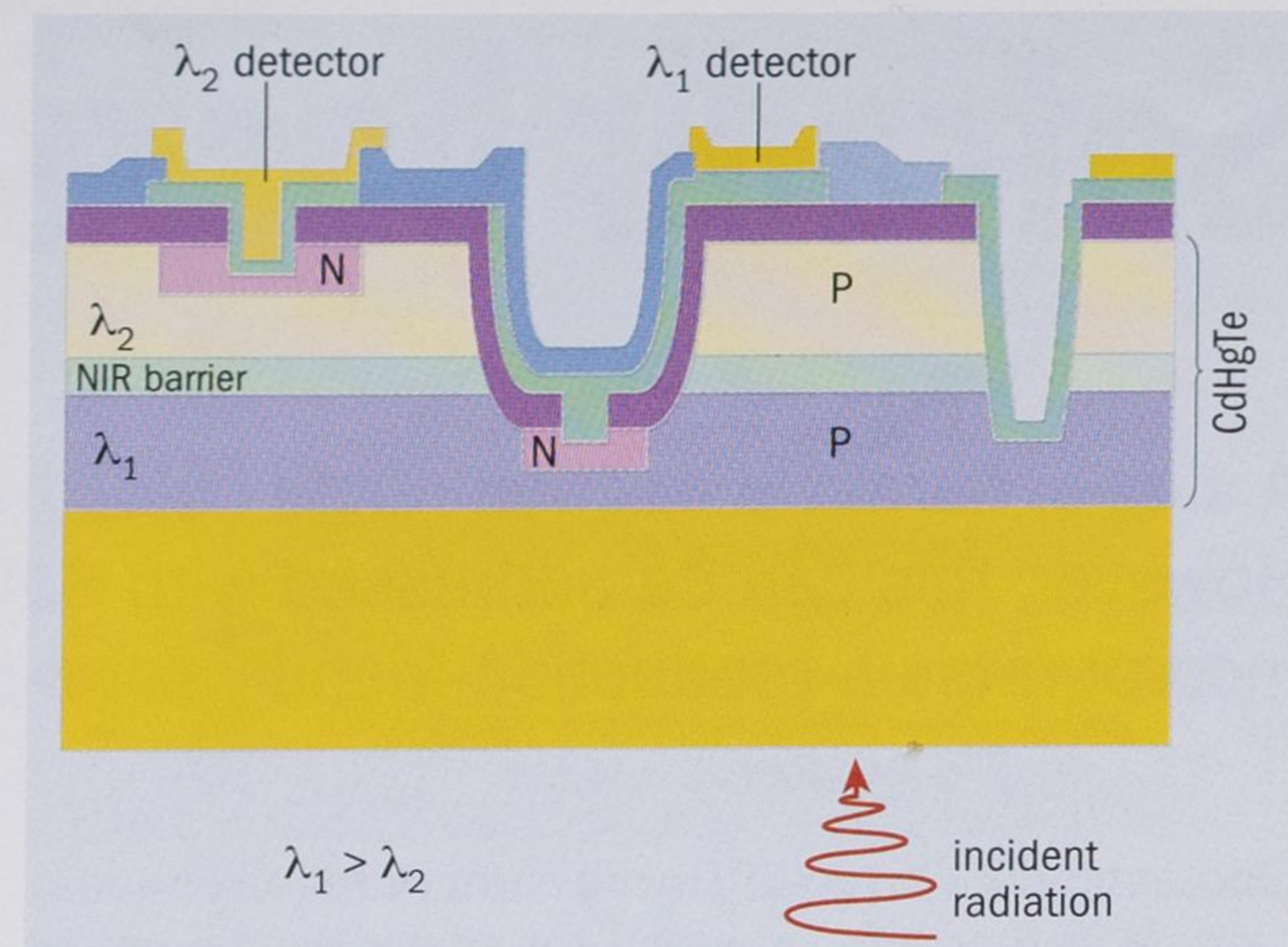


Fig. 1. Sofradir and CEA-Leti’s semi-planar architecture produces dual-band infrared detectors with temporal and spatial coherence. Temporal coherence results from the use of two independent contacts for each pixel. This creates two photodiodes delivering simultaneous detection. One photodiode is at the bottom of a hole etched in the longest cut-off wavelength absorption layer, and the other is on the surface. A barrier layer prevents electrical shorting between the diodes.

Our other design addresses this weakness, with simultaneous read-out of the two bands. It is a semi-planar structure that features two n-on-p diodes, which are formed on two different levels of the three-layer architecture (see figure 1 for details). Although spatial coherence is compromised in this design, due to a spatial shift between the two bands equal to a quarter of the length of the pixel, this can be corrected by system-level signal processing.

We describe this structure as semi-planar because the first photodiode is planar and the other is quasi-planar. Using this type of structure is beneficial because it allows us to employ processes that are similar to the standard ones used in the silicon industry. This leads to higher yield, low manufacturing costs and a potentially more straightforward ramp-up to mass production.

Other advantages of the semi-planar structure over the more conventional architecture include a higher manufacturing yield for LWIR pixels, according to our experience. In addition, the two detection bands can be optimized independently and cross-talk between them is minimized. Incorporating avalanche photodiodes and extra-low noise-equivalent temperature-difference (NETD) pixels into this design is also a possibility, which promises increased detector sensitivity.

Our detector development efforts have focused on improving material quality (see box “Growing HgCdTe detectors by MBE”), optimizing the photodiodes and improving the flip-chip bonding processes to reduce pixel pitch.

We have made good progress over the last few years and the performance of each band in our dual-band detectors now offers a very similar level of performance to single-band equivalents.

In 2007 we demonstrated a 320×256 pixel detec-

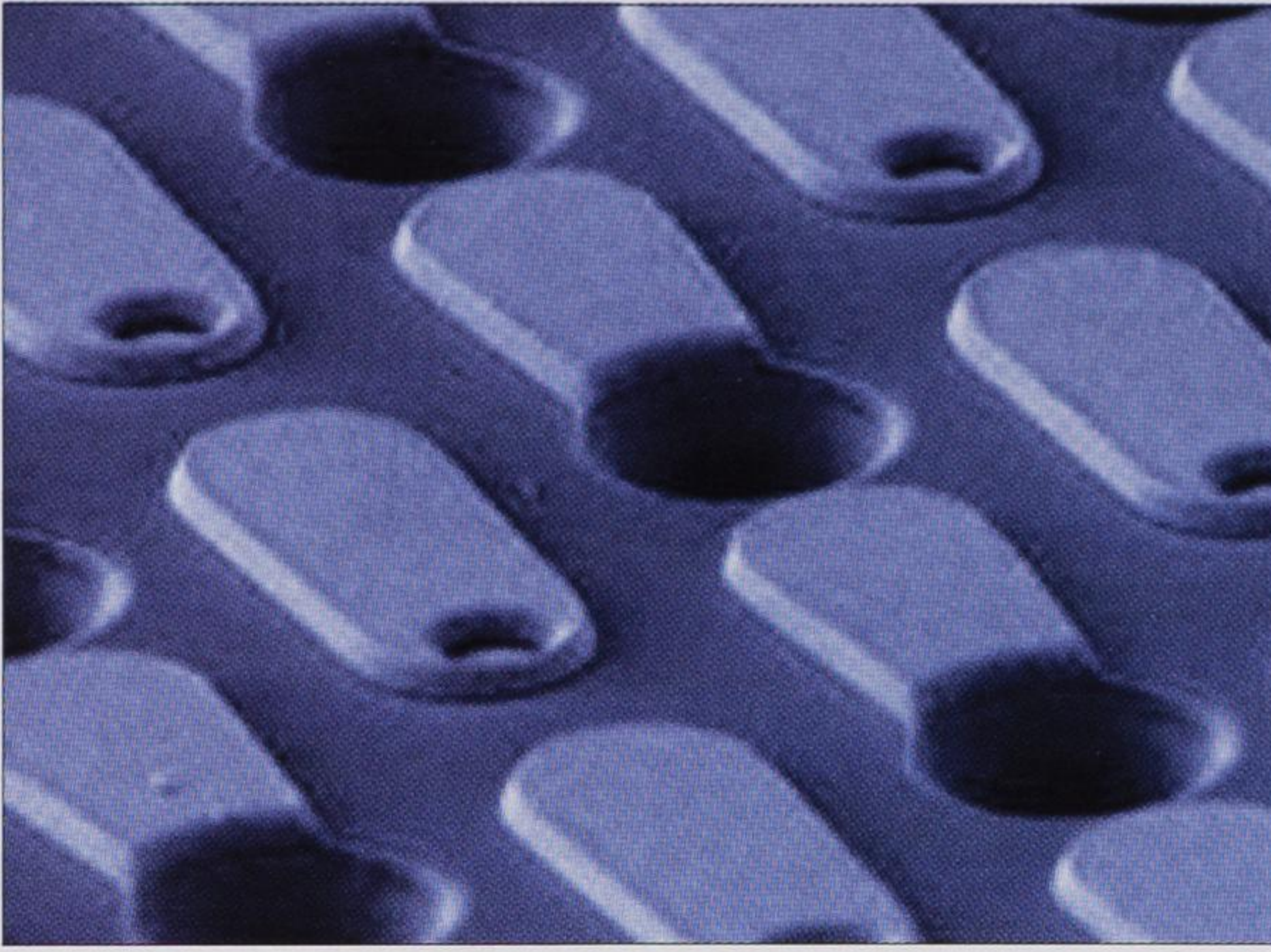


Fig. 2. Scanning electron microscopy images show the surface of Sofradir's semi-planar pixel arrays with a 24 µm pitch.

tor called Janus at the SPIE Defense, Security and Sensing meeting in Orlando, FL. This dual-band detector operated in the MWIR and featured a 30 µm pitch. During that year we also produced a 256×256 pixel MWIR/LWIR dual-band detector (see figure 3 for images).

More recently, we have reduced the pixel pitch to 24 µm and produced a 640×480 pixel detector operating at 60Hz. We aim to produce a dual-band 640×512 detector with 20 µm pitch this year. This scaling of the pixel dimensions aims to reduce the

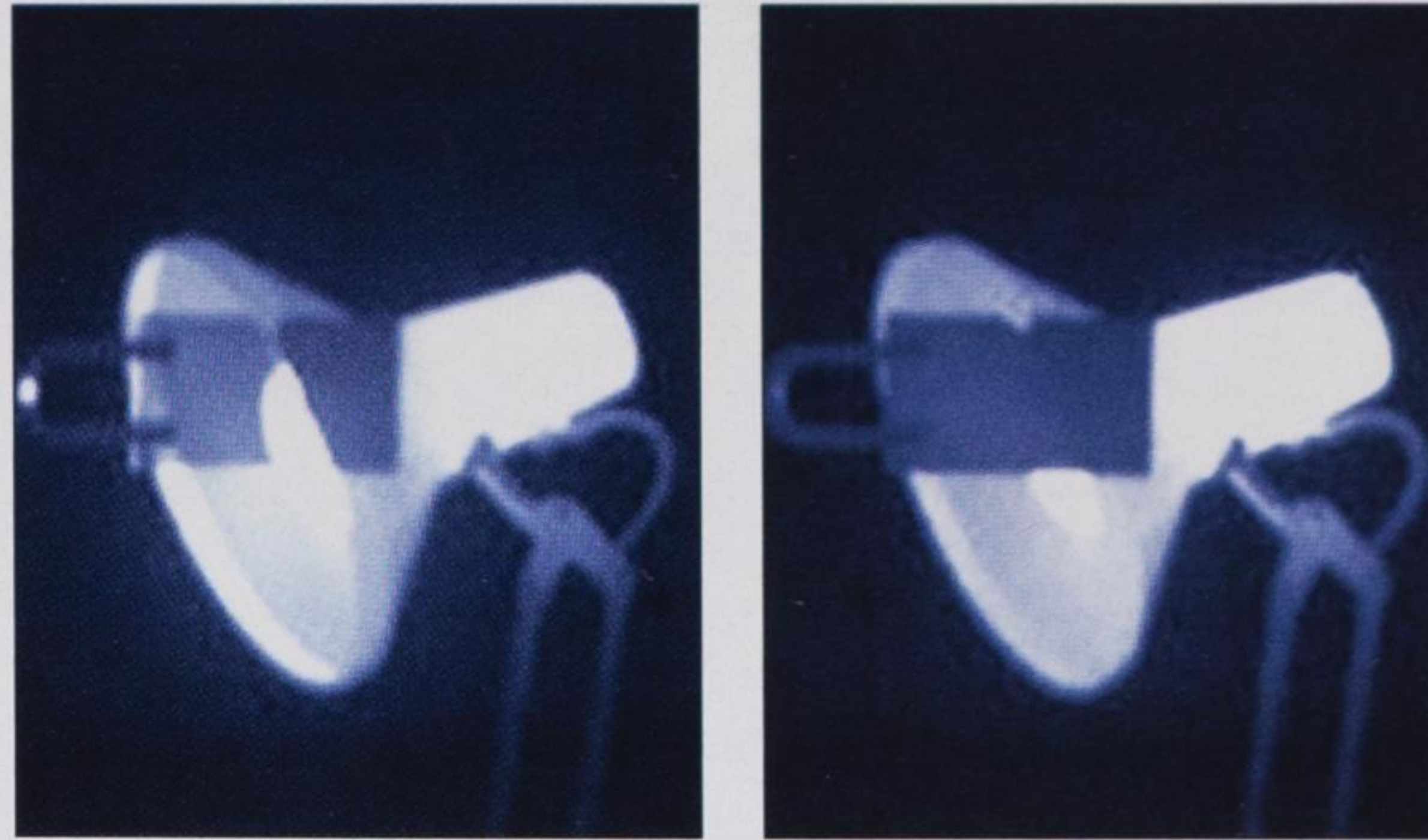


Fig. 3. Images taken with spectral bands centered at 5 µm (left) and 10 µm (right) can distinguish different details in this image of a table lamp, which is partially obscured by a credit card.

cost and weight of the FPA and its associated optics, while still allowing for high-yield manufacture. Progress has come through improvements in etching and deposition, advances in the process used to unite the detector to a CMOS read-out circuit and greater uniformity on large format arrays, which minimizes electrical performance dispersion.

One of our aims for the next few years is to open up new applications for our dual-band detectors by incorporating low NETD structures and avalanche photodiodes, which will improve performance at low infrared light levels. We also plan to address the important issue of cost-effective production. ●



About the author

Philippe Tribolet is Sofradir's vice-president of R&D, technologies and products. He directs production programs for French and international military, aerospace and security customers.

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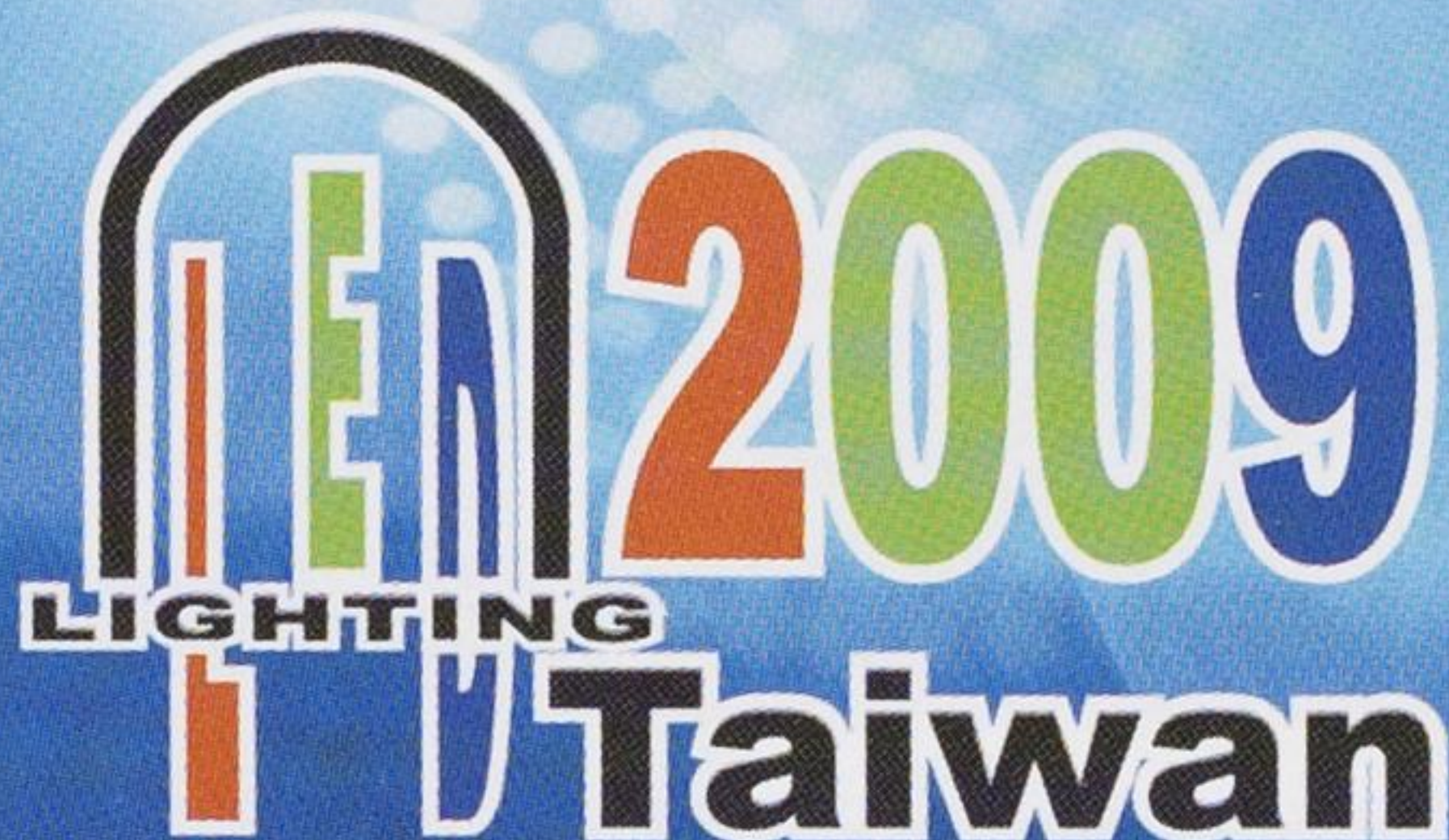
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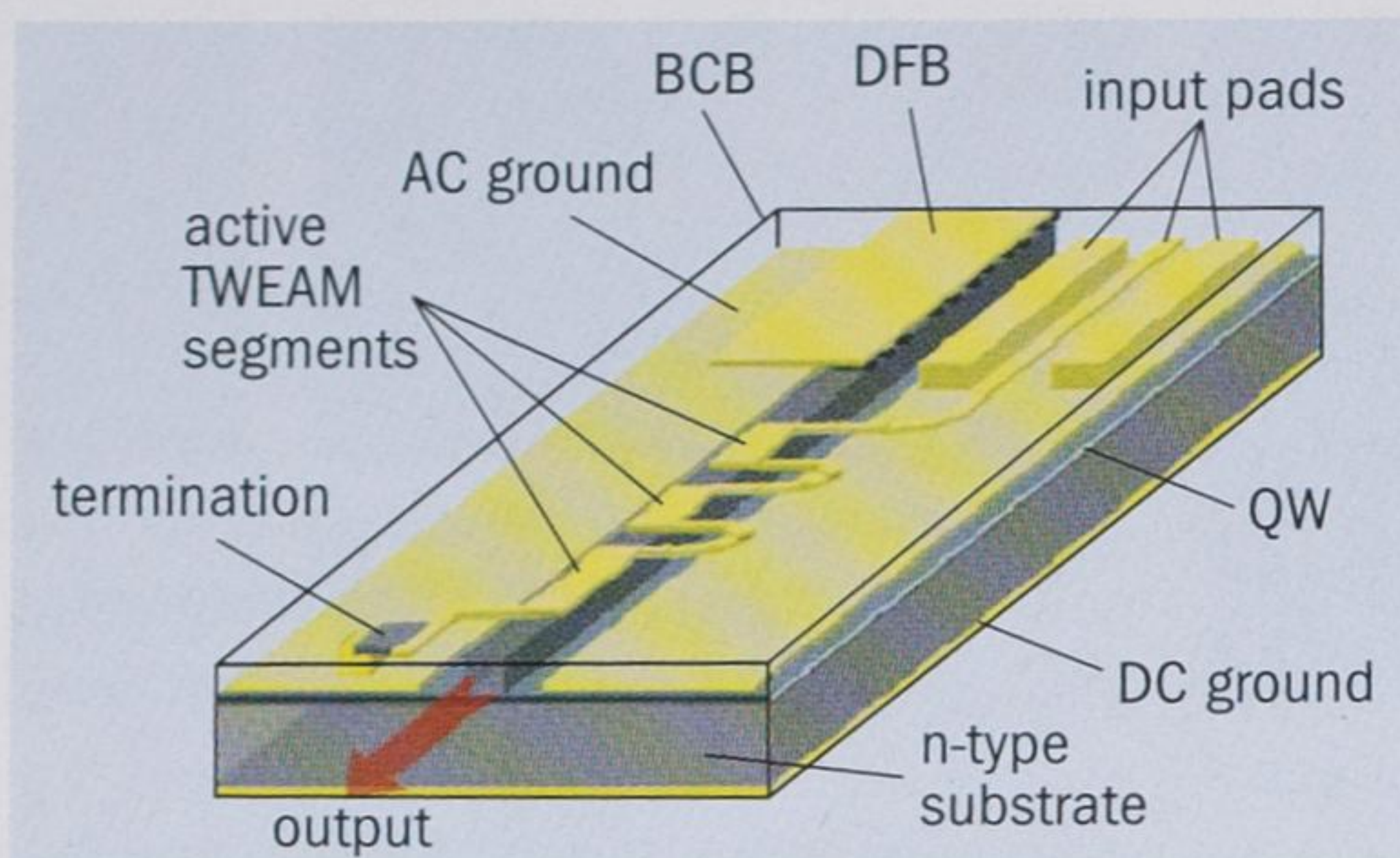
Monolithic chip eyes 100 Gbit/s Ethernet

Researchers at Kista Photonic Research Center and Syntune claim to have produced the first monolithic transmitter that can operate at up to 100 Gbit/s.

This chip combines a 1.53 μm distributed feedback (DFB) laser with a travelling-wave electroabsorption modulator (TWEAM) and promises to cut broadband access costs. An increase in Ethernet speeds is enabled, which will allow it to replace more-expensive wavelength division multiplexing equipment.

Funding for the chip's development came from a €3.9 million (\$5.6 million) European project called HECTO (High-speed electro-optical components for integrated transmitters and receivers in optical communication). This three-year program aims to fabricate transmitters and receivers for optical packet-switching networks based on serial 100 Gbit/s Ethernet signals.

The transmitter's high modulation speed



The 100 Gbit/s transmitter features a travelling-wave electroabsorption modulator, which contains three segments with lengths of 100, 40 and 40 μm . The DFB laser is 440 μm long and emits at 1.53 μm .

stems from good filter characteristics that result from the active segment design, according to lead author Marek Chaciński from Kista (see figure).

MOCVD growth created the laser struc-

ture and produced the modulator via a regrowth step.

The 180 μm long non-periodic TWEAM has three active segments and requires a 2.5 V peak-to-peak drive voltage to deliver a 10 dB optical extinction ratio. The DFB laser has a threshold current of 26 mA and a side-mode suppression ratio exceeding 40 dB. At 50 mA bias, 1.4 mW is emitted from the monolithic transmitter.

Initial values for the chip's transmission speed have been determined from measurements with a 50 GHz bandwidth commercial photodiode and subsequent modeling based on these results. "We are approaching testing of 100 Gbit/s with components developed in the HECTO project," explained Chaciński.



Journal reference

M Chaciński et al. 2008 *IEEE Electron Dev. Lett.* **29** 1312.

INTEGRATION

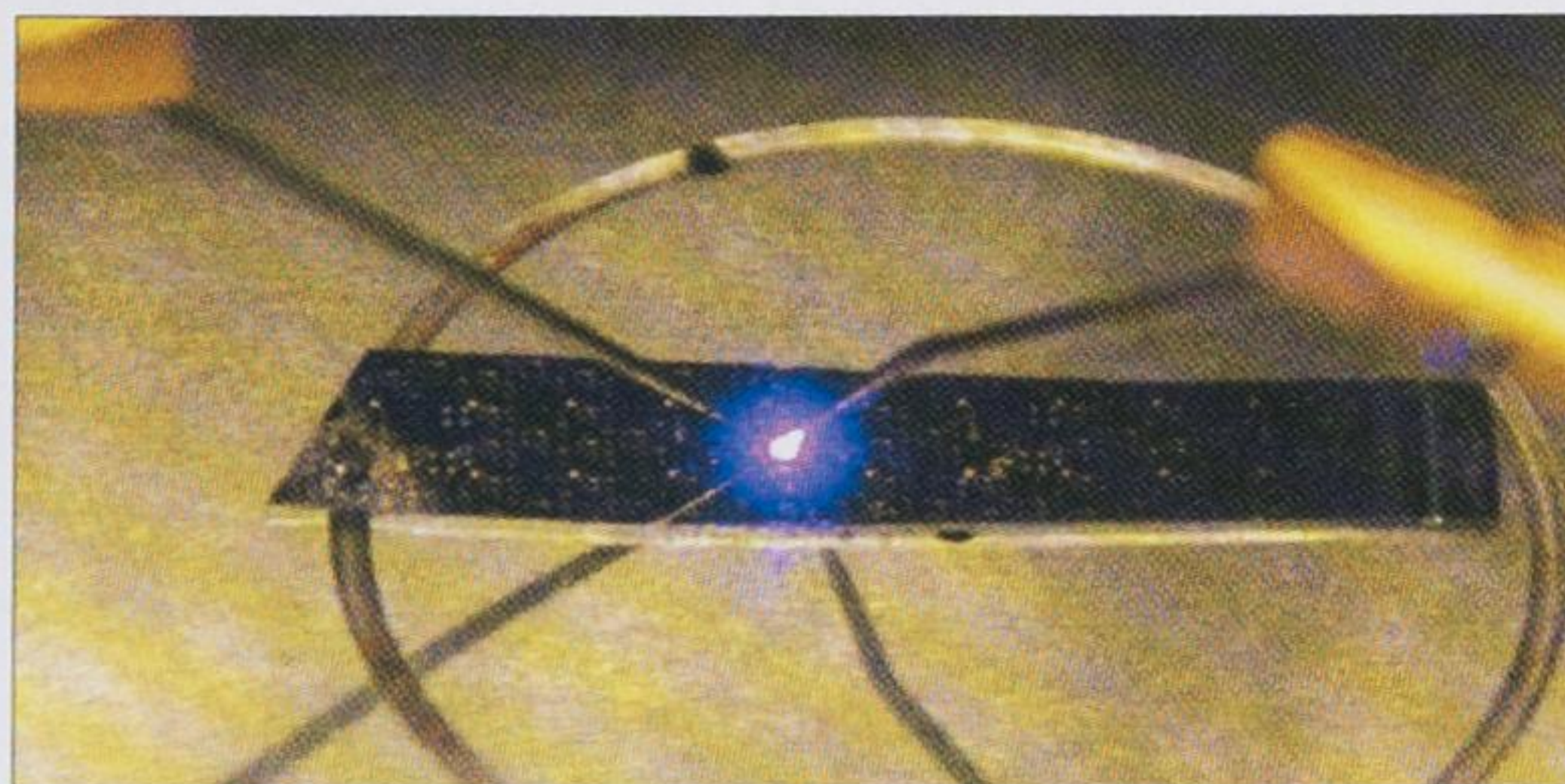
GaN LEDs find a new home on silicon (100)

Integration of photonics and silicon electronics has taken another step forward, thanks to the efforts of a French team that has produced the first nitride-on-silicon (110) LEDs.

Although this orientation is not used by silicon chip manufacturers, who build CMOS circuits on silicon (100), it is attracting the attention of research groups including IBM and Sematech. Advanced MOSFETs grown on silicon (110) with superior channel transport could lead to faster CMOS circuits.

The researchers from CNRS-CHREA and Riber produced their LEDs in an MBE reactor, with ammonia as the nitrogen source.

They deposited a 40 nm AlN buffer on 2 inch silicon (110), followed by a 0.22 μm stack of alternating GaN and AlN layers, which counteracts the tensile stress that occurs during wafer cooling. An LED struc-



LEDs built on silicon (110) produce similar output powers to those that are grown on silicon (111).

ture was grown on top of this.

In situ strain measurements with a Laytec sensor enabled the researchers to produce a crack-free structure, even after LED processing. "We can also follow strain relaxation with reflection high-energy electron diffraction (RHEED)," explained Benjamin Damilano from CNRS-CHREA.

On-wafer measurements of LED mesas that are 210 $\mu\text{m} \times 210 \mu\text{m}$ revealed 33 μW output at 100 mA and 428 nm, compared with 32 μW at 427 nm for the silicon (111) control

operated at the same current. Output peaked at 72 μW for a 300 mA drive current. However, Damilano points out that this measurement was taken at a distance of 1 cm from the wafer and the total light emitted from the silicon (110) LED is 720 μW .

Damilano believes that the output power could be increased with surface texturing and the addition of Bragg mirrors that prevent light absorption by the substrate. Growth conditions could also be improved.

GaN LEDs are usually manufactured by MOCVD and Damilano wonders whether this growth technique would produce better results. "I have a feeling that the first growth stages, such as buffer layer growth, are easier to control by MBE thanks to powerful *in situ* tools such as RHEED. However, I think that very good results could be obtained by combining MBE and MOCVD."



Journal reference

B Damilano et al. 2008 *Appl. Phys. Express.* **1** 121101.

LASERS

Quadruple core boosts cascade-laser output

Scientists have raised the efficiency bar for quantum cascade lasers (QCLs) emitting at about 10 μm . The 10.5 μm QCL made by ETH Zürich and AL Technologies operates at

room temperature with peak output powers up to 4.6 W and 4.3% wall-plug efficiencies.

Chemical spectroscopy and free space communication could benefit from these emitters because they require large peak and average powers in the mid infrared.

MOCVD growth produced the laser structure that consists of four active region cores, each containing 15 pairs of active and injec-

tor regions, separated by three InP stacks.

Devices that are 5.4 mm long and 49 μm wide delivered peak powers of 7.8 and 4.7 W at 243 and 300 K, respectively. Threshold current densities were 1.58 kA/cm² at 300 K.



Journal reference

A Bismto et al. 2008 *Appl. Phys. Lett.* **93** 231104.

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