

COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

October 2005 Volume 11 Number 9



INFRARED DETECTORS
GaAs-based QWIPs
deliver multi-band imagers

ALSO INSIDE

**Goodrich to buy
Sensors Unlimited**

**Nakamura talks up
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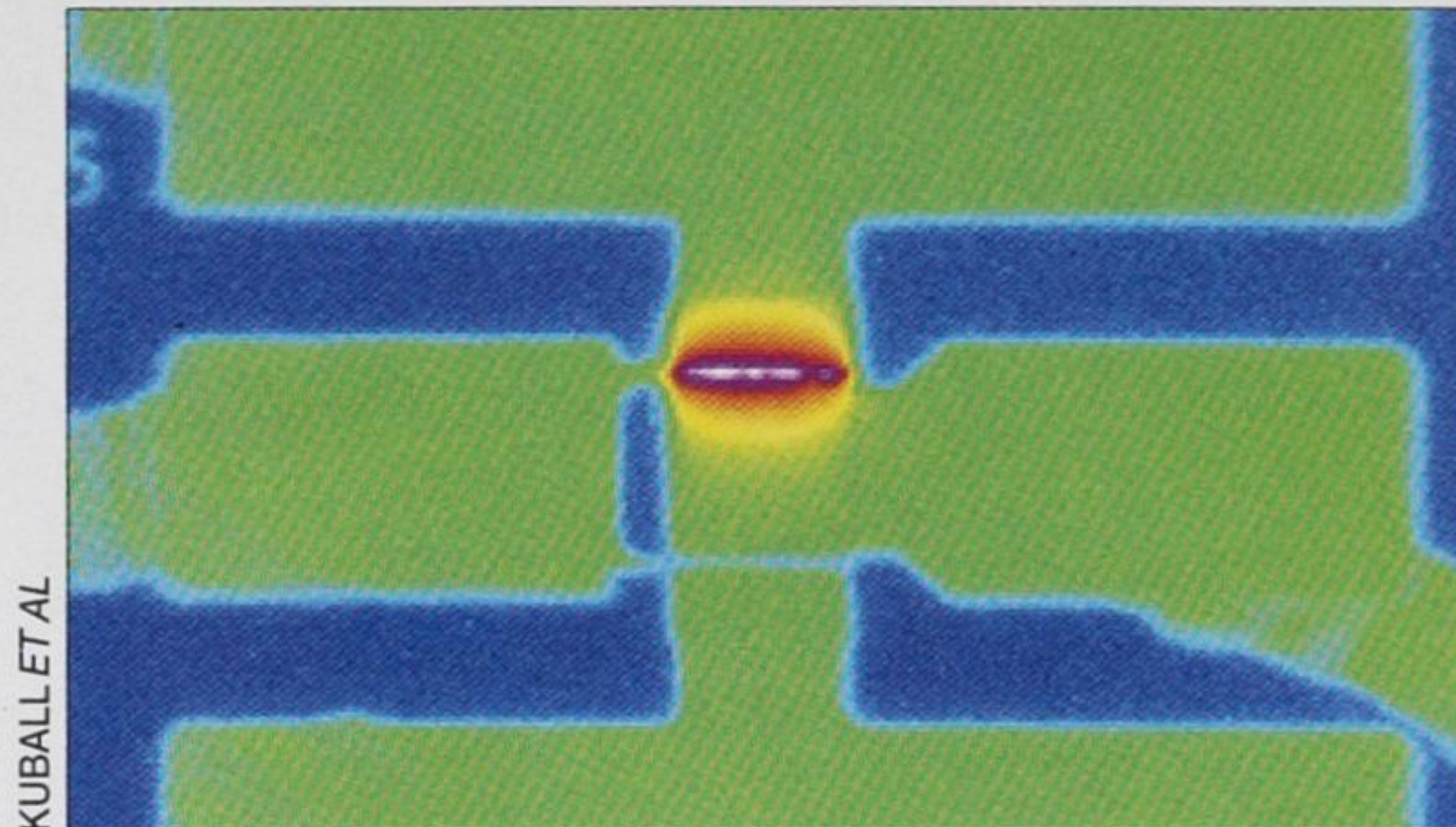
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Three-Fives and Silicon Heterostructures

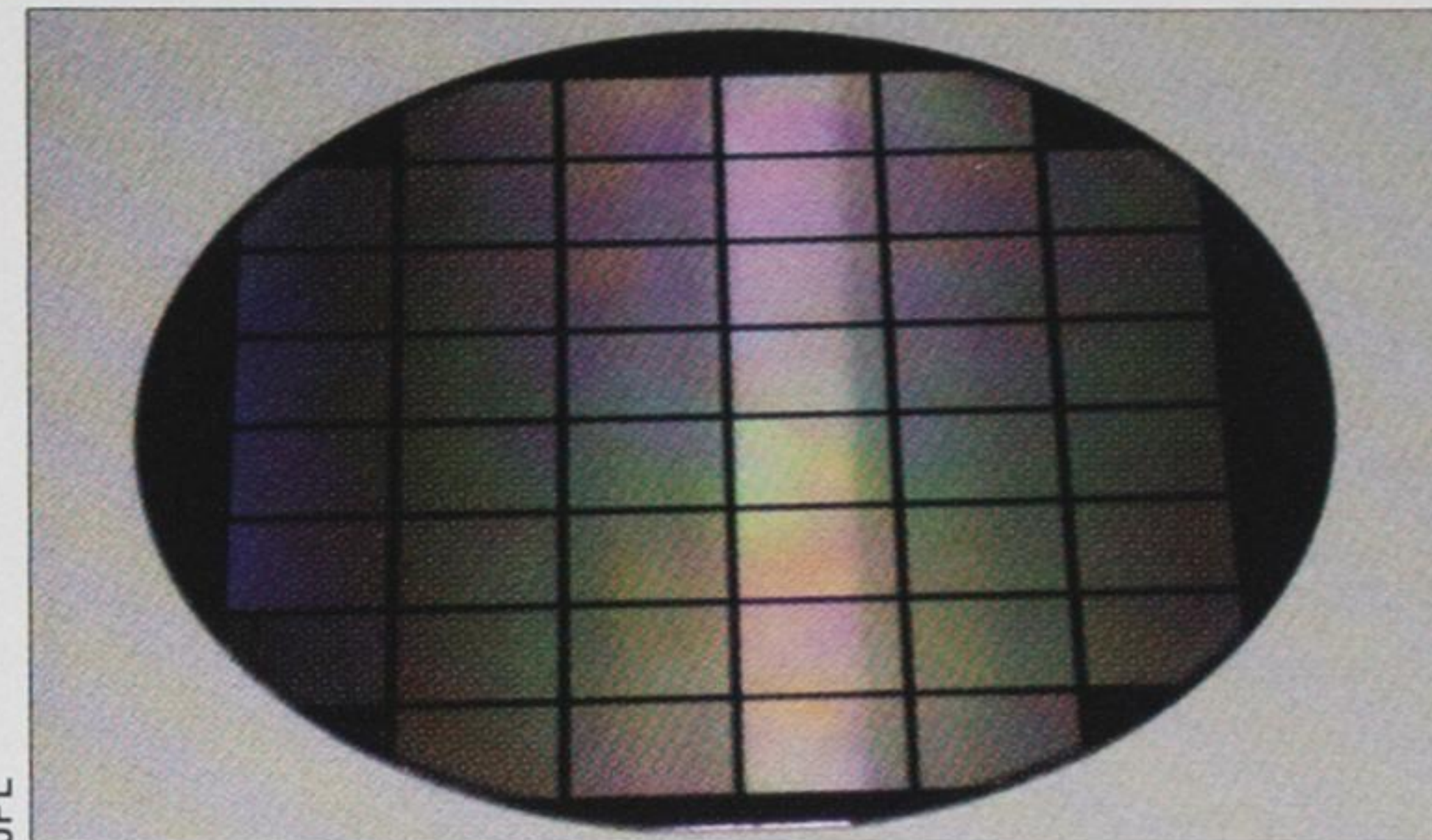
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Hot-spot alert: a combination technique could lead to more reliable GaN HEMTs. **p21**



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COVER STORY: INFRARED DETECTORS

25 Megapixel QWIPs deliver multi-color performance

The NASA Jet Propulsion Laboratory's quantum well infrared photodetector (QWIP) program has advanced from fabricating singleband detectors to imagers with multiple spectral bands. Sarath Gunapala explains why the latest detectors will benefit weapons detection and remote sensing.

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16 IMEC improves GaN HEMTs with ceramic substrates

Mounting HEMTs on AlN ceramic substrates is one technique for improving the thermal management that currently limits the performance of GaN-based RF power electronics. Jo Das and Marianne Germain from the Interuniversity Micro Electronics Center (IMEC) in Belgium outline this approach and the advantages it offers over competing technologies.

21 Complementary techniques expose GaN transistor defects

Integrating an infrared camera into a Raman microscope produces the ideal tool for improving the reliability of GaN HFETs, says Bristol University's Martin Kuball.

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Compound Semiconductor's circulation figures are audited by BPA International

On the cover: Quantum well infrared photodetectors, or QWIPs, that can image in multiple spectral bands promise to help both military and commercial users. The cover image shows electrical connections in the devices. Photo courtesy of NASA's Jet Propulsion Laboratory.

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Editorial

Flying high: Greg Olsen and SUI



For a demonstration of sheer human endeavor, it's difficult to imagine a greater sight than the launch of a rocket destined for outer space.

Just how that eight-minute journey into orbit feels is something that only very few of us will ever discover. But, sporting a wide grin and festooned with a Sensors Unlimited (SUI) badge, it's a feeling that Greg Olsen is now very familiar with.

The founder of Epitaxx and InGaAs camera specialist SUI, Olsen has been just as successful in his business dealings as he was in technological development. Through the timely sale of these successful ventures, Olsen has been able to fund his trip to the International Space Station, thus fulfilling the boyhood dream of millions.

And while Olsen flies as high as humanly possible, things are looking almost as good for SUI. In a deal that will cut Olsen's direct ties with the company, SUI will be acquired by Goodrich for \$60 million in cash. Under the wing of the Big Aerospace firm (fiscal year sales of \$5 billion or so) – where it will become part of Goodrich's optical and space systems group and be in direct contact with a key customer – SUI should be able to grow ever more quickly.

And SUI has plenty of other reasons to be cheerful. In the past month, it has delivered high-sensitivity InGaAs cameras to the US Army and secured a \$4.5 million research contract with DARPA's Microsystems Technology Office.

Olsen won't be involved with SUI for much longer – at least, not directly – but the success of the company was instrumental in enabling him to join the select band of individuals to experience the thrill of space travel.

At a reputed personal cost of \$20 million, that thrill is far from cheap. But just check out that pre-launch face on p5 – I'll bet it was worth every penny.

Michael Hatcher

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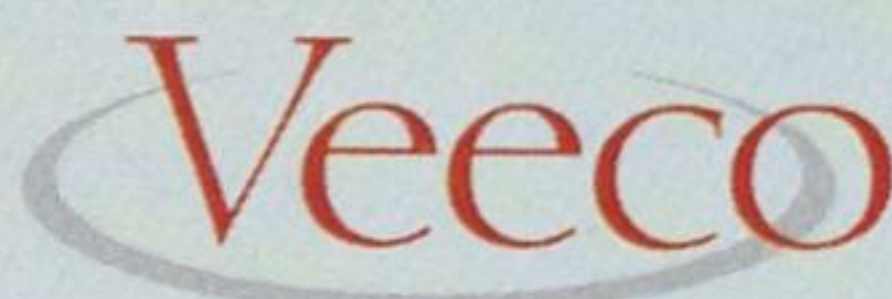
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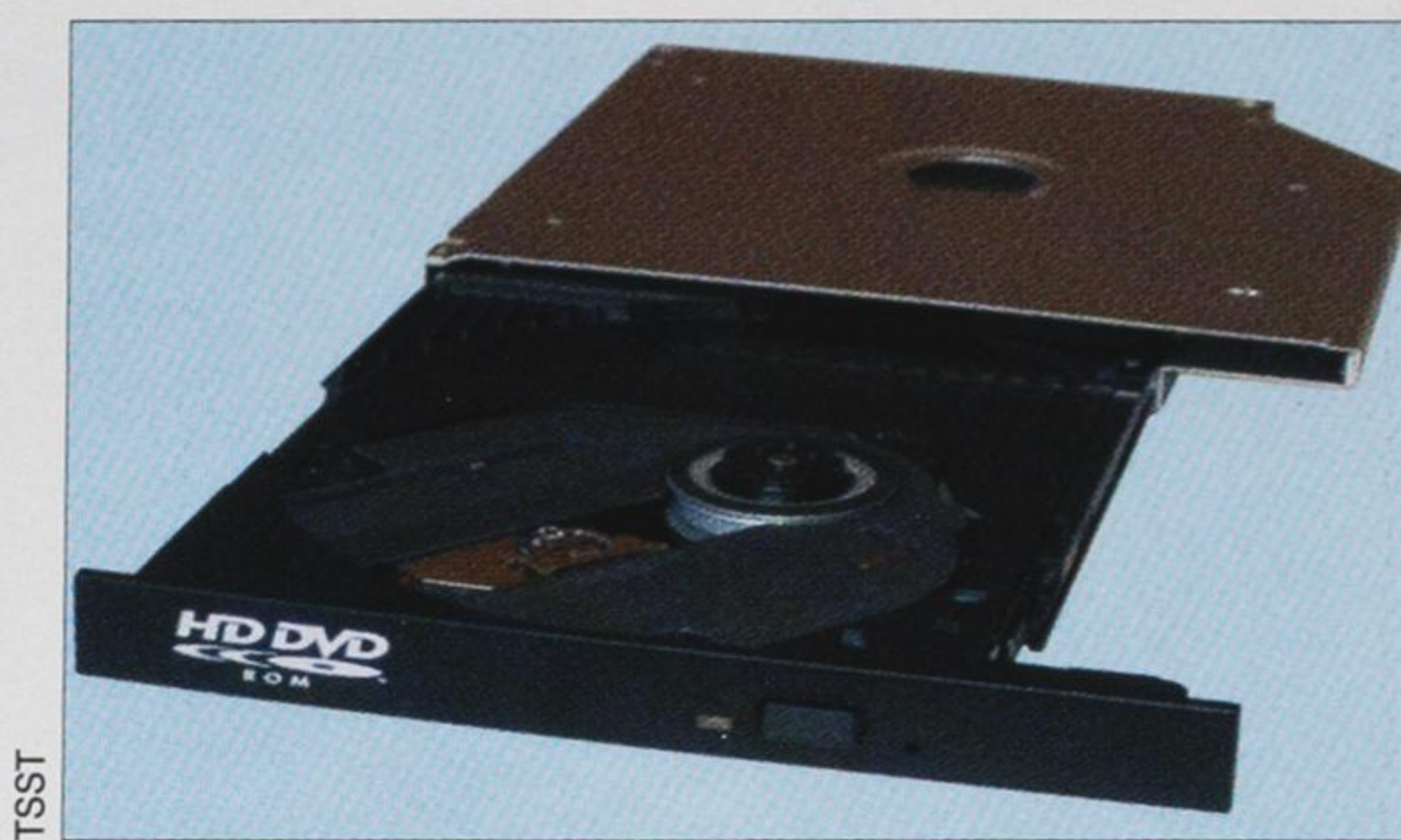
IT giants join Toshiba as HD DVD ramps

Intel and Microsoft have joined the HD DVD Promotion Group, giving huge industrial support to the switch to data storage technology based on GaN blue-violet laser diodes.

The HD (high-definition) DVD group's founding companies, which include the laser manufacturers Toshiba, NEC and Sanyo, said that the heavyweight backing from two of the world's key IT firms would speed up the penetration of HD DVD into the market.

As the GaN-based technology begins to become a commercial reality, the supporters of HD DVD are in competition with the Blu-ray Disc venture led by Sony and Matsushita. The two camps recently attempted to settle on a unified format, but talks broke down without agreement.

"The capacity for volume production of HD DVD discs is already in place," said Shiroharu Kawasaki, the CEO of Memory



Designed for use in notebook PCs, this is the first slimline HD DVD drive from Toshiba Samsung Storage Technology. It features a GaN laser diode and conventional laser technology for standard DVD and CD use.

Tech, a key partner in the HD DVD group. The company will manufacture the HD discs that are read using a blue-violet laser.

Hisashi Yamada, who represents Toshiba

at the DVD Forum, added: "Hollywood studios are now working on preparation of DVD content, and I look forward to the near future, when people everywhere will be able to enjoy high-definition images on TV and their PC."

The HD DVD disc format uses an identical structure to that of current DVD technology, something that its backers see as a key advantage compared with Blu-ray. Meanwhile, Toshiba recently developed a dual-layer recordable HD DVD disc that can hold up to 30 GB of data.

And that's not all. Toshiba's joint venture, Toshiba Samsung Storage Technology, has just released the first slimline HD DVD drive designed for use in notebook PCs. The drive can read high-density data using a blue-violet laser diode, and it also incorporates conventional laser technology to read and write both DVDs and CDs.

Cree leads 100 mm SiC substrate launch

by Richard Stevenson in Pittsburgh, PA

Cree announced the commercial launch of its 100 mm (4 inch) n-type SiC substrates and epitaxy material at the International Conference on Silicon Carbide and Related Materials (ICSCRM) in Pittsburgh, PA, in September.

The Durham, NC, materials supplier and chip manufacturer developed the 4 inch substrate through a program with the Air Force Research Laboratory. Previously it offered 3 inch SiC material as standard.

According to Cree, the larger format could enable the production of twice as many devices per wafer compared with the 3 inch material.

"Cree's launch of 4 inch substrates and epitaxy establishes that SiC can be a high-volume, production-oriented material within the semiconductor industry," said the general manager of Cree Materials, Lyn Rockas. "It demonstrates Cree's technology and commitment to develop material products targeted to the needs of the commercial market."

The company's 100 mm substrates will soon face competition from rivals produced by Intrinsic Semiconductor. These will be launched during the first quarter of 2006.

At ICSCRM, Cengiz Balkas, Intrinsic's CEO, told delegates that the company has produced 100 mm wafers of both the 4H and 6H polytype, with micropipe densities as low as 1 cm^{-2} and 30 cm^{-2} , respectively.

Delegates were also shown images of 3 inch micropipe-free substrates. "More than just a yield improvement, micropipe-free substrates introduce a new category of product, opening up new device possibilities," said Balkas.

"Large-area devices that switch 100 A or more cannot be manufactured cost effectively even with defect densities as low as one micropipe per square centimeter. Zero micropipe material will thus be critical to the commercial availability of next-generation high-power devices for electric utility controls, hybrid electric vehicles, and other power chip markets," he said.

Caracal, a manufacturer of SiC wafers located in Ford City, PA, used the Pittsburgh venue to announce itself to the industry. The company, which has 12 staff, a 10 000 ft² facility and has raised over \$9 million, has been operating in stealth mode since early 2004 but says that it will soon begin commercial shipments. Caracal claims that because it uses source materials based on gases rather than powders to produce substrates, it can cut the cost of making SiC wafers by almost 90%.

The start-up will offer semi-insulating and conducting SiC wafers in both 6H and 4H polytypes, with or without a SiC-based epitaxial layer. Caracal has already produced 100 mm wafers using its technology, and expects to begin commercial shipments before the end of this year.



Greg Olsen, the founder of Epitaxx and InGaAs image sensor manufacturer Sensors Unlimited, was aboard the International Space Station (ISS) as *Compound Semiconductor* went to press. He blasted off from the Baikonur Cosmodrome in Kazakhstan on September 30 in a Soyuz rocket on a 10-day trip. "It's really nice here," Olsen said in a live broadcast from the ISS. "It's nice and roomy."

Nakamura team promises brighter LEDs with non-polar GaN structures

A research program headed by compound semiconductor pioneer Shuji Nakamura has developed thin films based on non-polar and semi-polar GaN.

According to Nakamura, who revealed the development at a press conference in Tokyo, the novel structures could result in much brighter LEDs and more reliable lasers, while GaN transistor technology could also benefit.

Conventional GaN devices, such as the high-brightness (HB) LEDs manufactured by Nichia, Lumileds and others, are typically deposited as thin-film structures with a polar orientation. This is due to the symmetry of the hexagonal GaN crystal, and means that conventional devices have strong built-in electric fields (see box).

“[This] puts a fundamental limitation on device performance,” said Nakamura. “Such fields interfere with the proper recombination of electrons and holes to make light.”

Under a Japanese Science and Technology Agency (JST) project, researchers at the University of Tsukuba, Tokyo University of Science, and the University of California Santa Barbara (UCSB) have developed GaN semiconductors with a different crystal symmetry.

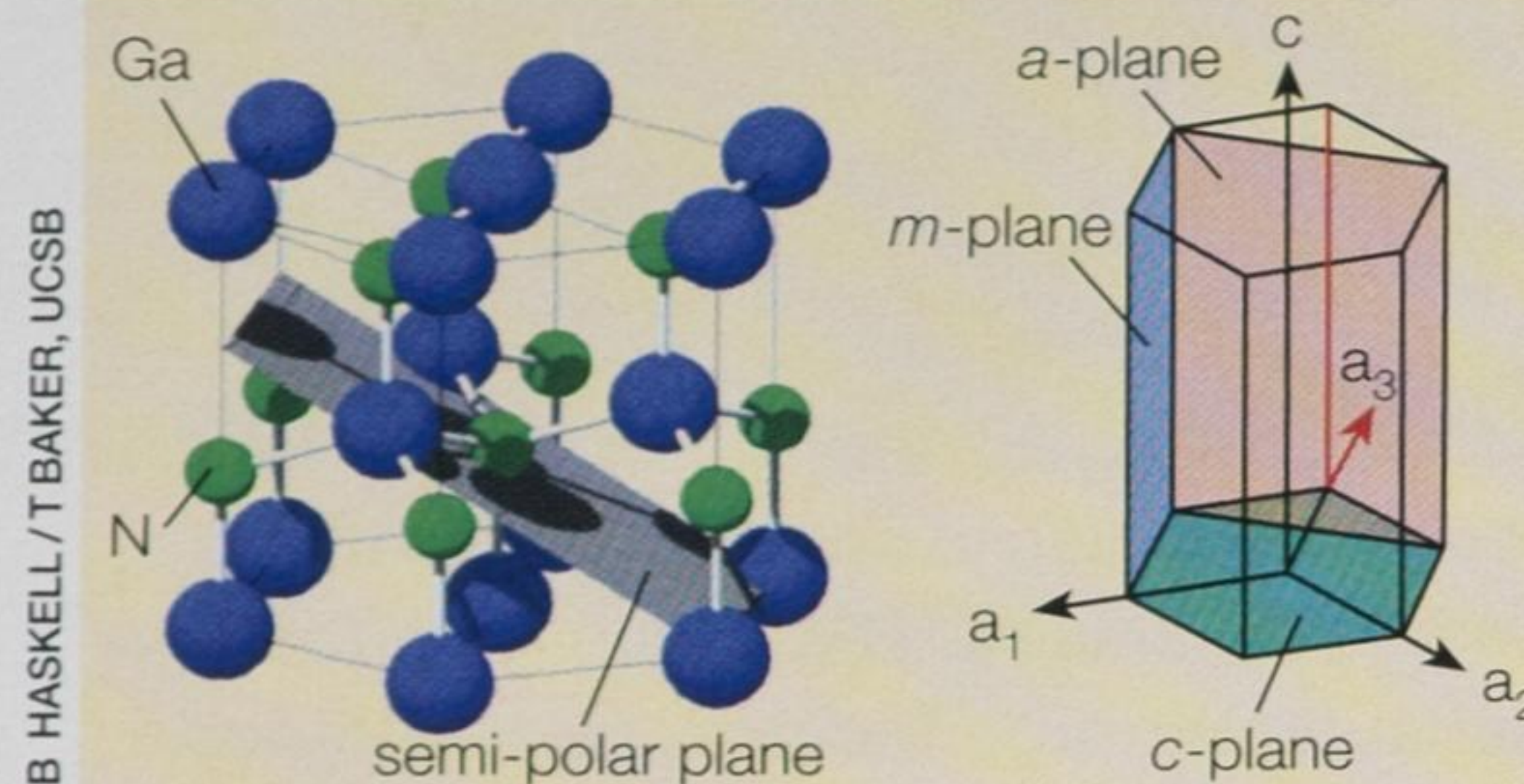
Changing symmetry

In structures that feature the novel crystal orientation, electron-hole recombination should be more efficient, leading to brighter blue, green and white LEDs. “There are indications that we’re going to see multiple-times improvement in light output, once device layers have been further optimized,” said Paul Fini, one of the UCSB researchers.

This is partly because of a lower resistance in the p-doped layer of the new structures – traditionally the most difficult GaN layer to optimize. The high resistance in this layer of conventional GaN devices limits LED performance owing to the excess heat that it creates. With the non-polar crystal, p-type conductivity is improved, which should reduce heating effects and result in more reliable, longer-lasting diodes.

According to Nakamura, there are indications that the LED efficiency and output power saturate at much higher drive currents than is typical for conventional polar LEDs. This suggests a potential use for the devices in demand-

The hexagonal GaN crystal



UCSB’s Paul Fini likens the GaN crystal structure to a hexagonal prism: “The ends are the polar c-plane, while the prism ‘sidewalls’, which are perpendicular to the c-plane, are the non-polar a-planes and m-planes. Any ‘inclined’ planes in between are called semi-polar planes.”

As the diagram shows, atoms in a GaN crystal stack up in hexagonal layers of either gallium or nitrogen. Because nitrogen is much more electronegative than gallium, a relatively strong electric field is generated perpendicular to these atomic layers. In contrast, says Fini, the non-polar a-plane and m-plane have an equal number of gallium and nitrogen atoms and therefore no net electric field is generated.

Semi-polar planes in quantum well structures have an inclined orientation with respect to the c-plane, m-plane or a-plane. The electric field is weaker than “conventional” polar GaN used in commercial devices.

ing applications such as car headlamps.

In addition, the light emitted by the non-polar and semi-polar structures is polarized. This could benefit LCD backlighting applications, since displays based on the technology normally require a polarizing filter. Designers could eliminate the filter, possibly yielding almost twice as much usable light.

“Until recent work at UCSB, few, if any, groups could grow smooth, planar non-polar or semi-polar GaN films,” Fini explained. “It turns out that the growth conditions needed to make these smooth films can be quite different to those typical for conventional (polar) c-plane films.”

Fini and his colleagues at UCSB have used all three major growth techniques – MOCVD,

MBE and hydride vapor-phase epitaxy (HVPE) – to make device-quality non-polar and semi-polar films. “For thick films of more than 10 μm , HVPE is superior by far, since its growth rate can be over 100 μm per hour,” Fini said. “This lends itself well to the development of free-standing GaN substrates.”

LEDs have been fabricated on both non-polar and semi-polar crystal planes, and Fini told *Compound Semiconductor* that there was no difference between the two in terms of the difficulty of device fabrication. “We haven’t fabricated a non-polar or semi-polar laser, but that’s coming soon,” he predicted.

All of the novel films have been grown on various orientations of sapphire, SiC and LiAlO_2 . “To get non-polar GaN we can use r-plane sapphire, and to get semi-polar GaN we use m-plane sapphire,” said Fini.

Devices based on the novel crystals could quickly be commercialized, he added. “The film quality is good enough that test structures can be regrown for evaluation. In the past, non-polar and semi-polar films were so rough that they couldn’t be used for devices at all.”

“We believe that non-polar and semi-polar devices will see quite rapid commercialization, since although their optimal growth conditions are different to conventional c-plane devices, they’re not hard to find,” Fini added. “After device film growth has been optimized, all subsequent device processing would be nearly identical to conventional devices.”

If commercialization does progress as Fini predicts, it will be the JST and UCSB that control its deployment, as the two entities jointly own the intellectual property relating to the novel technology.

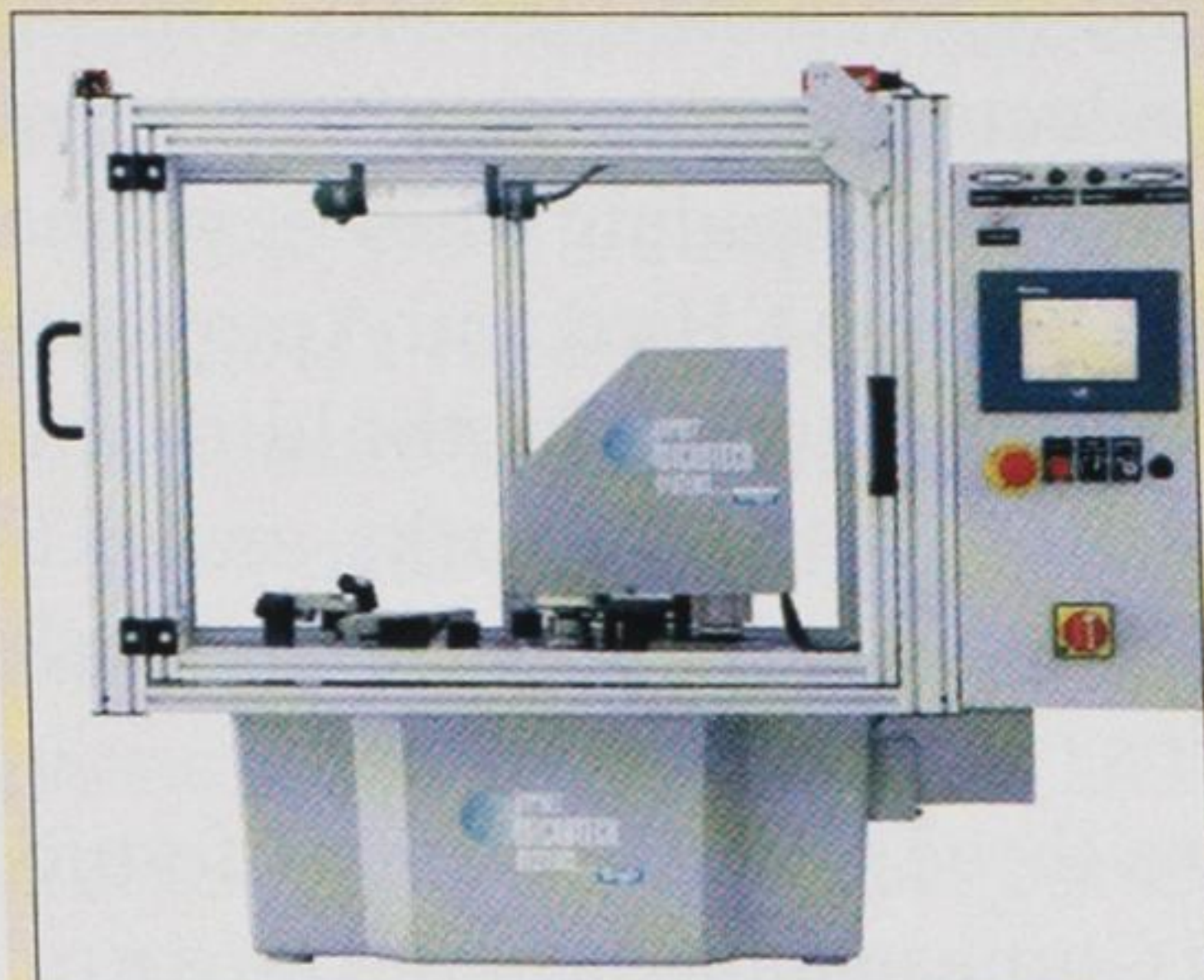
Although the initial benefits are most likely to be seen in LED applications, the non-polar structures have advantages that could be exploited in the manufacture of GaN lasers and in some microelectronic devices. Lasers grown in the new orientation will require much lower defect densities than comparable LED structures, but Fini believes that they should exhibit a lower threshold current and better efficiency than c-plane lasers. At his Tokyo press conference, Nakamura added that the peak wavelength shift of non-polar GaN LEDs with increasing drive current is much less prevalent than in conventional devices.

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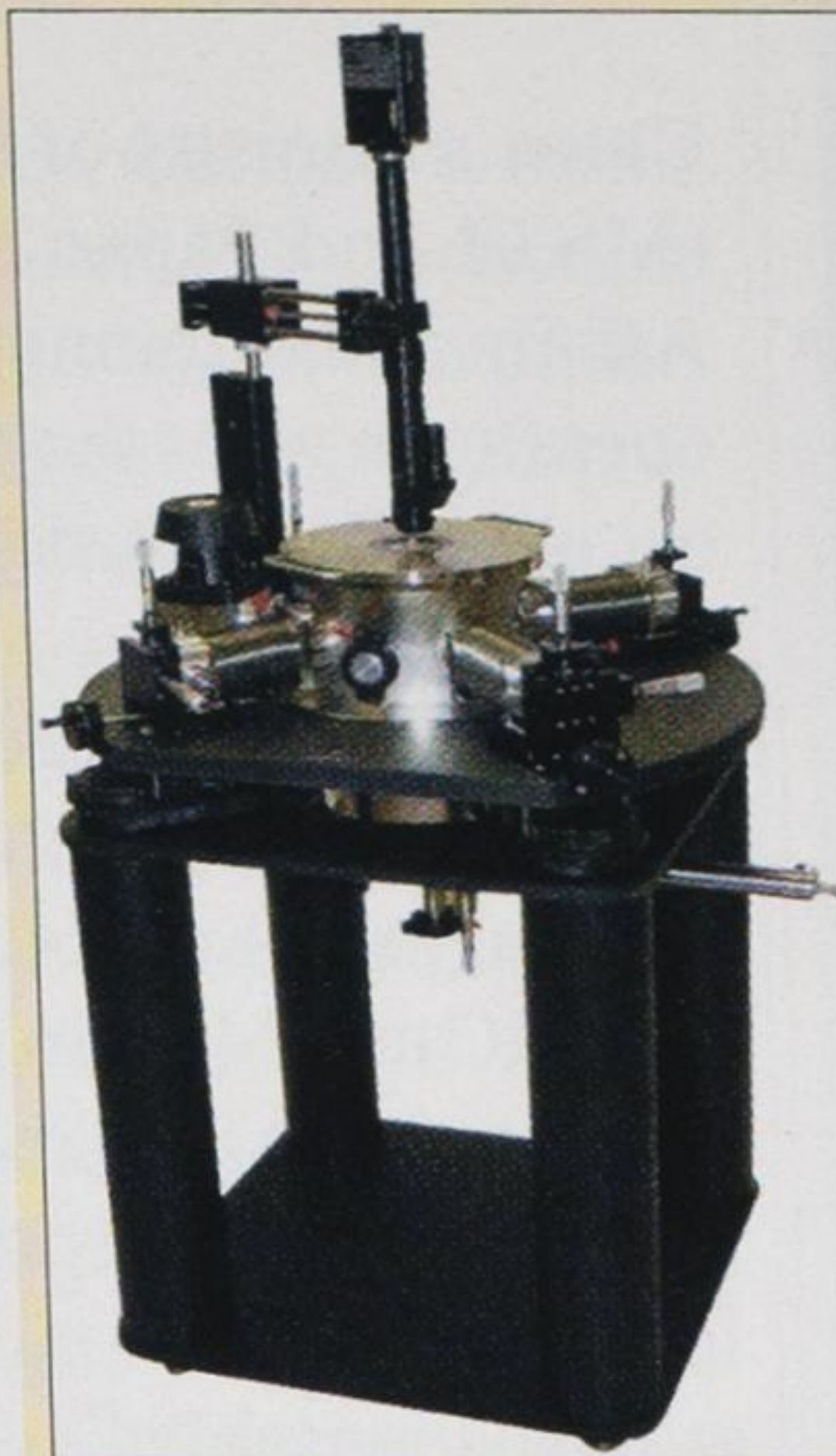
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The leading European manufacturer of high-quality SiC substrates for power electronic, RF and optoelectronic applications has achieved a further milestone in its product portfolio. After recently presenting the commercial availability of 2 inch SI-SiC-substrates at the ICSCRM in Pittsburgh, SiCrystal now announces the availability of high-quality 3 inch semi-insulating-SiC-substrates for Q1/2006. According to the Germany-based company these new, premium quality and economically priced products provide significant performance



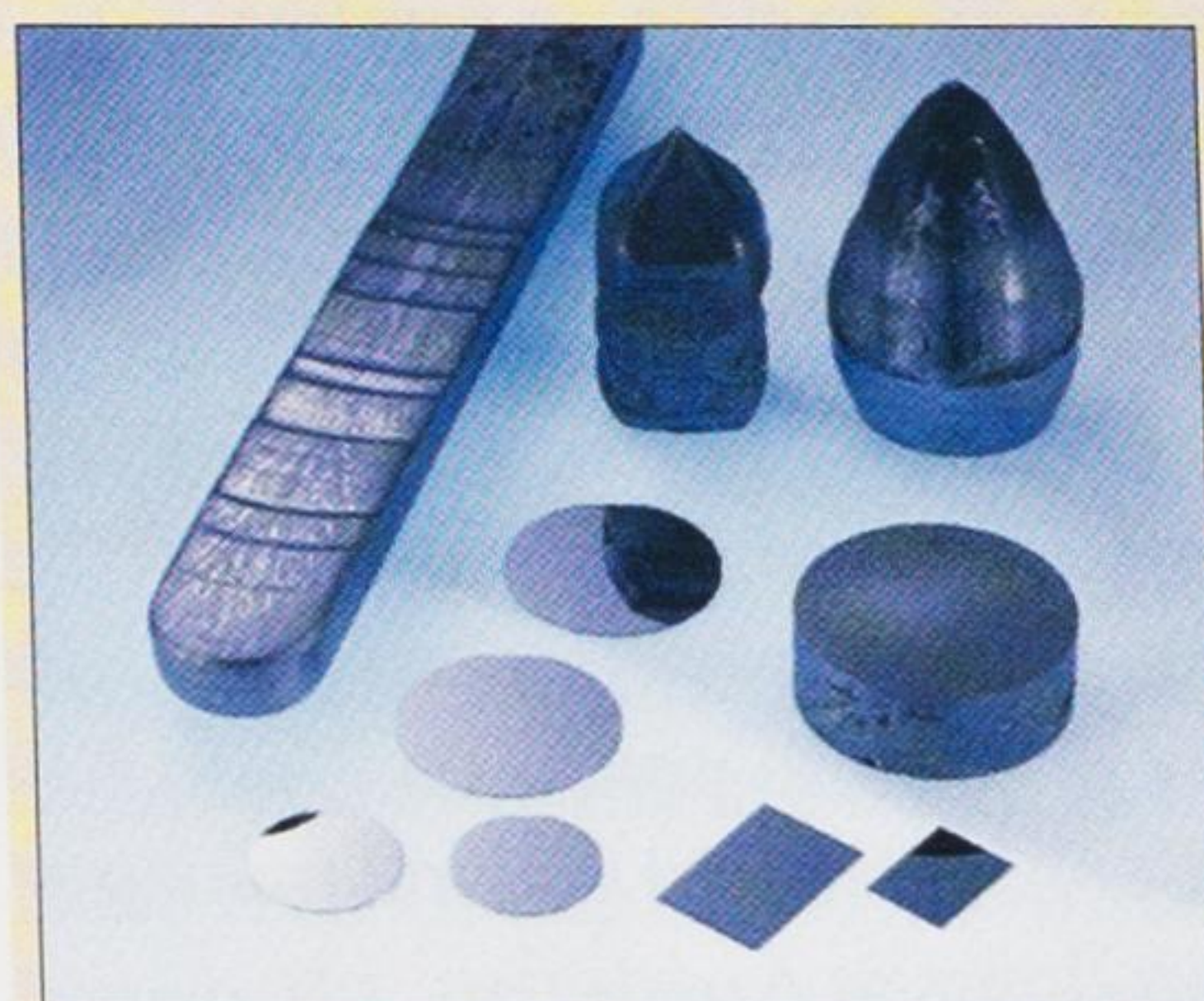
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Japan and China sign '4G' co-operation deal

China's Ministry of Science and Technology (MST) and Japan's Ministry of Internal Affairs and Communications (MIC) will co-operate on what they call fourth-generation, or "beyond the third generation" (B3G), technologies.

"B3G systems are expected to play an especially significant role as a global broadband system, to be realized by around 2010," said the MIC and MST in a joint statement.

"In order to realize B3G at the earliest possible stage and promote its development, international harmonization and co-operation are indispensable."

That co-operation will involve high-level meetings at least once a year to establish the focus of joint research and development work and approaches to standardization. This will include joint technological symposia.

Those symposia will involve experts from academia, government and industry, and could also involve participants from Korea.

According to China's MST, there are now

more than 360 million cell-phone subscribers in the country, indicating an astonishing rate of growth over the past few years.

In terms of the current breakdown of components found in Chinese handsets, analyst firm Semiconductor Insights found in a recent tear-down analysis of leading Chinese phone brands such as Ningbo Bird and Amoi that Philips has a very strong foothold in the power amplifier slot. Skyworks and RF Micro Devices appeared to be neck-and-neck behind Philips.

"There are three key differences found between the Chinese handsets and those of North America, Europe and Japan," said Gregory Quirk, a systems analyst for Semiconductor Insights.

He explained: "The number of different component vendors used in Chinese handset designs is greater; larger vendors have fewer design wins; and no single company seems to have secured the supply chain, leaving the marketplace open to all."

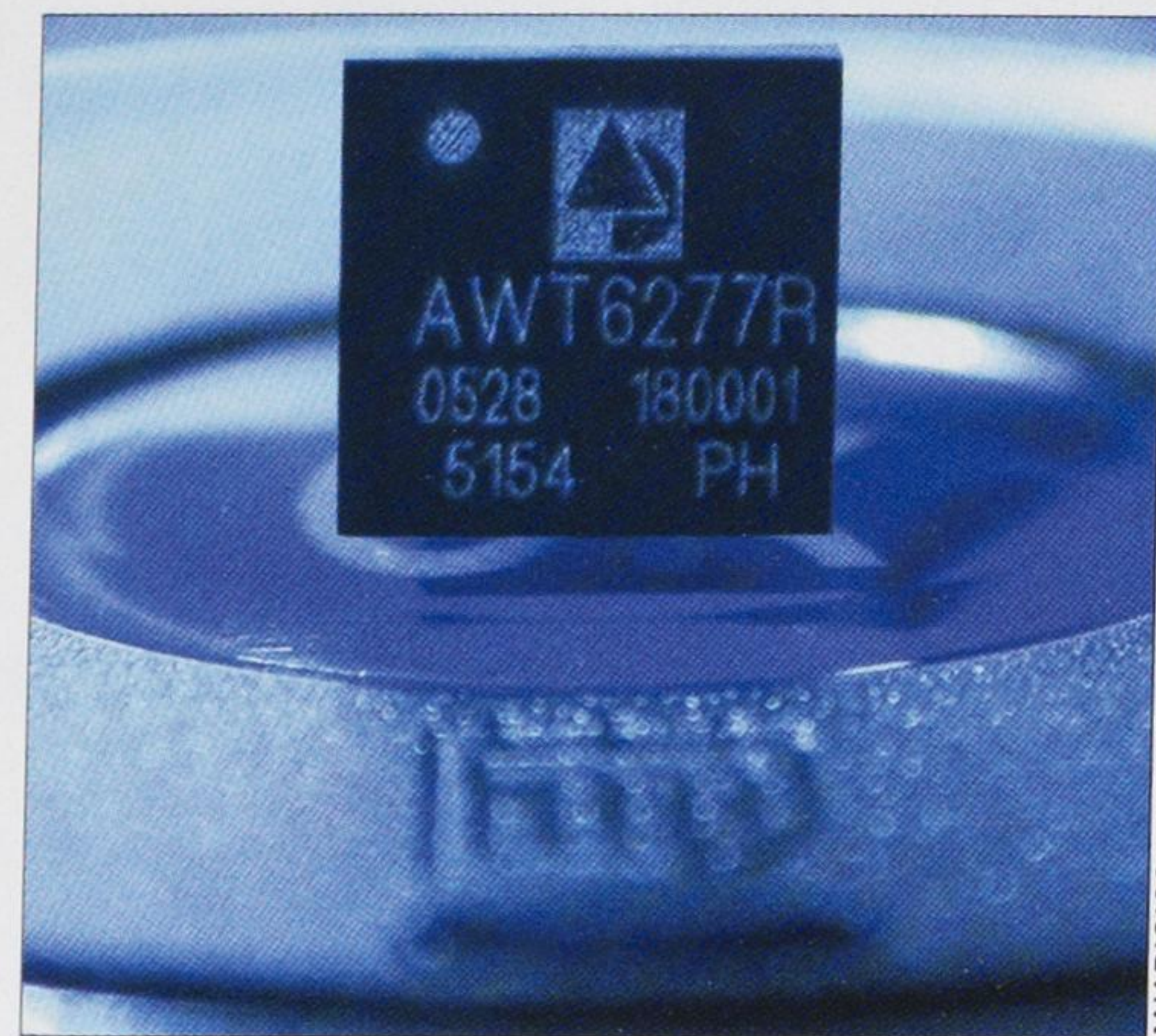
Anadigics ups guidance on strong sales

Stronger-than-expected GSM product sales have prompted RFIC manufacturer Anadigics to raise its guidance for its latest quarter.

The Warren, NJ, company now expects to post \$28-\$29 million in net sales, which would represent a 10% improvement on the previous revenue estimate and a sequential growth rate of around 20%.

Anadigics has also introduced a raft of new products for use in high-end handsets, including the latest generation of its High-Efficiency at Low Power (HELP) power amplifiers (PAs) for CDMA applications. These new PAs feature the company's exclusive InGaP integration technology, which produces bipolar and FET structures on the same die. The so-called "HELP2" PAs are said to achieve industry-leading efficiency across different output power levels, specifically at low-range and mid-range powers where the PA typically operates.

Also using the integration technology are three new wideband-CDMA (W-CDMA) PAs designed for the latest 3G wireless protocol, known as high-speed downlink packet access (HSDPA), which were recently released. "The



Having launched a raft of new products designed for the more advanced handsets, Anadigics is hoping to gain on market leaders RFMD and Skyworks.

migration of 3G W-CDMA technology to HSDPA enables a new class of wideband services for consumers while simultaneously raising the bar on the power consumption requirements of mobile products," said Ali Khatibzadeh, senior VP and general manager of wireless products at Anadigics.

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Korean chip manufacturers ramp up HB LED capacity

Several MOCVD systems from Aixtron are set to boost the manufacturing capacity of high-brightness (HB) LEDs in Korea. The Aachen-based firm says that LED chip makers in the country have recently increased their activity and gained market share in high-end products.

One system – a repeat order for an AIX 2600G3HT model – will be shipped to Samsung Electro Mechanics near Seoul. Samsung is the world's third-biggest mobile phone manufacturer, and it also delivers mobile-phone subassemblies, such as LED flashlights and keypad LEDs, to other companies.

Another order has been placed by the Korea Photonics Technology Institute (KOPTI), located in Gwangju. The city is embarking on

a project, called LED Valley, that aims to make it one of the most innovative LED production centers in the world – as well as one of the globe's top five photonics clusters – by 2010.

KOPTI has ordered two MOCVD systems: a 19 × 2 inch Thomas Swan Close Coupled Showerhead (CCS) reactor for the development and production of GaN LEDs; and an 18 × 3 inch 2600G3 reactor for the development and manufacture of GaAs-based UHB-LEDs.

Also increasing production capacity is LED wafer and chip supplier EpiValley, which has placed an order for two more Thomas Swan CCS reactors (each with 19 × 2 inch wafer capacity). The company supplies fast-growing LED chipmakers in Korea and Taiwan.

German lighting supplier Hella unveiled this prototype all-LED headlamp at the Frankfurt Motor Show in September. The headlamp, which features the first dynamic cornering light to use solid-state technology, uses a sophisticated array of plastic lenses to form a low beam, a high beam, and a daytime running light.

Hella, whose designers have developed the headlamp with the Japanese LED supplier Stanley, says that by 2008 the output from the LED prototype will equal that of a xenon headlamp – if white LED output continues to increase as expected.

"Hella is taking further innovative steps towards full-LED headlamp production by 2008 or 2009," said the company.



Cree reports 86 lm XLamp LED in lab test

By Tim Whitaker

Cree Lighting claims that its XLamp 7090 LEDs have demonstrated a maximum luminous flux of 86 lm and an efficacy of 70 lm/W at 350 mA in a laboratory development.

It says that this represents a 43% increase in brightness compared with the maximum luminous flux of its white XLamp 7090 power LEDs that are now in production. This suggests a maximum rating of 60 lm for production XLamp 7090s, although the datasheet on Cree's website quotes a typical value of 45 lm.

Steve Johnson, who heads the Lighting Research Group at the Lawrence Berkeley National Laboratory, said Cree's result indi-

cates that the LED industry is at least two years closer than previously predicted to achieving the "holy grail" output of 150 lm/W.

"Cree's [development] means the LED industry is advancing brightness at a far greater pace than anticipated," said Johnson.

"The announcement is significant because we achieved these results with our standard XLamp package," added Cree's Norbert Hiller. "[This] indicates that power LEDs are rapidly moving up the performance curve similar to advances we continue to make with small LED chips."

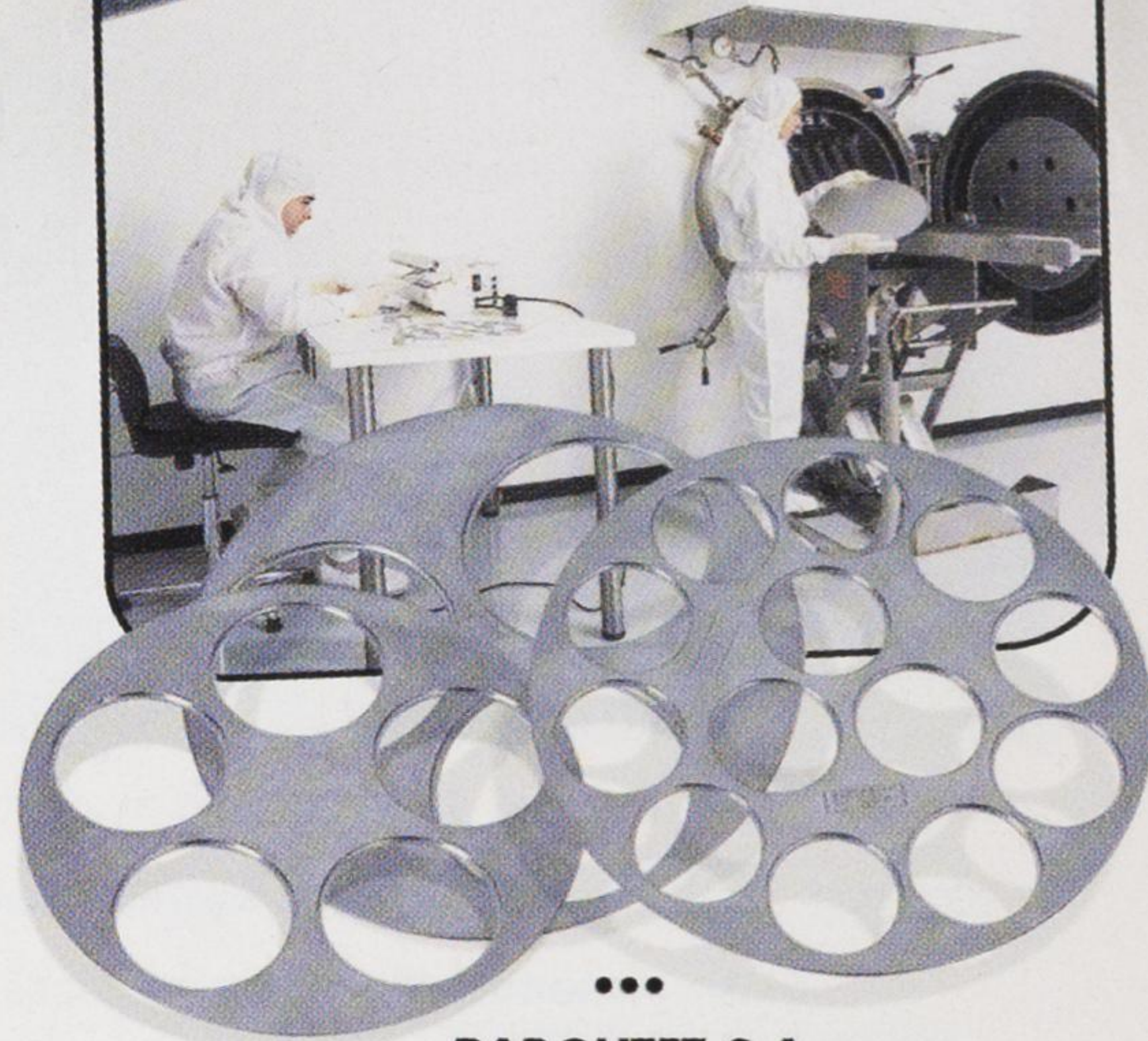
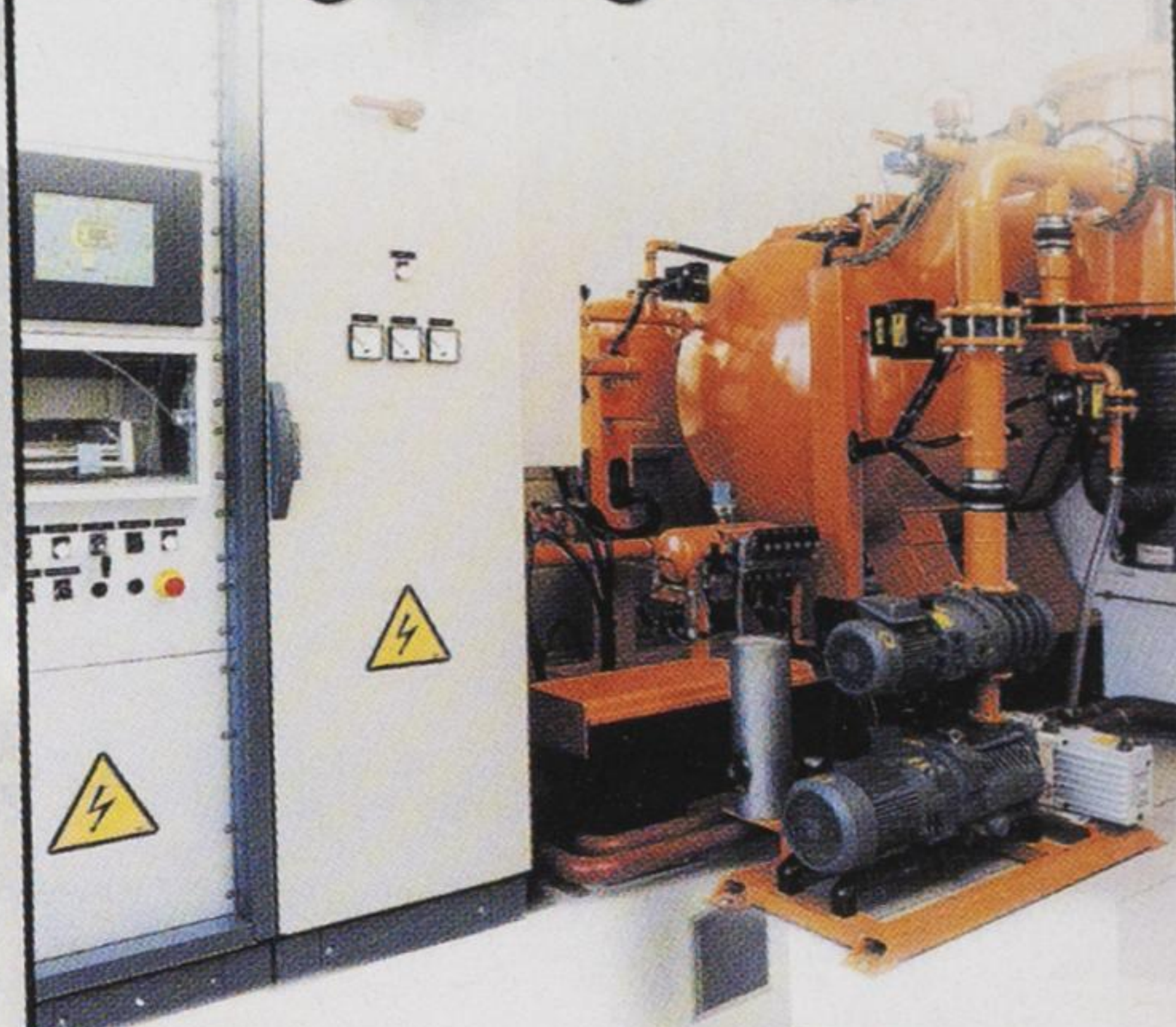
Tim Whitaker is editor of LEDs Magazine.

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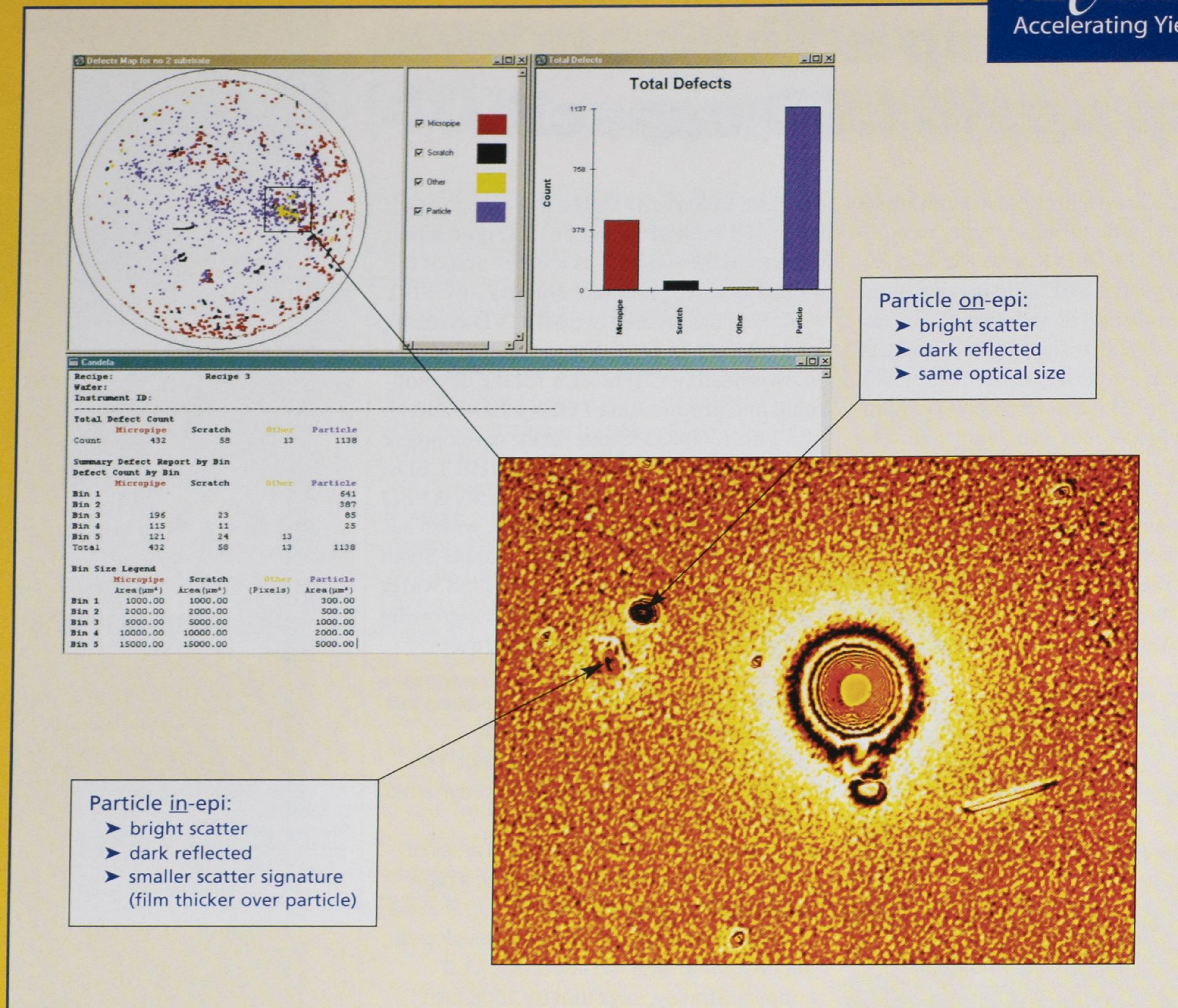


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WiMAX firms line up for Nitronex GaN transistors

Nitronex, the Raleigh, NC, company developing GaN-based power transistors, has released its first commercial products.

The first family of GaN-on-silicon devices comprises 10 W and 50 W power transistors targeted at broadband wireless access infrastructure. The Nitronex transistors support WiMAX applications operating in the 2.5 GHz and 3.5 GHz frequency bands, and are the first commercial products to be manufactured using the company's "SIGANTIC" platform.

"The release of these products marks an important milestone in the semiconductor industry," said Chris Rauh, the company's VP of sales and marketing. "We are proud of this 'first-of-its-kind' accomplishment."

Crucially, Nitronex already has a customer lined up and ready to deploy the devices. Korea's RFHIC Company plans to use the 50 W version, known as the NPT35050, in a forthcoming line of high-power modules aimed at WiMAX and other applications.

"We need to deliver 10 W of average power to meet our customers' latest needs," said David Cho from RFHIC. "We believe that GaN-based RF power transistors from Nitronex are key to a number of [our] markets."

A number of other customers are thought to be evaluating the Nitronex devices currently, while further products in the family are set to be introduced in the near future. These will include transistors operating at the higher frequency of 5.8 GHz, and are planned for introduction next year.

With sample kits now available for \$950, Nitronex says that initial shipments of the NPT35050 part will begin shortly. All four of its GaN-on-silicon products are expected to be released to production in March 2006.

Manufacturing the GaN devices on 4-inch silicon wafers allows Nitronex to use standard packaging, test and assembly equipment, resulting in faster qualifications and lowering overall device cost.

Four-chip FET shows record output power

Japanese chip manufacturer Toshiba says that it has developed a GaN-based field-effect transistor (FET) that emits a record 174 W at 6 GHz, a key frequency band for broadband wireless communication protocols such as WiMAX.

Toshiba described details of the breakthrough at last month's International Conference on Solid State Devices and Materials (SSDM) held in Kobe, Japan. The company says that the high power output is the result of an optimized epitaxial structure.

The HEMT process employed features

improvements in AlGaN and GaN layer thicknesses and doping levels, as well as a change in the distance between the source and drain. Combined with a new gate electrode structure, the various advances cut gate leakage current by 97% compared with conventional technology. A stepper exposure tool is now being used in the lithography stage.

The FET consists of four GaN chips, which is said to minimize heating effects that are detrimental to device performance. Following further refinements of the transistors, Toshiba plans to release samples next year.

Diamond firm claims Schottky breakthrough

A company in the UK says that it has fabricated a Schottky-barrier diode based on diamond that operates at 1700 V and handles more than 10 A cm⁻².

Element Six made the diode in collaboration with power electronics specialist Dynex Semiconductors and Cambridge University's engineering department. It says diamond can compete with devices based on wide-bandgap compound materials such as SiC and GaN.

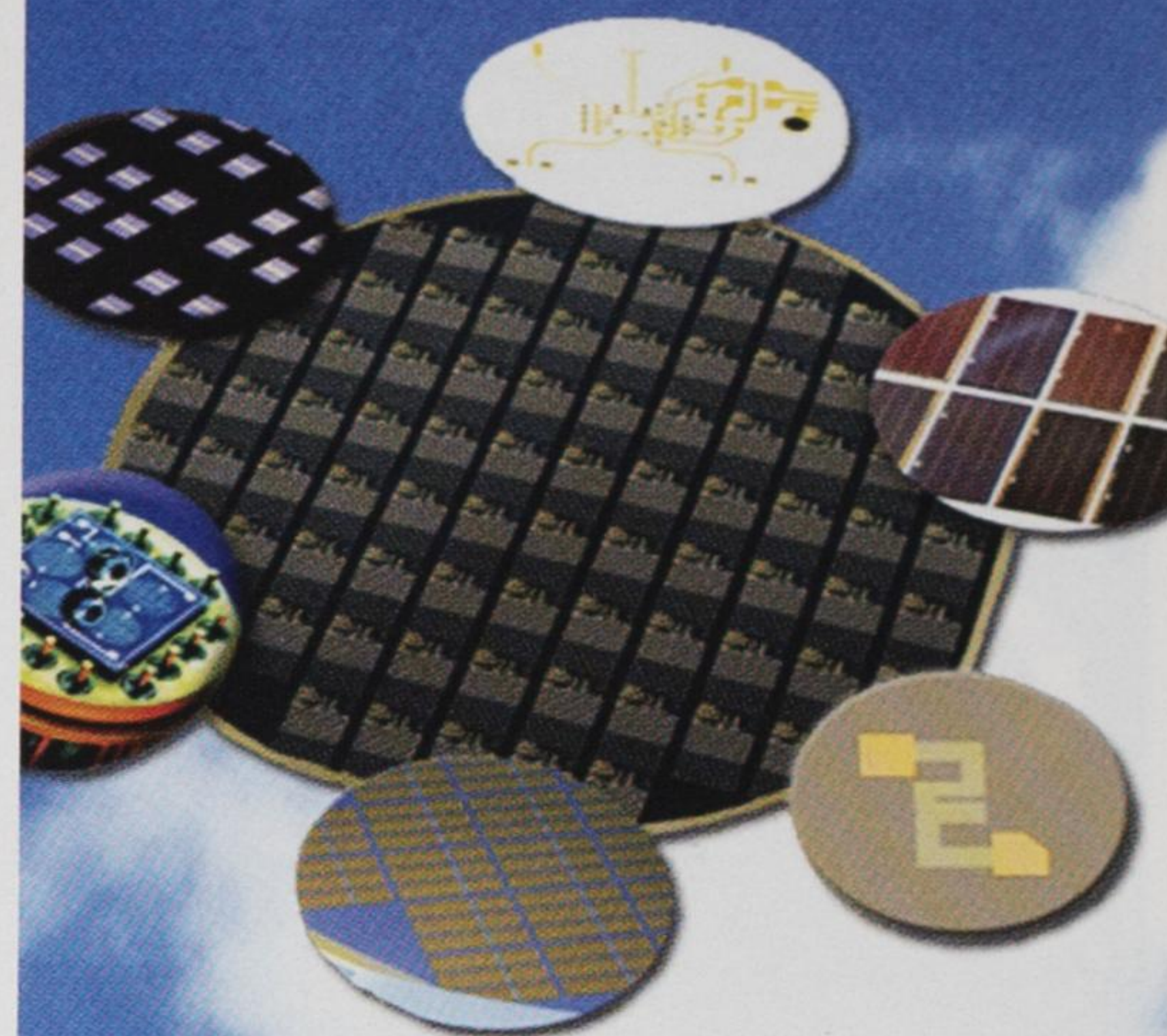
"High-voltage devices for advanced appli-

cations including traction motor control and power distribution will need high-performance materials," said the firm in a statement.

"Element Six has now demonstrated that there is an opportunity for diamond technology to 'leapfrog' over SiC by fabricating single-crystal CVD diamond Schottky diodes."

Element Six research manager Steve Coe said that the company was working on a number of other electronic devices: "Schottky diodes will be the first of many new products."

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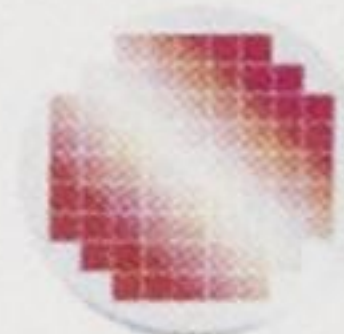
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Rajiv K. Agarwal, Ph.D.

Lead Research Engineer

Q

I am experiencing high n type background doping levels in my MOCVD process when I grow GaAs and AlGaAs devices. I think the problem is in the arsine I use. I'm buying the best grade available. What can I do?

A

Higher background levels of n type dopants in GaAs and AlGaAs structures are caused by trace levels of germanium, silicon and sulfur species present in the arsine. As customer applications evolve, the purity requirements for arsine must as well. Until recently, background doping levels of $10^{15}/\text{cm}^3$ were considered acceptable in most applications. In general, most currently available high-purity grades of arsine can satisfy these requirements. However, process changes and demand for more sophisticated devices have resulted in the need for lower background doping levels. To address these more stringent requirements, Air Products is introducing Megabit™ III arsine, our purest grade available. Our new Megabit III arsine has significantly reduced the amounts of germanium, silicon and sulfur species. Testing done at an independent laboratory proved the effectiveness of Megabit III on thick gallium arsenide films, with excellent results. In all cases, the background doping level was $<<10^{14}/\text{cm}^3$. Our research has shown that Air Products' Megabit III arsine will perform more consistently and produce fewer defects in our customers' finished products.

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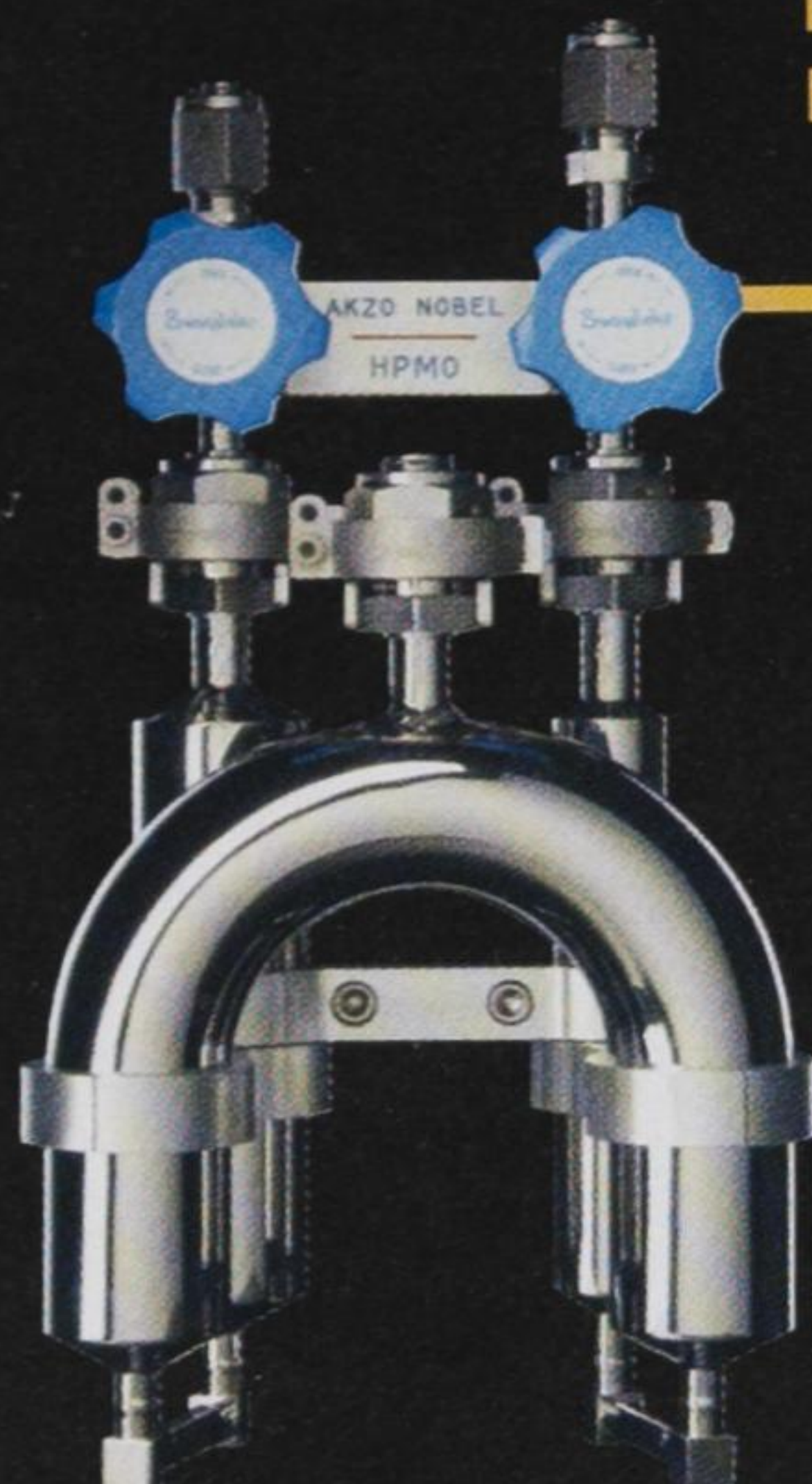
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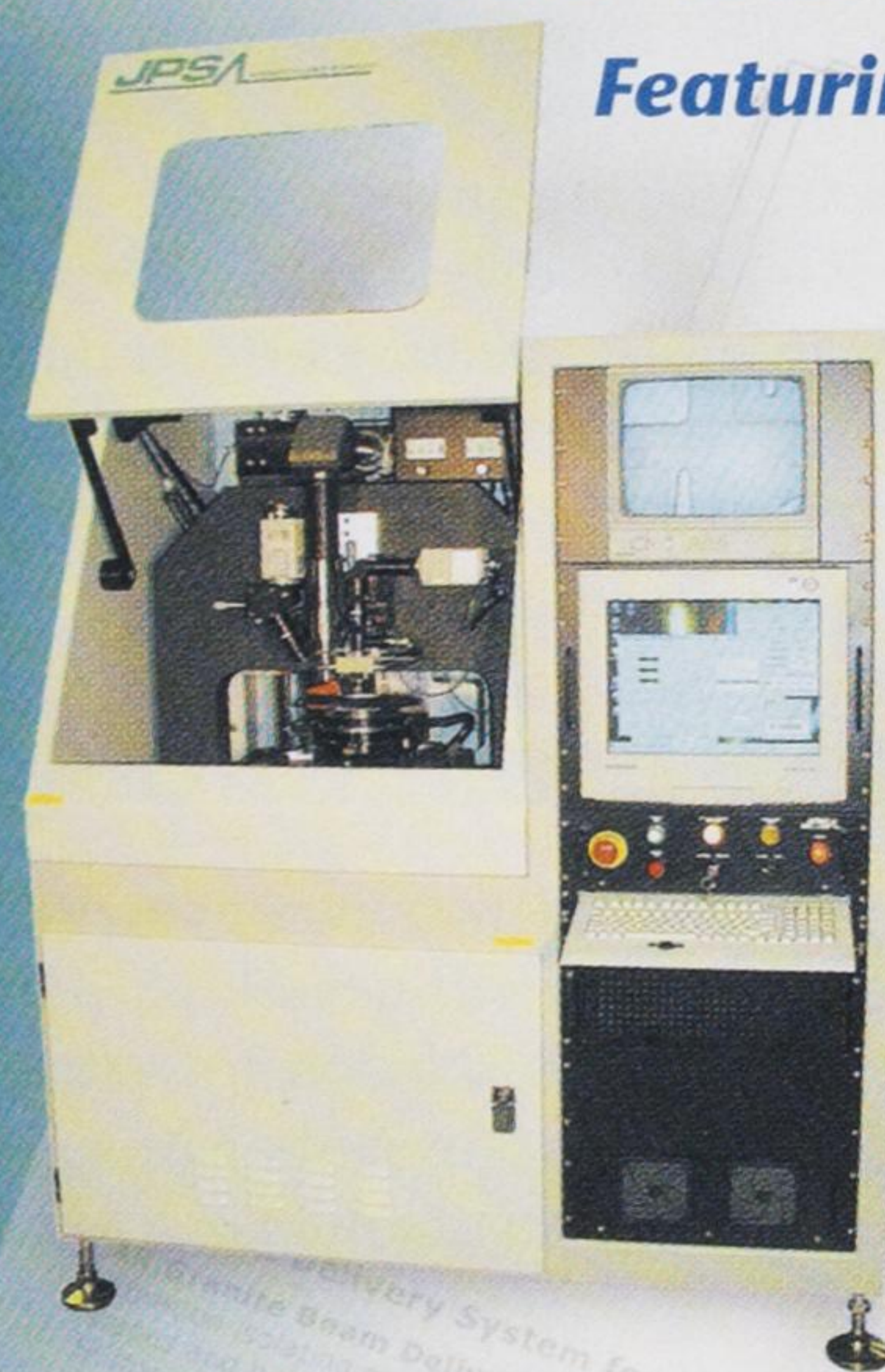


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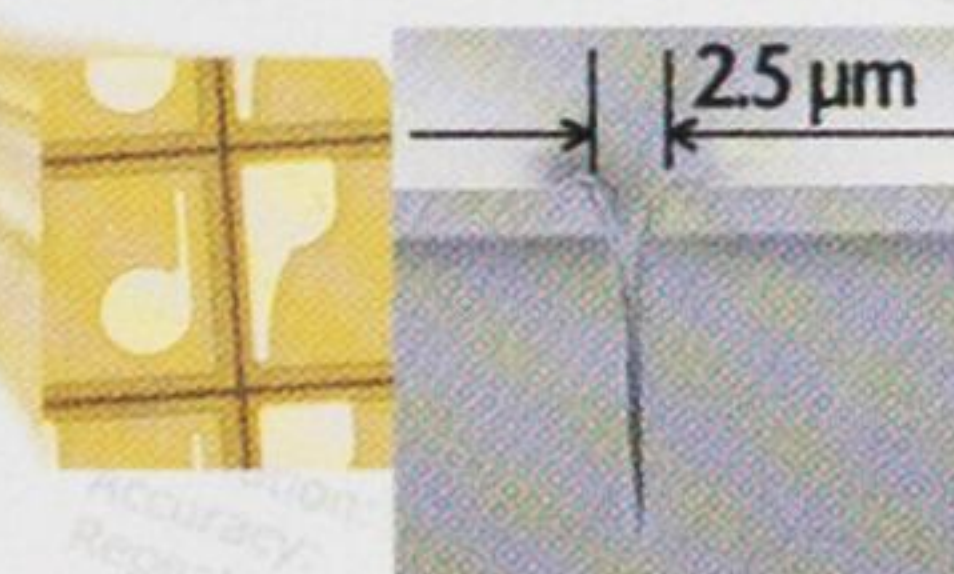
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Defense giant buys Sensors Unlimited

Aerospace and defense system giant Goodrich Corporation is to acquire InGaAs detector specialist Sensors Unlimited (SUI) for \$60 million in cash.

Pending US regulatory approval, the deal, which has been approved by the management of both companies, will see SUI become part of Goodrich's existing optical and space systems division, based in Danbury, CT.

Fiber-optic chip manufacturer Finisar, which holds a minority stake in SUI, is set to gain \$12 million when the sale is closed. This is expected before the end of the year.

Goodrich, which has its headquarters in Charlotte, NC, makes a huge range of aerospace products, from engine control systems to landing gear, and boasts that its products can be found on most aircraft in the world.

While SUI describes the switch in ownership as a merger, there is no doubt which will be the dominant partner. Goodrich's sales in

2004 were worth almost \$5 billion, compared with SUI's \$19 million.

Marshall Larsen, CEO of Goodrich, says that the InGaAs sensors made by SUI could be incorporated into its airborne reconnaissance systems. These are already used by the UK's Royal Air Force and are also set to fly with the Polish equivalent.

"SWIR sensors and near-infrared imaging systems, created with InGaAs technology, will significantly strengthen our position in surveillance and reconnaissance systems," said Larsen. And that's not the only application that could benefit. "Our laser perimeter awareness systems that support homeland security needs may also incorporate SWIR technology," added the CEO.

SUI has a 39,000 square foot facility in Princeton, NJ, and employs more than 50 people in manufacturing and engineering roles.

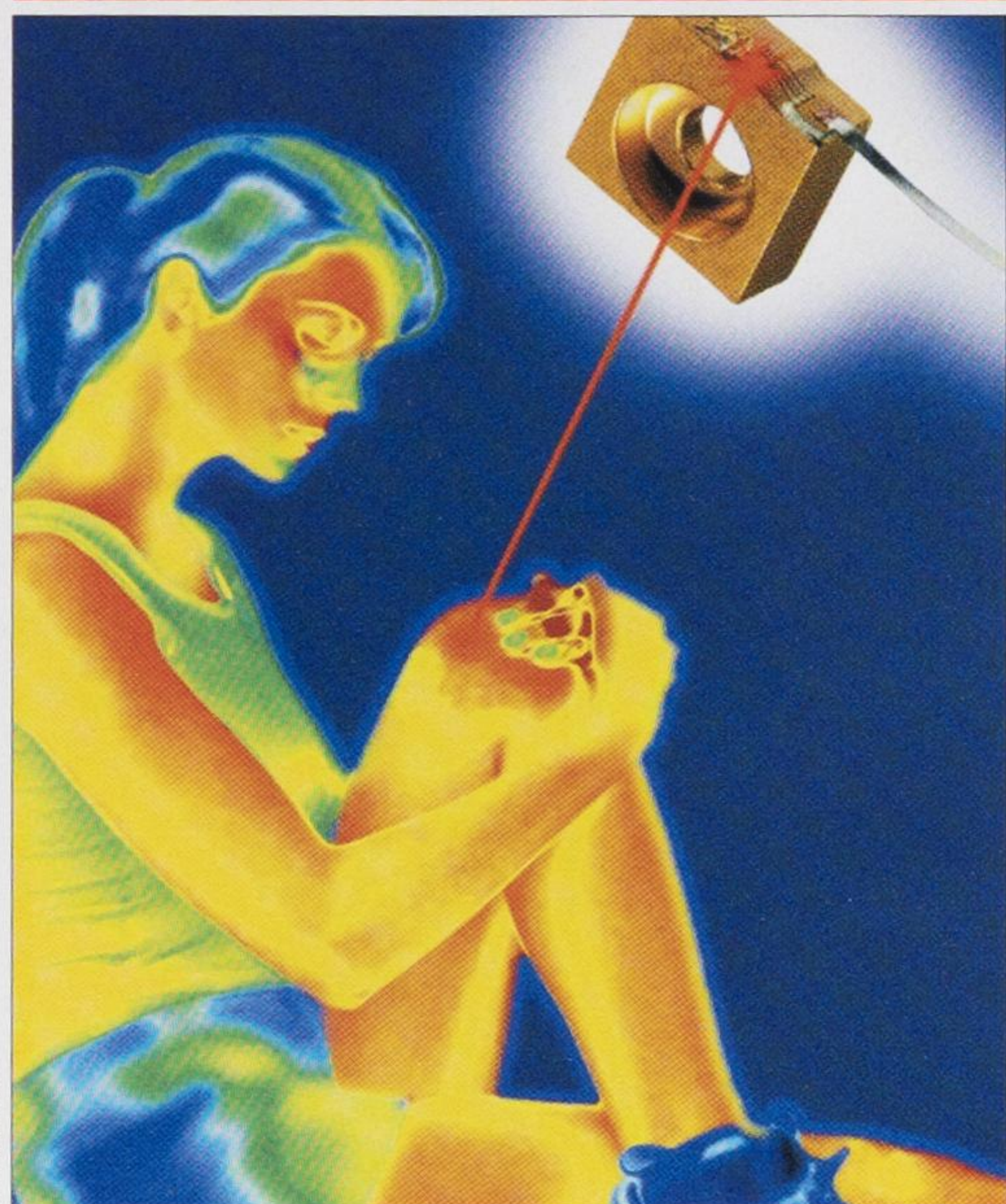
The company was acquired by Finisar at the

height of the photonics boom in August 2000 in a stock transaction valued at a now incredible \$700 million. SUI regrouped in late 2002 following a management buy-back led by its founder, Greg Olsen, for only \$6.1 million.

SUI continues to attract funding and has won a \$4.5 million contract to develop a 1280 × 1024 focal plane array (FPA) from the Defense Advanced Research Projects Agency (DARPA) Microsystems Technology Office.

The FPA will form the basis of an uncooled dual-wavelength camera that is sensitive between 0.4 μm and 1.7 μm and capable of fulfilling DARPA's goal of identifying a human target at 100 m under no-moon conditions.

SUI has also delivered four small, high-sensitivity SWIR camera prototypes for the US Army. The camera has a 320 × 240 pixel FPA, weighs less than 80 g with the lens removed, and was designed in conjunction with US-based Kaiser Electro-Optics.



OSRAM OS

Osram Opto Semiconductors has released its first commercially available visible-range laser diode. The 650 nm emitter, which has an output power of 500 mW, is targeted at medical applications such as photodynamic cancer therapy and ophthalmology. Osram claims that the laser's typical lifetime of 4000 h at 20 °C is four times longer than the minimum requirement for lasers used in medical applications. The lasers are produced on 4 inch material at Osram's Regensburg facility, and use the AlInGaP material system.

Finisar VCSELs power Logitech mice

Logitech has launched a new optical mouse for PC users that features VCSELs supplied by the US chip manufacturer Finisar.

A laser in the tracking system of the cordless device enables it to work over a wider range of surfaces than is possible with LED-based trackers. Last year Logitech introduced laser-based mice for the first time, although that laser tracking system was provided by Agilent.

The VCSELs used in Logitech's V400 cordless mice are manufactured at Finisar's Advanced Optical Components (AOC) division in Texas. Finisar, of Sunnyvale, CA, acquired AOC from Honeywell in 2004.

AOC supplies Philips with a "twin eye" laser sensor assembly that incorporates a new

VCSEL-based design, which Philips then sells to Logitech.

AOC's VCSEL is fabricated directly on top of a monitor photodiode. Finisar says that this shrinks the overall size of the tracker while allowing longer battery life thanks to low power consumption.

The deployment should help Finisar to reduce its dependency on the cyclical telecoms market by widening its applications base.

Finisar's CEO, Jerry Rawls, says that the VCSELs could also find applications in identification devices, printers and mobile phones.

Finisar posted a record revenue in its most recent financial quarter, and Rawls says that the company is on a "march to profitability".

In brief

- **Alfalight** has released its Combined Power Module II (CPM-II) diode laser. According to the company, the CPM-II incorporates the high brightness of the previous-generation CPM and adds precision wavelength control through integrated temperature stabilization, making it ideal for pumping fiber lasers at 976 nm.
- Optical component manufacturer **Princeton Lightwave** has introduced an InGaAs/InP single photon avalanche diode

aimed at applications in the scientific, communications, and medical markets. The detector can be used for quantum information processing, long-range light detection and ranging, and long-range terrestrial and satellite free-space communications.

- **nLight** has released a continuous-wave diode laser capable of delivering 5 W at 975 nm. It is claimed to be an ideal pump source for doped fiber lasers and amplifiers.

Danish start-up grabs Infineon's dilute nitrides

By Michael Hatcher in Glasgow, UK

Alight Technologies, a university spin-out company based in Copenhagen, Denmark, has agreed to take over Infineon Technologies' dilute nitride VCSEL technology platform.

The German chip manufacturer sold off much of its fiber-optic business to Finisar earlier this year in what turned out to be a protracted transaction, although that deal did not include its GaInNAs technology. While full details of the acquisition have not been revealed, it is understood that Infineon will not hold any equity in Alight after the deal.

The Danish firm, which announced the switch at the European Conference on Optical Communications (ECOC) in Glasgow last month, will acquire manufacturing equipment, intellectual property rights and 1300 nm wafers.

"We are addressing a growing need in the market for high-power and high-speed single-mode VCSELs at 1300 nm," said Alight's CEO, Steen Gundersen.

"The combination of a qualified material platform and our add-on technology creates a unique opportunity for Alight and our partners, and we are on track to make it happen."

By "add-on" technology, Alight is referring to its proprietary photonic bandgap (PBG) structures that enable singlemode, high-power output from VCSELs. Because the PBG reduces the mode volume, which is required for high-speed operation, there is no need to reduce the VCSEL's oxide aperture. The PBG structure can also be adjusted to increase the mode size if necessary.

The Danish company says that the acquisition will enable it to transform promising prototypes that are still under development into full-blown products. Dirk Jessen, Alight's vice-president of business development, pointed out that the VCSELs would be able to compete directly with distributed feedback

(DFB) and Fabry-Perot edge emitters. He believes that Alight structures could be pushed to emit as much as 10 mW singlemode power at 850 nm, and more than 2 mW singlemode over a wide temperature range at 1300 nm.

Spun out of the Technical University of Denmark in 2002, Alight already has expertise in VCSEL design, as well as ultraviolet and electron beam lithography capability. The company had previously fabricated prototype dilute-nitride structures, but Jessen said that Infineon's platform had the advantage of having already been put through extensive reliability testing.

While targeting the fiber-to-the-home market with its products, Alight hopes that its technology will also be applied in non-telecom applications such as medicine and printing. The company is also taking part in research into the delivery of RF over fiber.

Korean firm RayCan was among other companies offering long-wavelength VCSEL technology at ECOC. RayCan was marketing 1550 nm and 1310 nm InP-based devices alongside standard singlemode 850 nm VCSELs.

In other developments announced at the event, the German university spin-off company u²t Photonics revealed that it had been working with Lucent Technologies to produce an advanced InP-based photoreceiver for 40 Gb/s networks.

First prototypes of the balanced photoreceiver were developed in collaboration with Bell Laboratories' Photonic Networks Research Department, and custom-manufactured at the Heinrich-Hertz Institut in Berlin.

Meanwhile, Intel's optical products division revealed that it had signed a deal with Fujitsu, which will deploy the company's tunable laser in its networks. "We are seeing a dramatic growth in tunable laser deployments across the industry," said Intel's Gary Wiseman.

In brief

● Optoelectronic chip manufacturer

Bookham is to sell up to 9.2 million shares of its common stock in a public offering. Eight million shares will be sold initially, with a further 1.2 million on offer if the sale is over subscribed.

● Deloitte and Touche, the official auditors for **Avanex**, have expressed unease about the company's ability to remain a going concern. The accounting firm believes that additional funding will need to be secured by the Californian enterprise.

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Springthorpe bags award

The Veeco-sponsored MBE Innovator Award for 2005 has been won by Tony Springthorpe from the Institute of Microstructural Sciences in Canada. The North American MBE organization made the award at its recent conference in Santa Barbara.

Springthorpe is credited with making pioneering contributions to *in situ* monitoring and

control of the epitaxial growth process. In particular, this includes the development of narrow optical-bandwidth pyrometry to measure growth rates on large rotating substrates, and to monitor the pre-growth oxide desorption process. Both techniques have been adopted in MBE production. Springthorpe was presented with a \$3000 honorarium and a plaque.

\$17 m raised by Molecular Imprints

Imprint lithography equipment supplier Molecular Imprints (MII) has raised \$17 million in Series C financing.

MII's chief executive Norm Schumaker said: "We are committed to enabling nanoscale manufacturing in markets such as LEDs for solid-state lighting."

The company has also appointed former ASML executive John Doering as its new VP of marketing.

Precursor could be key to safer epitaxy

Metalorganics specialist Rohm and Haas Electronic Materials (RHEM) has developed a new precursor for germanium that could result in safer growth of high-purity films based on the material.

Iso-butyl germane is a liquid precursor that is said to be less toxic than regular germane.

According to RHEM, it could benefit triple-junction solar cells compromised by a germanium memory effect.

Crystal IS appoints ex-RFMD director

Crystal IS, the Green Island, NY, company developing ultra-low defect density AlN substrates, has appointed Joseph Smart as VP of device development.

Smart, who is also a member of the *Compound Semiconductor* editorial board, will lead the development and production of ultraviolet light emitters and will also be involved in some marketing activities.

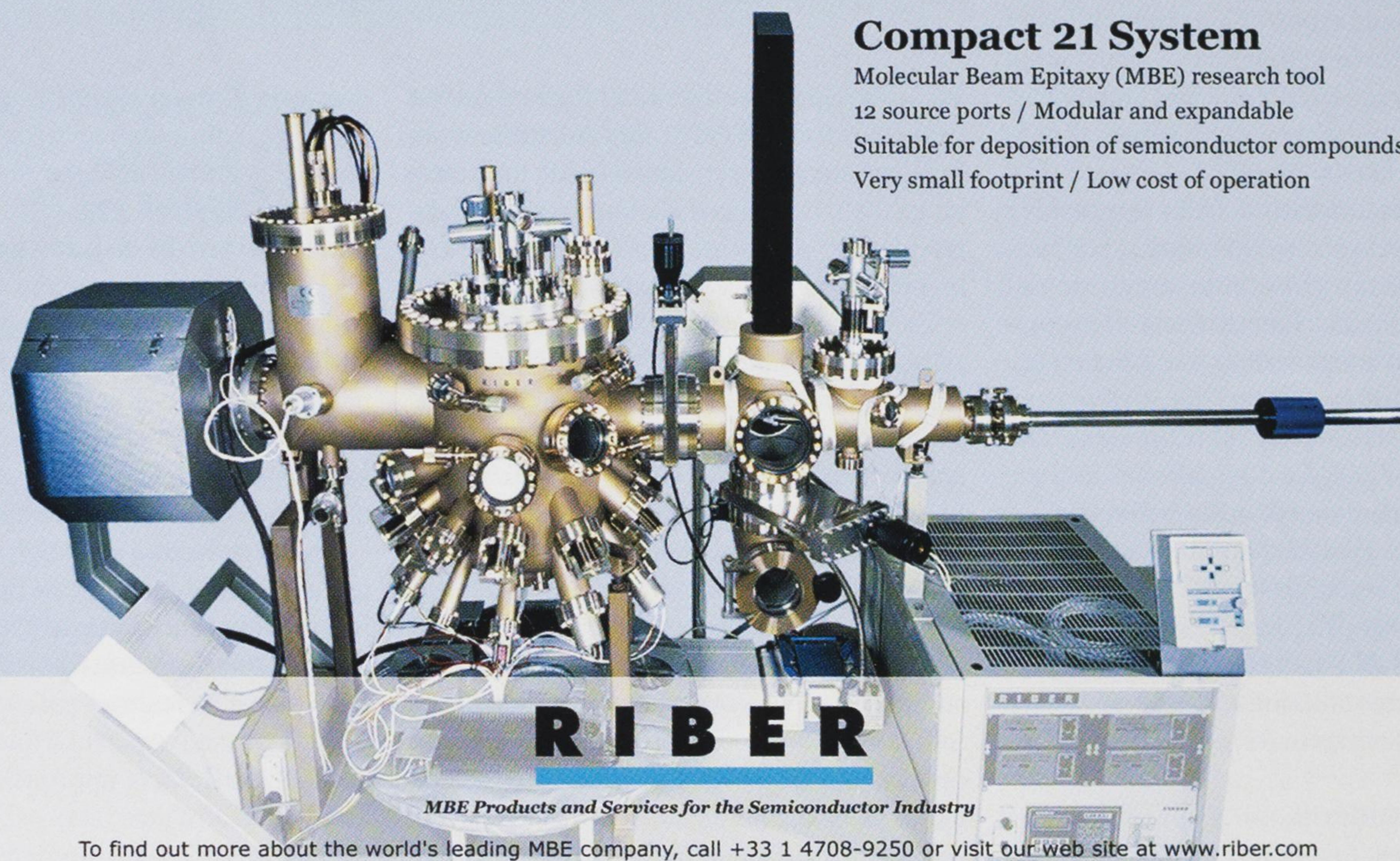
The Cornell University graduate has been working on GaN for over 10 years. He was a co-founder of RF Nitro Communications, the wide-bandgap device developer acquired by RF Micro Devices in October 2001, and he was director of GaN technology and materials at RFMD until recently.

Crystal IS currently produces 1-inch diameter AlN substrates, but the company plans to have 2-inch versions available in 2006. Smart added that the company is actively pursuing device technologies suited to AlN bulk substrates.

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IMEC improves GaN HEMTs

Mounting HEMTs on AlN ceramic substrates is one technique for improving the thermal management that currently limits the performance of GaN-based RF power electronics. **Jo Das** and **Marianne Germain** from the Interuniversity Micro Electronics Center (IMEC) in Belgium outline this approach and the advantages it offers over competing technologies.

Telecommunication providers, the automotive industry and manufacturers of power-conversion systems are all taking increasing interest in GaN-based electronic devices. And although space and military end-users are driving most of today's developments, GaN is widely seen as a promising technology for high-power amplifiers in 3G/4G wireless base stations.

GaN technology offers RF power electronics the combination of high output-power density (even at high frequency), high output impedance, large bandwidth and high linearity that is not possible with existing silicon-LDMOS or GaAs PHEMT technologies. However, the transition from impressive device performance to real market penetration demands the affordable integration of HEMTs into circuits. Future wireless telecommunication systems will also require a very high level of integration. This advance can only be achieved through miniaturization and integration of passive components, and the use of short interconnects to the active device. For RF power systems, combining thermal management and high-level integration is a major challenge. The high current densities inherent to GaN HEMTs require inventive, thermally viable solutions to integrate active and passive devices in RF applications.

Substrate options

One solution is to emulate the GaAs industry's adoption of monolithic microwave integrated circuit (MMIC) technology, with

The system-in-a-package approach

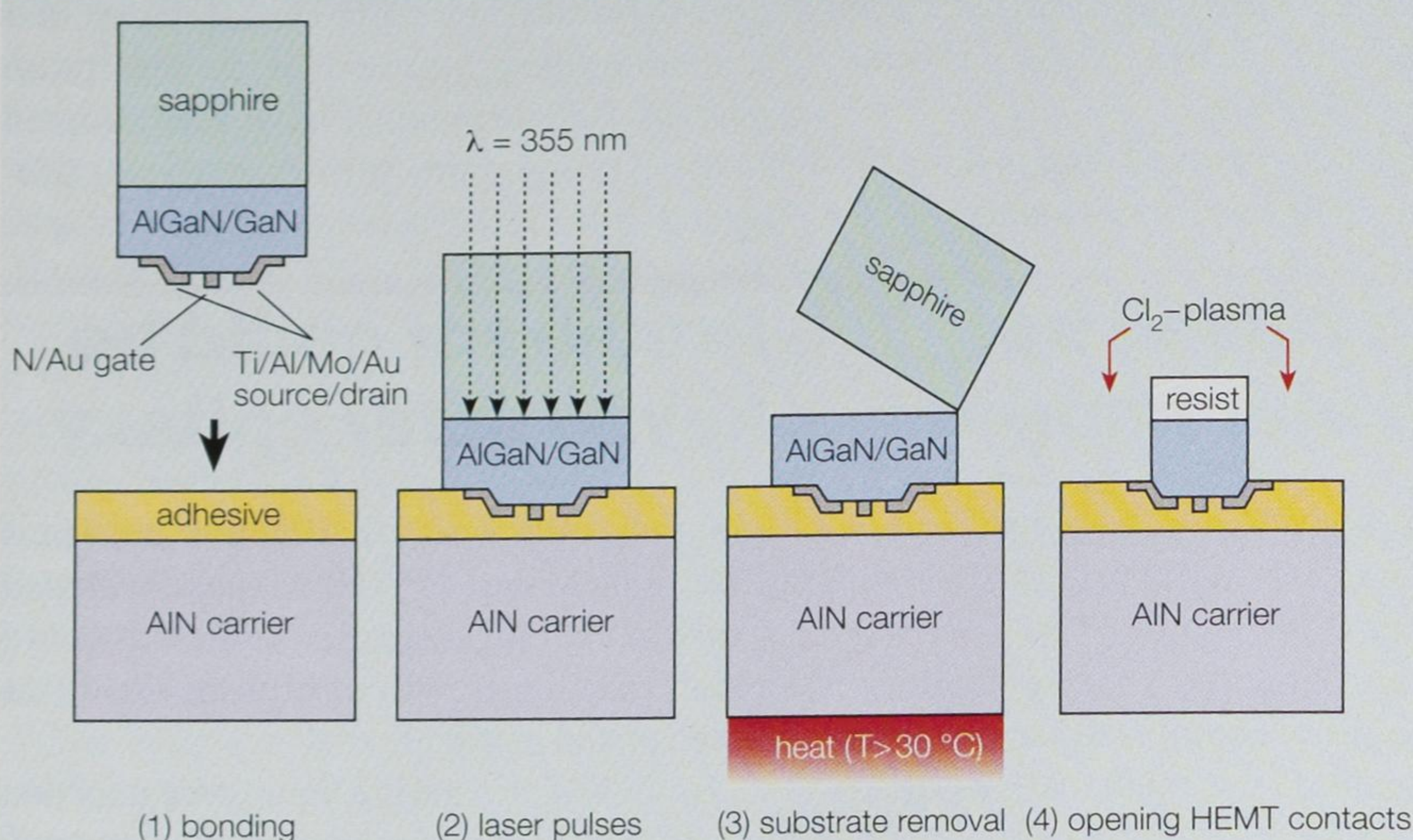


Fig. 1. IMEC's approach combines the benefits of epitaxial growth on cheap sapphire substrates and the excellent thermal properties of ceramic AlN.

The IMEC team, which is funded by the European Space Agency, uses MOCVD to grow the AlGaIn/GaN HEMTs on sapphire. This stage includes capping heterostructures with an Si_3N_4 layer to passivate surface states. The layer protects the surface during subsequent

processing steps, which improves process reproducibility and yield, and also doubles the device's current density and output-power density at RF frequencies.

After epitaxial growth standard processes are used to fabricate the

active and passive circuitry formed on the same substrate. Ideally, this substrate must fulfill all the requirements relating to epitaxial growth, high thermal conductivity, high-frequency performance (low RF loss), manufacturability and cost.

GaN native substrates meeting these criteria are unavailable, and although free-standing GaN wafers are under development, prohibitive costs prevent a monolithic approach that demands large-diameter wafers. SiC substrates produce good epitaxial material, and have been used in GaN MMIC circuit demonstrators. However, low-defect-density SiC substrates are not readily available, and processing this hard material is difficult. In addition, the high cost of the semi-insulating SiC substrates needed for high-frequency devices is a major barrier to the widespread use of GaN technology.

Sapphire substrates present another option, but sapphire's low thermal conductivity is a major problem. Silicon wafers are also

promising low-cost substrates for GaN epitaxial growth, but the performance of these devices is limited at higher frequencies.

GaN system-in-a-package

To optimize performance and cost, the Interuniversity Micro Electronics Center (IMEC) in Belgium has investigated an alternative to the monolithic integration approach that offers a greater flexibility of substrate: the system-in-a-package concept, with a multi-chip module (MCM) technology.

The system-in-a-package approach integrates multiple components on a high-density interconnect substrate. MCM allows active devices to be integrated on a low-cost substrate that also features passive circuitry previously formed as part of a three-dimensional stack. This flexible approach optimizes the cost to performance ratio.

IMEC grew GaN devices on sapphire, which is cheaper than SiC, but still capable of producing high-quality, III-nitride het-

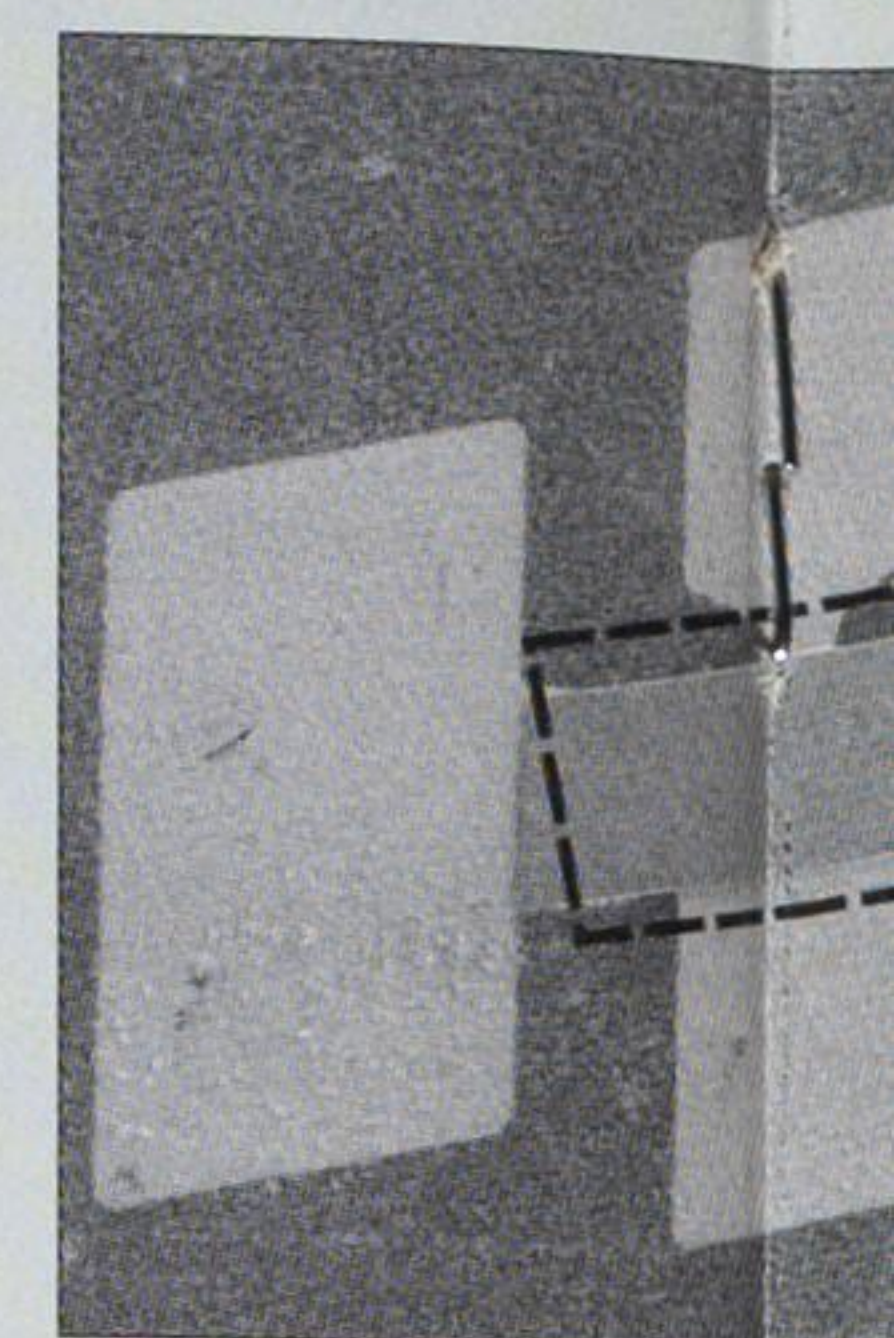
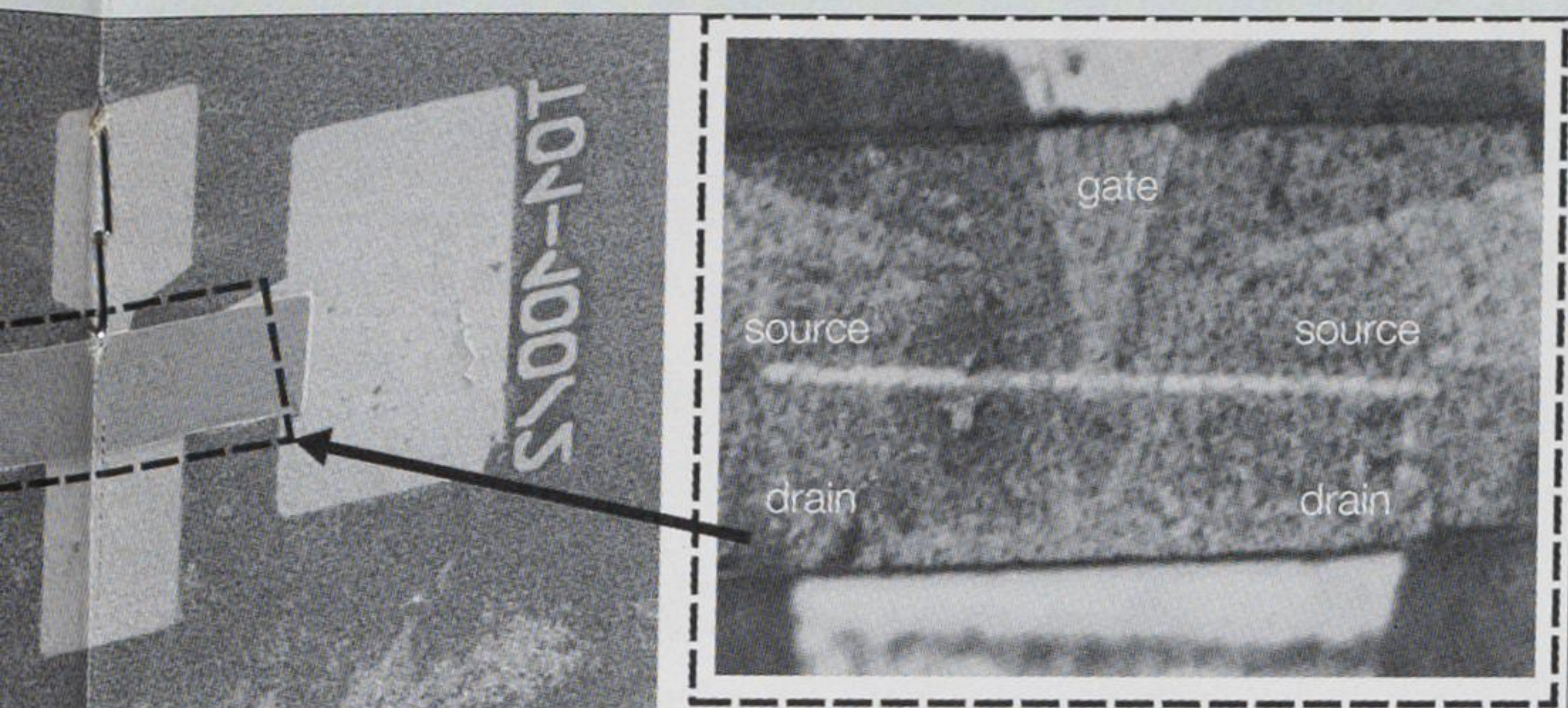


Fig. 2 (above). The large sapphire substrates. **Fig. 3 (right).** The HEMT falls slightly after the heterostructures, increasing self-heating.

HEMTs. After device AlGaIn/GaN HEMT is passive circuitry formed on the substrate, followed by substrate removal by figure 1). A single device is then mounted upside-down on the high-power ultraviolet substrate's backside

Ts with ceramic substrates

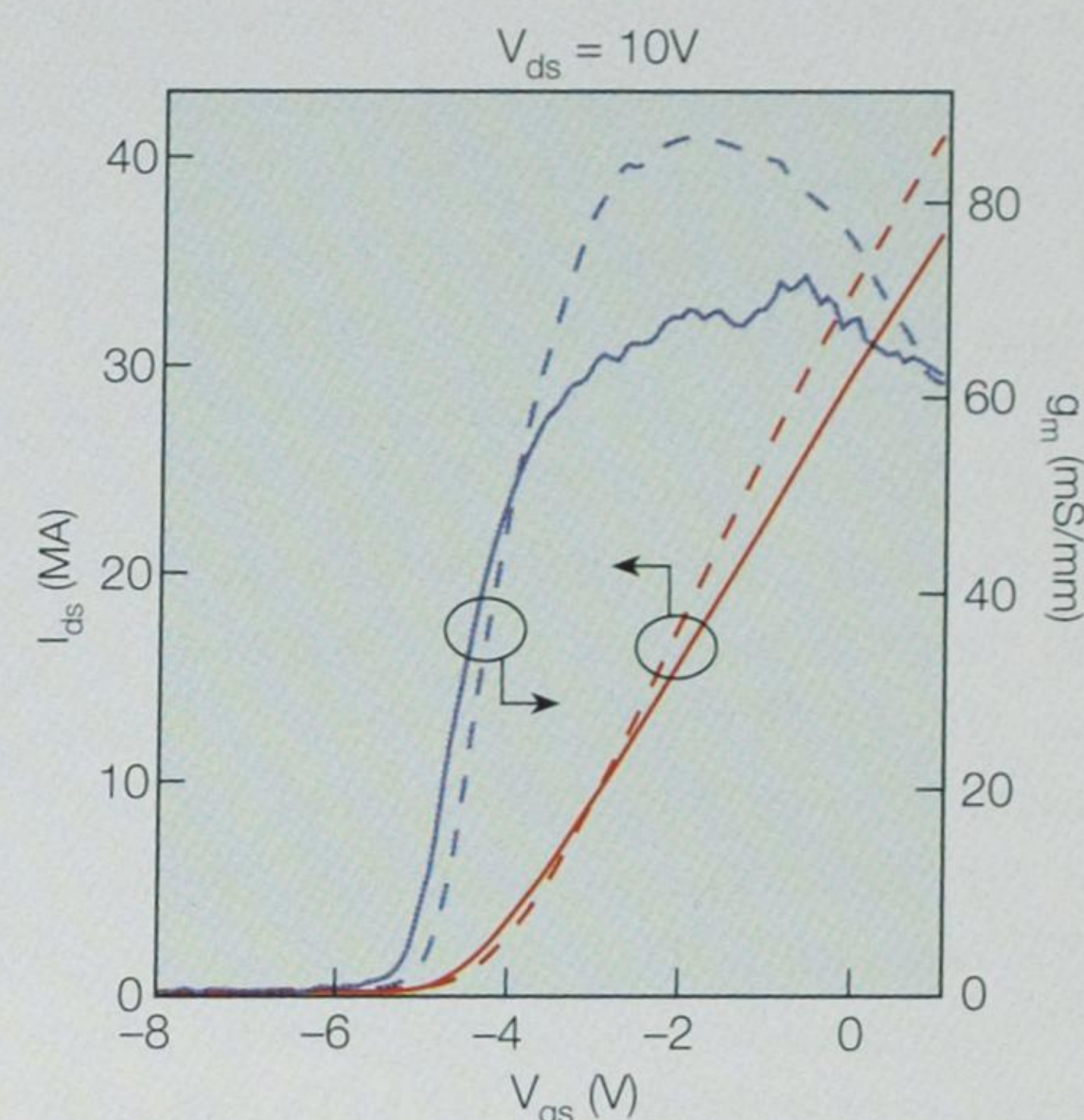
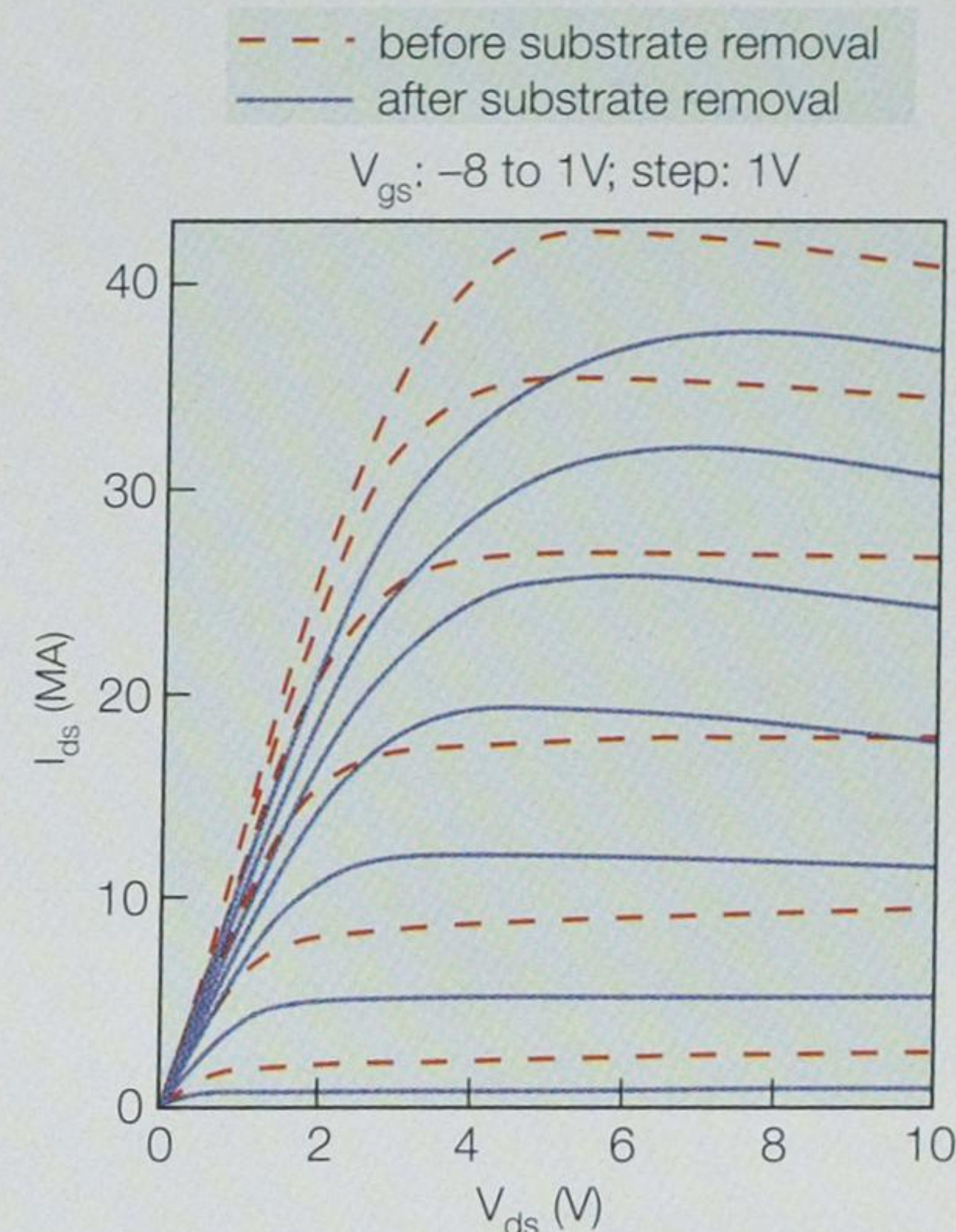


The laser-lift off technique that removes AlGaIn/GaN HEMTs from sapphire substrates is thought to be suitable for high-volume manufacturing. The HEMT's drain-source current (I_{ds}) and transconductance (g_m) after the laser lift-off process, probably as a result of either stress in the heterostructure, electron traps at the back surface of the device, or self-heating of the transistor after substrate removal.

After device dicing, a single HEMT is embedded in the carrier formed on the AlN carrier, followed by sapphire removal by laser lift-off (see figure 2). The single device die is bonded on the AlN carrier, before ultraviolet pulses fired at the backside remove the

sapphire wafer. This process causes fast, local decomposition of GaN located near the GaN-sapphire interface, separating the substrate from the HEMT. Finally, chlorine-plasma etching exposes contacts to the HEMT from the backside (see figure 2).

To analyze the impact of HEMT embedding and sapphire removal we



have compared the device's DC characteristics, such as the drain-source current (I_{ds}) and the transconductance (g_m), both before and after sapphire removal (see figure 3). After substrate removal the threshold voltage changed from -5.0 to -5.2 V, and the maximum transconductance fell by 15%. The changes could be

caused by stress in the heterostructure, electron traps at the back surface of the device, or increased self-heating of the HEMT after substrate removal. Further investigations will be required to find the exact cause. However, the HEMT performance is expected to improve significantly via use of an adhesive layer with increased thermal conductivity.

"System-in-a-package technology will be far cheaper than MMICs on SiC."

MARIANNE GERMAIN

heterostructures. Ceramic AlN was chosen ahead of the widely-used glass for the MCM-substrate, because of its high thermal conductivity of 180 W/mK.

Although various methods can be used to mount active die onto the ceramic AlN substrate, including flip-chip technology and wire-bonding, IMEC has pursued a different approach that improves the chip's thermal management (see box). The process involves direct mounting of active die on AlN, followed by sapphire substrate removal. IMEC's method offers new ways

to improve hybrid integration of high-power, multi-finger devices that deliver the power densities required for RF devices used in base stations.

Multi-finger devices typically use air bridges to connect isolated contact areas, which are compatible with flip-chip integration. IMEC's method, however, can form large multi-finger devices without air bridges. After devices are diced and bonded onto the AlN carrier and the sapphire substrate is removed by laser lift-off, chlorine-etching exposes the isolated contact areas on the backside of the HEMT. Interconnects are then formed by copper electroplating (see figure 4 p18). IMEC is currently investigating different adhesives to bond the device onto the AlN carrier, because the adhesive's thermal conductivity is crucial to optimizing the HEMT's thermal performance.

The multilayer MCM technology's advantages for RF systems include the selection of materials such as copper and benzocyclo-

butene that are relatively easy to deposit at low cost; coplanar waveguide interconnects that offer greater performance and flexibility without the need for through holes; and high-quality integrated passive components that can be fabricated with excellent reproducibility and tolerance. The IMEC MCM technology can be used in conjunction with an extensive design library for the passives that is validated up to 50 GHz.

For GaN devices, this RF integration approach delivers flexibility of substrate choice that creates the freedom to optimize the performance to cost ratio. Sapphire substrates are sufficient for epitaxial growth, despite their poor conductivity, because they provide a good platform for producing high-quality material. Different characteristics are required for the MCM substrate, including affordability, good thermal management and low loss at RF frequencies. These needs can be met with AlN ceramic substrates, which are available in sizes up to 10×10 cm. →

Although the laser lift-off process should not influence HEMT performance, minimal changes to the transistor's characteristics do occur (see box "The system-in-a-package approach"). Despite these minor drawbacks, thermal simulations suggest that the system-in-a-package process produces circuits with better thermal performance than those that use a flip-chip configuration. They show that the operating temperature of a HEMT fabricated using MCM technology, with an improved design working under typical conditions, is far less than 100 °C. Under identical conditions, a HEMT on a sapphire substrate operates at 200 °C, which reduces its reliability. Although these results are still to be confirmed with thermal measurements, experiments have shown that using just the flip-chip process reduces the temperature of a HEMT on a sapphire substrate delivering an output of 5 W/mm from 200 to 100 °C.

The simulations also show that with a flip-chip configuration, the HEMTs can only dissipate power via the solder bumps. However, the laser lift-off process allows heat loss through thermal leakage pads on

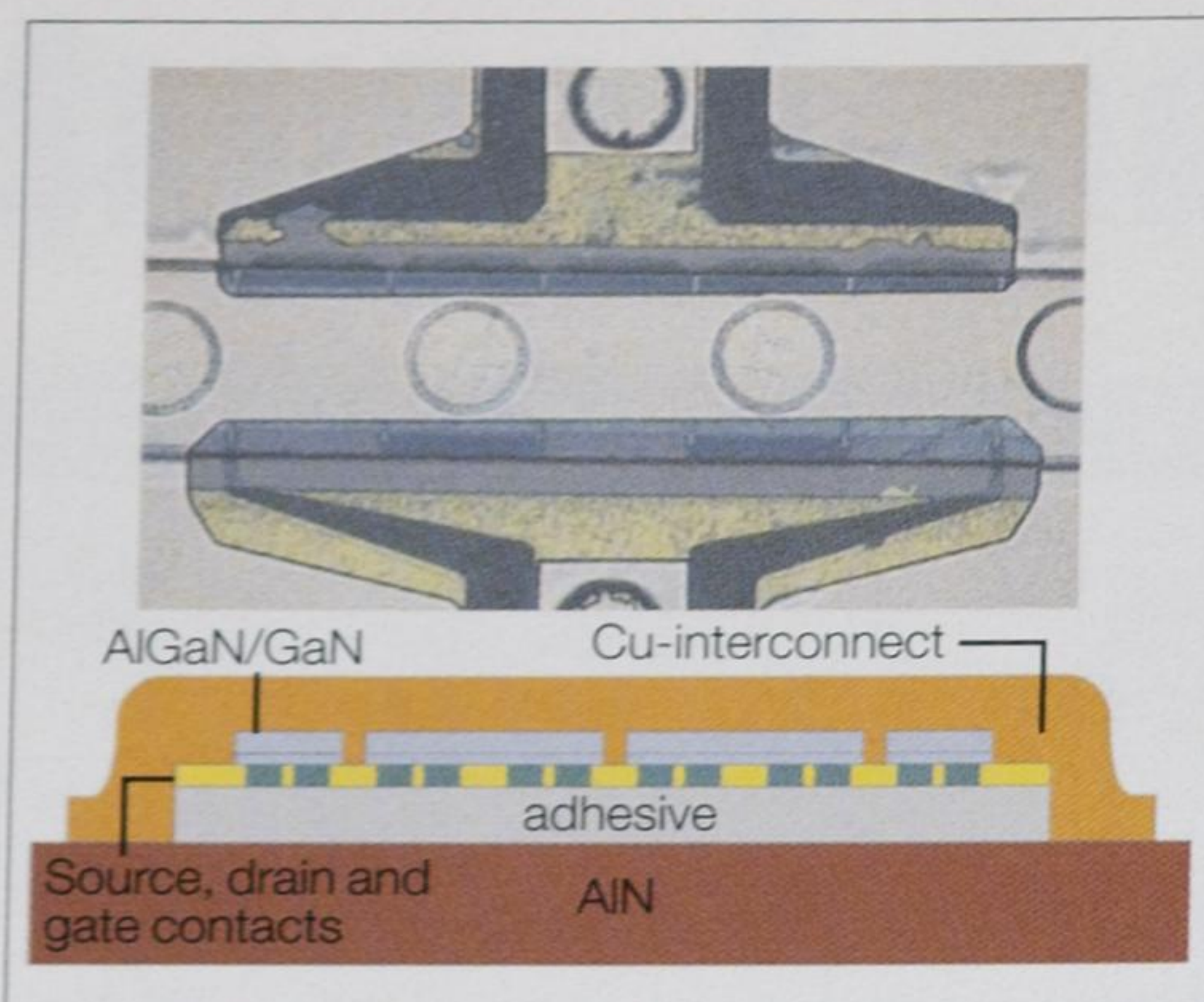


Fig. 4. IMEC is currently investigating using different types of bonding material to improve the thermal dissipation of its multiple finger devices.

the interconnects and the thin bonding layer. Thermal management can be further improved after sapphire removal by encapsulating the HEMT with better heat-conducting materials, and by increasing the adhesive layer's thermal conductivity. These refinements produce low device operating temperatures that enable high currents at

high drain-source voltages.

Some GaN LED manufacturers have shown that the laser lift-off process is compatible with high-volume manufacturing. Consequently, we believe that this approach to removing the substrate is comparable to the classical flip-chip process in terms of cost. However, we think that system-in-a-package technology will be far cheaper than MMICs on SiC, and offer the optimal solution in terms of the cost to performance ratio.

Further reading

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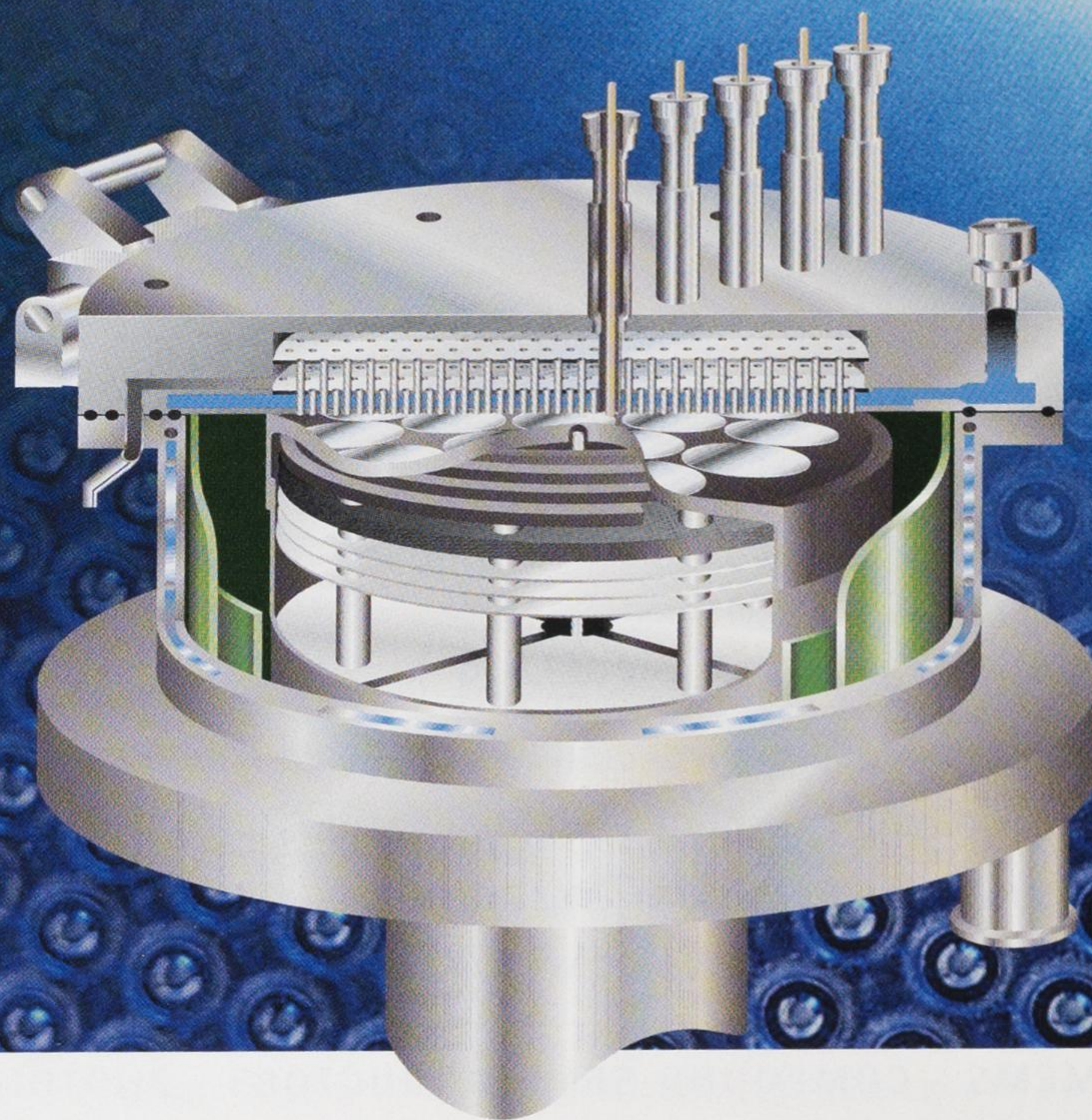
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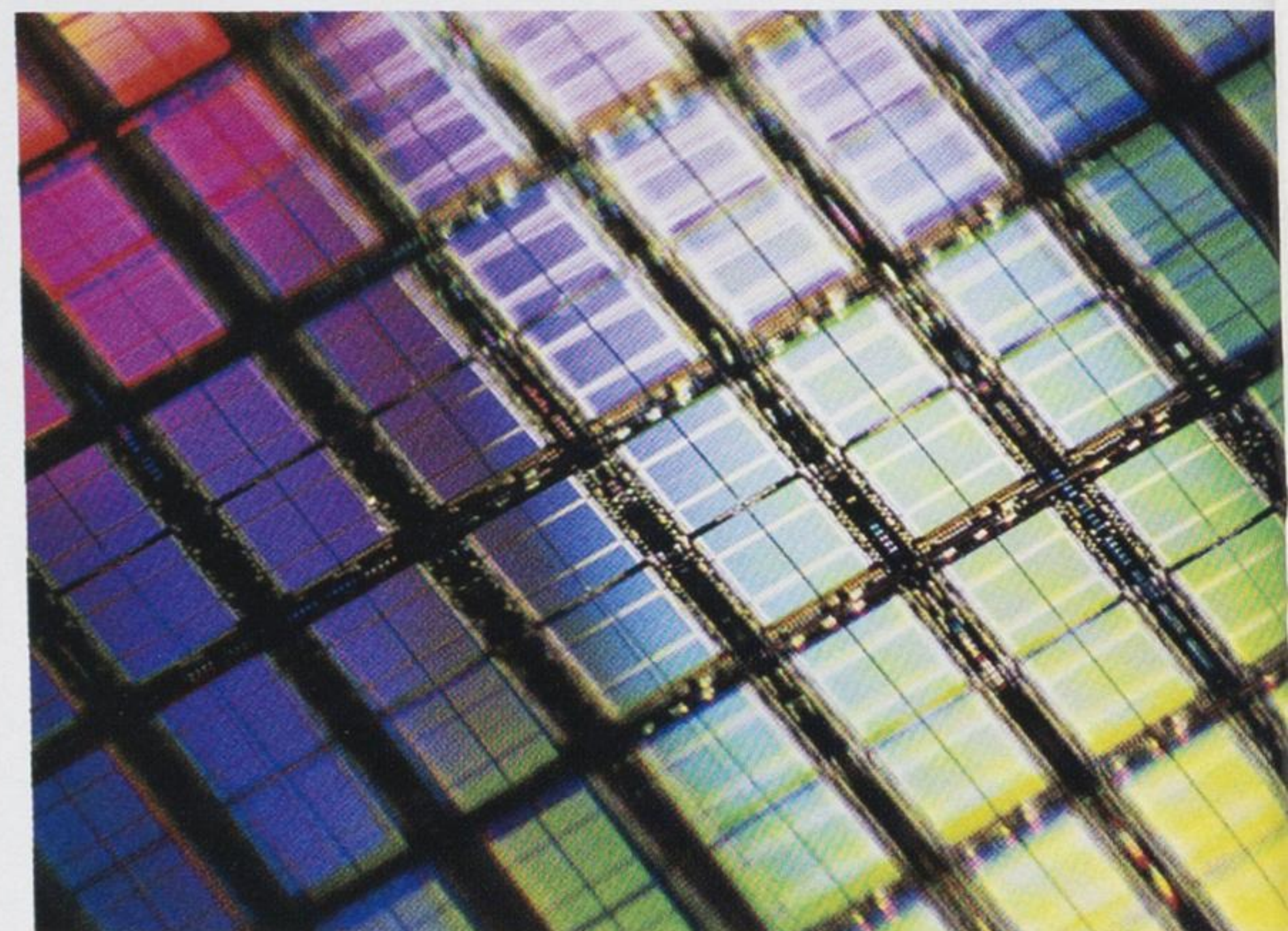


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SURFACE TECHNOLOGY SYSTEMS

Complementary techniques expose GaN transistor defects

Integrating an infrared camera into a Raman microscope produces the ideal tool for improving the reliability of GaN HFETs, says Bristol University's **Martin Kuball**.

Device reliability is a major challenge for GaN microelectronics. For example, AlGaIn/GaN-based HFETs developed for next-generation millimeter-wave communication links and radar systems still lack the required reliability for real-life applications, even though their performance has generally reached an acceptable level. Consequently, improving reliability has been identified as a key task in DARPA's latest wide-bandgap program (see *Compound Semiconductor* May p31).

Transistor reliability is strongly affected by self-heating effects – the increase in temperature caused by ohmic heating. Failure mechanisms are often driven by high temperatures, and greater failure rates occur at elevated temperatures. As a result, mapping a device's active temperature provides information that can be used to optimize the transistor's performance and improve its reliability.

Unfortunately, traditional thermal imaging techniques such as infrared (IR) thermography have insufficient spatial resolution to accurately measure peak device temperatures in many of today's GaN devices. For example, in AlGaIn/GaN HFETs, heating occurs at the source-drain device opening, in a 0.5–1.0 μm -sized region beside the gate contact. These local temperature variations cannot be resolved with IR thermography. Instead, this technique averages temperatures over a much wider area, giving incorrect values for the device peak temperature and an underestimation of the potential risks for device failure.

Micro-Raman spectroscopy, however, can measure AlGaIn/GaN HFET temperatures with sub-micrometer spatial resolution. By analyzing the phonon energies associated with lattice vibrations, the technique reveals that devices with various layouts and fabricated on different substrates can experience a temperature rise of up to 150–200 °C, even at moderate power densities.

GaN HFETs have been investigated previously with a 488 nm laser which excites the



Raman spectra (see *Compound Semiconductor* December 2001 p26). Because this wavelength is below GaN's bandgap, the incident light produces no device heating. Measuring the changes in phonon energy produced by passing a current through a device can determine the temperature rise in the transistor's active area at the site of the micrometer-sized focused laser beam. The recorded temperatures are averages over the Raman probing depth, which is typically 1–2 μm for a confocal microscope. In practice, however, depth resolution is determined by GaN layer thick-

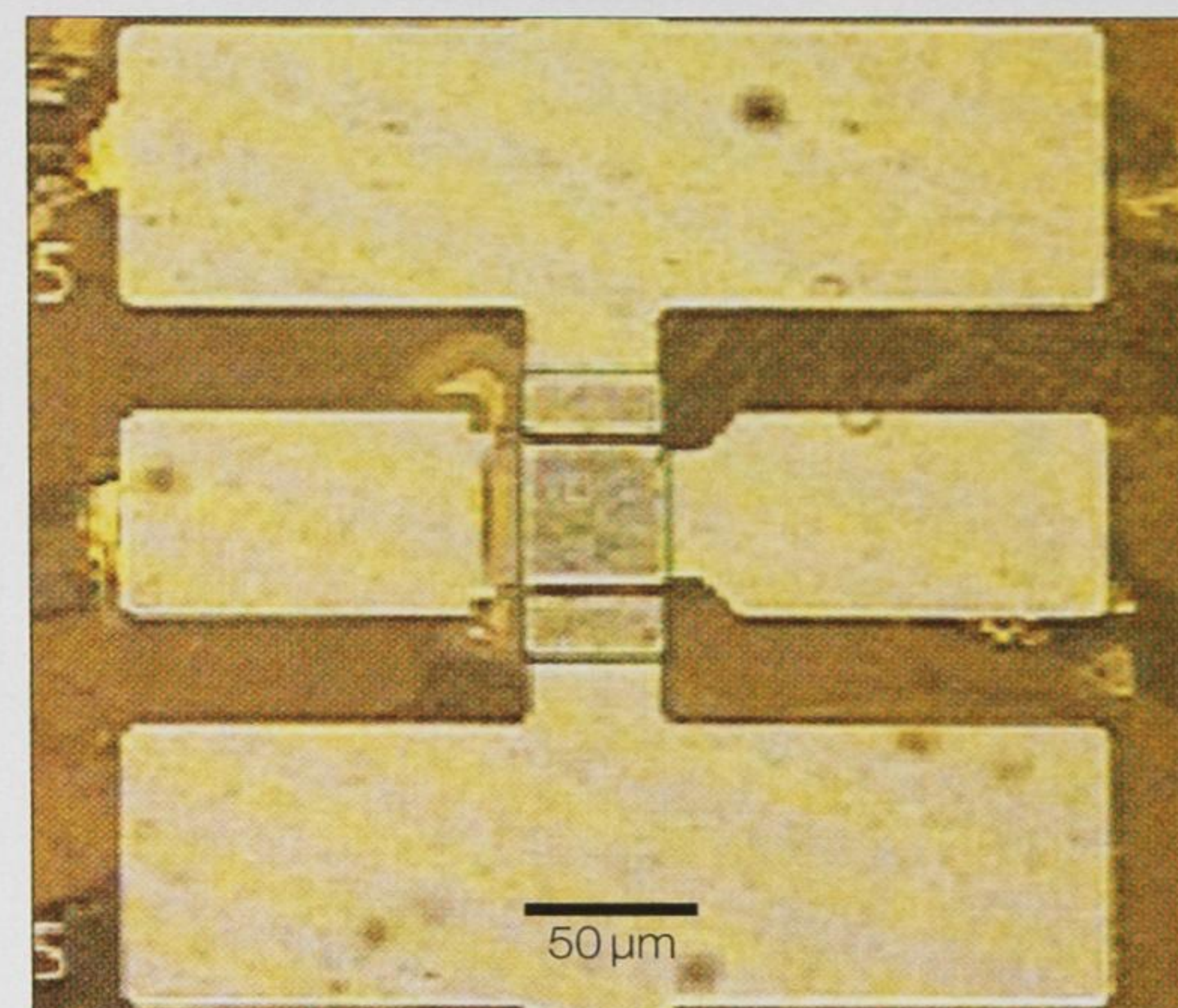


Fig. 1. The integrated Raman spectroscopy and infrared thermography system (left) combines the best of both techniques to allow investigation of micrometer-scale local heating in AlGaIn/GaN HFETs (above).

ness, which is usually about 1 μm . This leads to an underestimation of the channel temperature by a few per cent.

The Raman technique

In principle, Raman spectroscopy can determine temperatures of up to 1200–1300 °C. The technique's spatial resolution is adequate for most device analysis considering the thermal diffusion lengths in GaN. If a higher spatial resolution is required, selected applications can use atomic force microscopy (AFM), but AFM-based thermal imaging cannot determine the device's actual temperatures unless the thermal resistance between the AFM tip and device is known. Alternative optical techniques also have their downsides. Liquid-crystal-based thermal imaging, for example, is limited by phase transition temperatures.

The Raman technique does have its own drawbacks, however. Although micro-Raman spectroscopy offers a higher spatial resolution than traditional IR thermography, it lacks the sub-second recording speed of IR thermography. Raman thermal maps are created by raster-scanning the laser beam over the device

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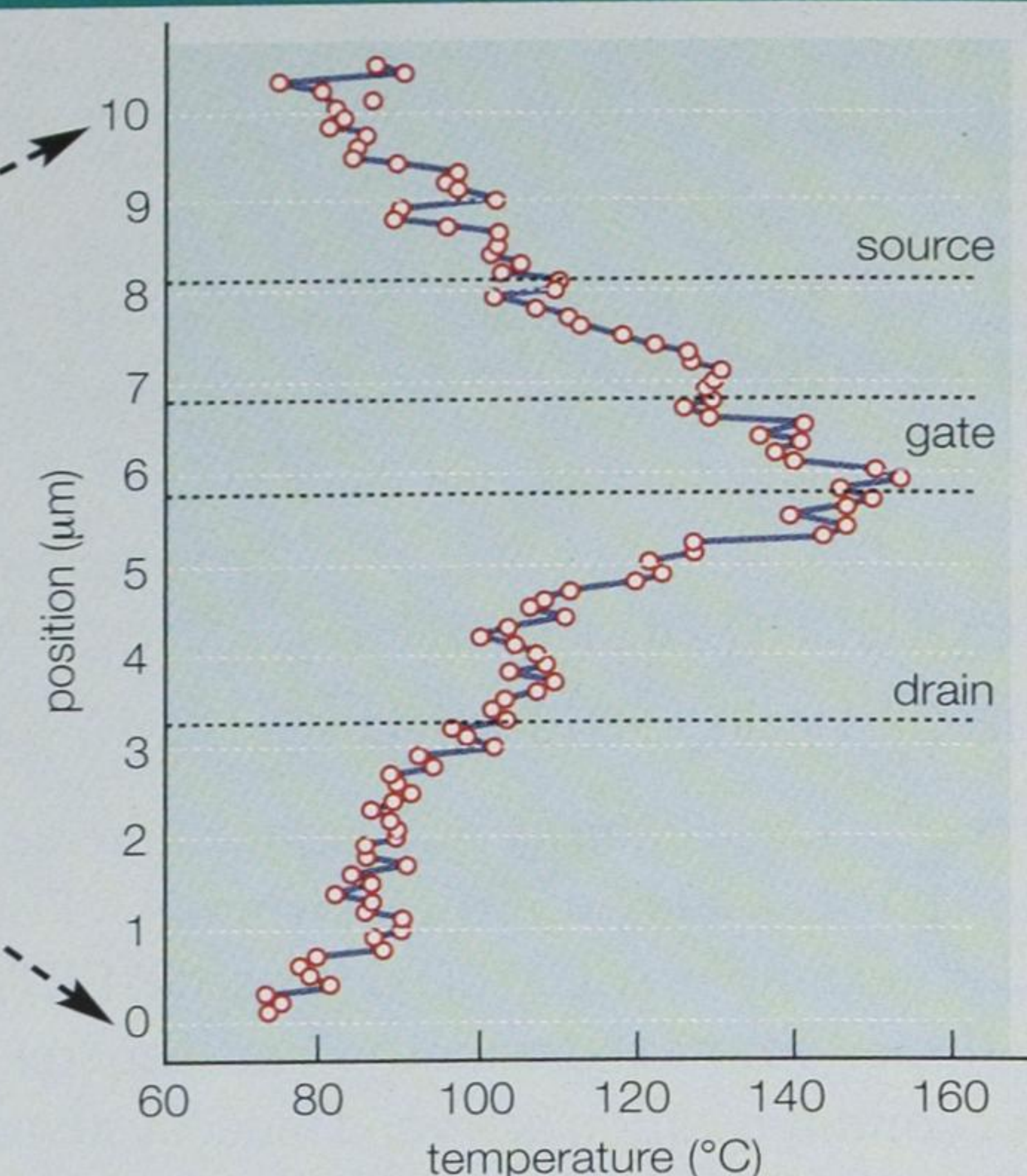
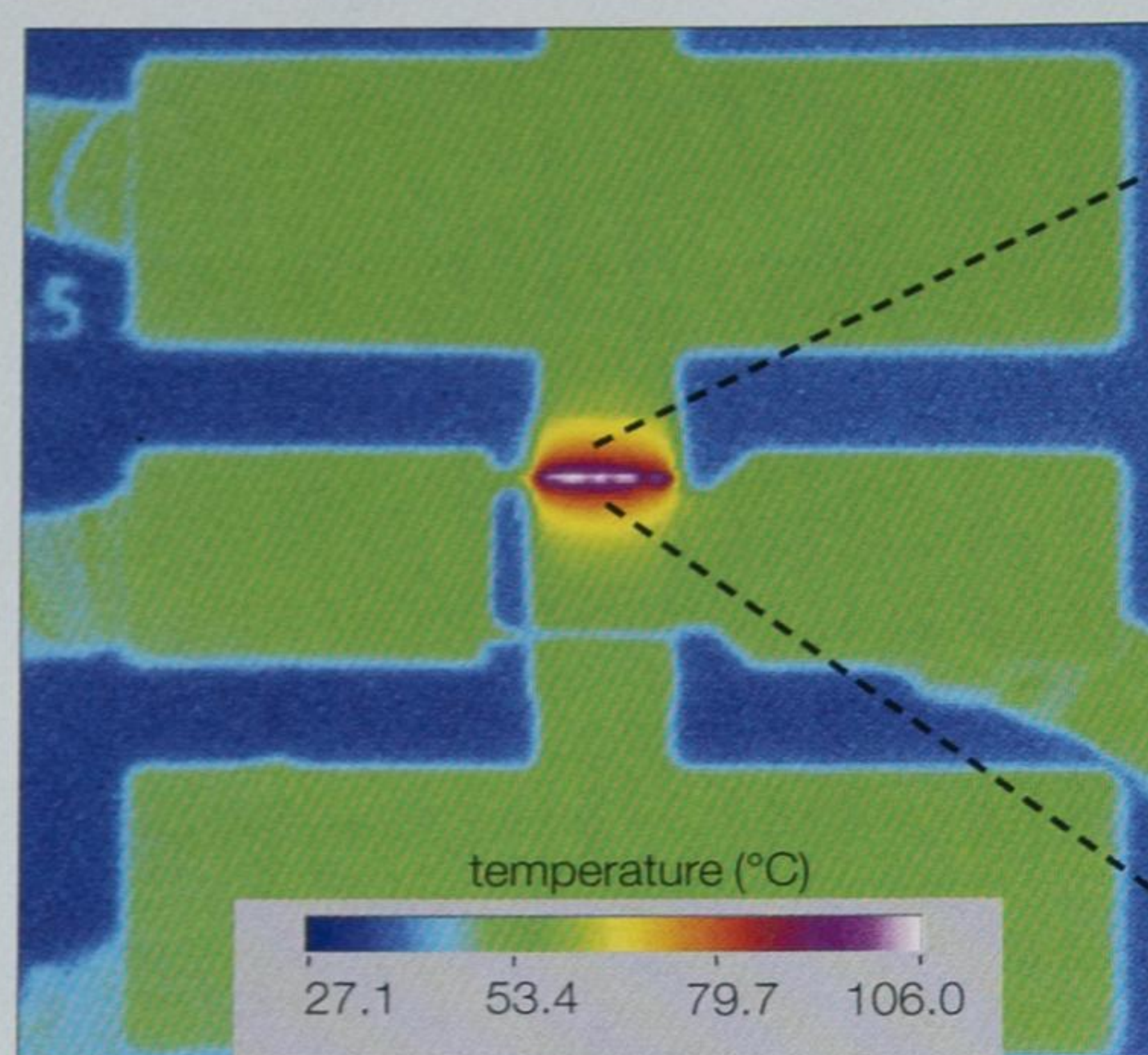


Fig. 2. The IR image (photographic image) provides a quick temperature profile of the whole of QinetiQ's AlGaIn/GaN HEMT, while the Raman spectroscopy linescan (graph, right) delivers high-spatial-resolution temperature readings of the local hotspot. This device was operating at 40 V and 25 mA DC.

surface and dwelling for several seconds at each temperature-measurement point. Consequently, analysis is limited to relatively small areas, and so the Raman method cannot easily be applied by itself to the large ensembles of devices used for wafer screening and reliability optimization.

So the challenge is to deliver high-spatial-resolution temperature mapping of many transistors within a reasonable timeframe. An integrated system, containing an IR thermography instrument with an InSb detector and a Raman spectrometer, has been developed at Bristol University, UK, in partnership with Quantum Focus Instruments of San Diego, CA, and UK-based Renishaw. The collaboration is supported by UK funding agencies the Engineering and Physical Sciences Research Council (EPSRC) and the Ministry of Defence (MoD) and has recently demonstrated a prototype (figure 1).

Integrated results

An IR temperature map of an AlGaIn/GaN HFET obtained with the integrated system, alongside a Raman temperature linescan of the device's active area, is shown in figure 2. The peak temperature rise occurs near the gate contact edge, the location of the device's highest electric field strength. As expected, the IR image provides a lower estimate of peak temperature than the Raman measurements, due to spatial averaging associated with the IR technique.

The Raman and IR measurements complement each other in several ways. The IR tem-

perature images can quickly identify areas of interest (hotspots), but are limited to 5–10 μm resolution. The Raman spectroscopy measurements, on the other hand, deliver fast sub-micrometer resolution temperature profiles, although mapping a large area using this method would be very time consuming. Absolute temperature accuracy decreases with increasing temperature for IR measurements, while the reverse is true for the Raman technique. Using Raman spectroscopy data, temperature accuracy is about ± 5 °C for temperatures in the range 100–150 °C, but this uncertainty decreases with increasing temperature, while IR images typically deliver temperature precision that is within a few per cent of the absolute temperature.

With its 1–2 μm depth resolution, and the capability to analyze phonon energies of both the GaN device layer and the underlying substrate, Raman spectroscopy can also provide three-dimensional thermal imaging (this is not possible with conventional IR thermography alone). However, unlike IR thermography, Raman measurements are unable to determine the contact temperature – unless the transistor has a flip-chip geometry, in which case measurements can be made through the substrate.

Micropipes and dislocations

Integrating Raman spectroscopy and IR thermography produces a single instrument with the flexibility and spatial resolution needed for today's GaN microelectronics production challenges, such as wafer screening

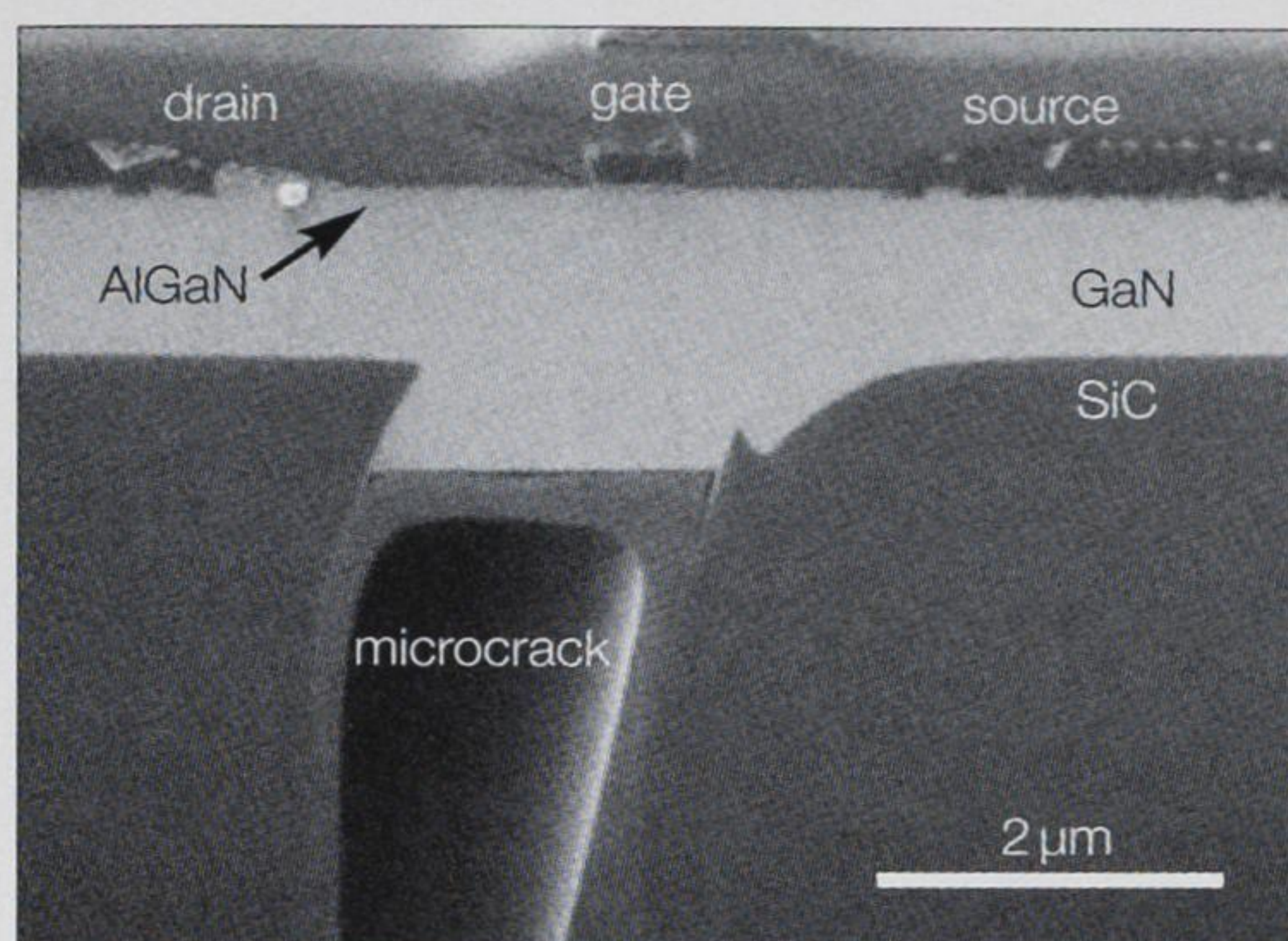


Fig. 3. The Raman temperature map (right) reveals the location of a hotspot in a QinetiQ 4 × 250 µm multi-finger AlGaIn/GaN HFET device. A subsequent focused ion-beam image (above) reveals the cause of the hotspot – a micro-crack in the underlying SiC substrate.

and reliability optimization. The integrated instrument has been used by UK-based QinetiQ, a partner within the EPSRC/MoD project, to optimize AlGaIn/GaN HFET device performance and reliability. Raman measurements have identified transistor hotspots caused by micro-pipe and micro-crack defects in the underlying SiC substrates (figure 3). Due to their low density, which will continue to fall as the SiC substrate technology matures, these particular imperfections only tend to affect the performance of larger multi-finger devices. However, more microscopic defects such as dislocations were identified as sources for local inhomogeneous device heating, suggesting that these more common imperfections are a potentially more general source of device failure. Lateral variations in the defect density across the SiC wafer can also cause a sizable spread in device temperature that leads to variations in failure rates and reliability over a wafer (figure 4).

Optimized device packaging, such as flip-chip mounting for future “system in a package” designs, can also be developed with the integrated instrument, so long as optical access to the devices can be gained. Efforts directed at enhancing flip-chip devices, in collaboration with researchers at IMEC in Belgium, are already under way.

Although up until now the combined Raman spectroscopy and IR thermography instrument has only been applied to GaN transistors, the system is suitable for all wide-bandgap devices. And with some minor adaptations, the tool could also be used to investigate lower-bandgap silicon and GaAs devices, using the same approach to determine temperature.

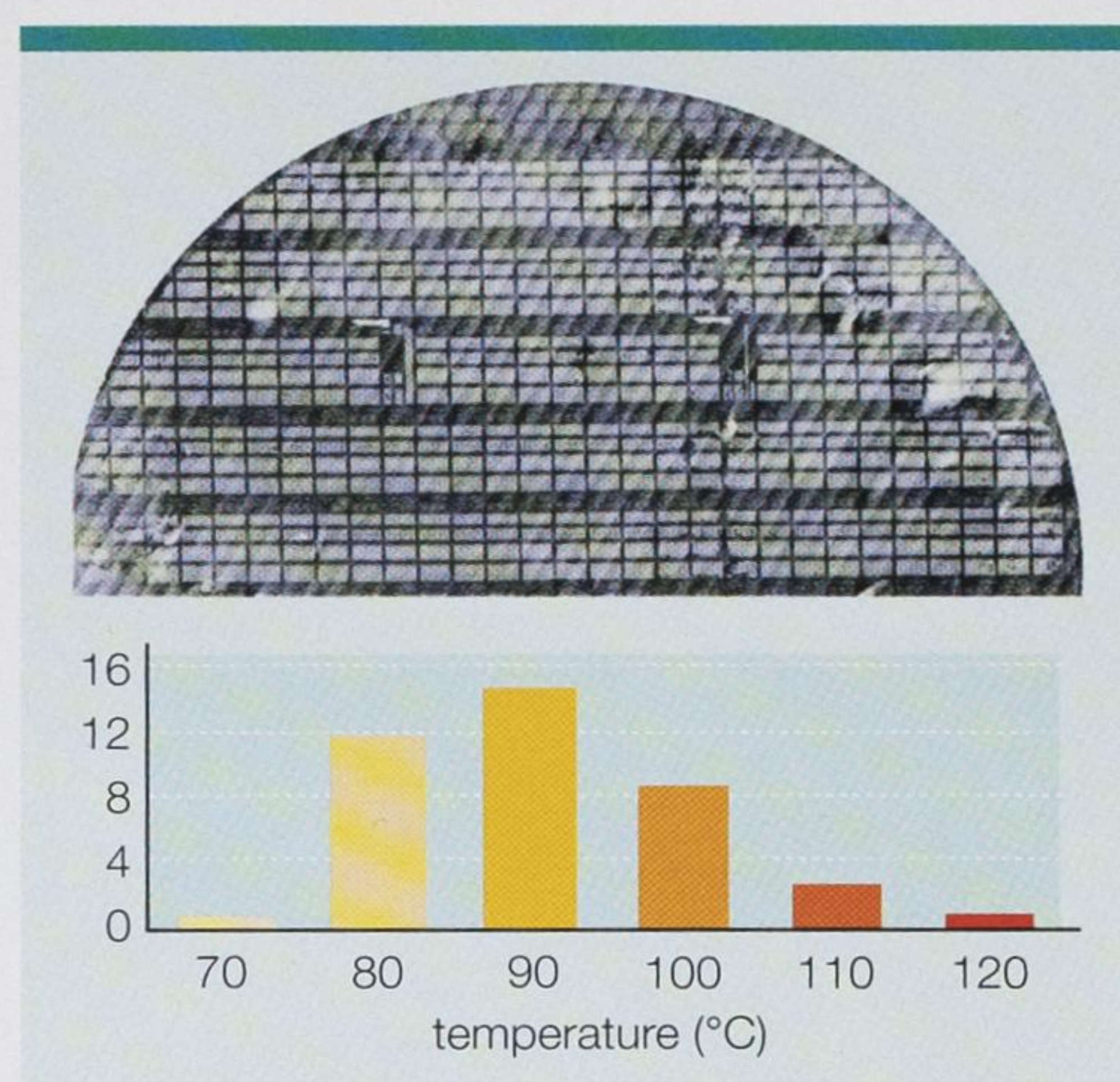
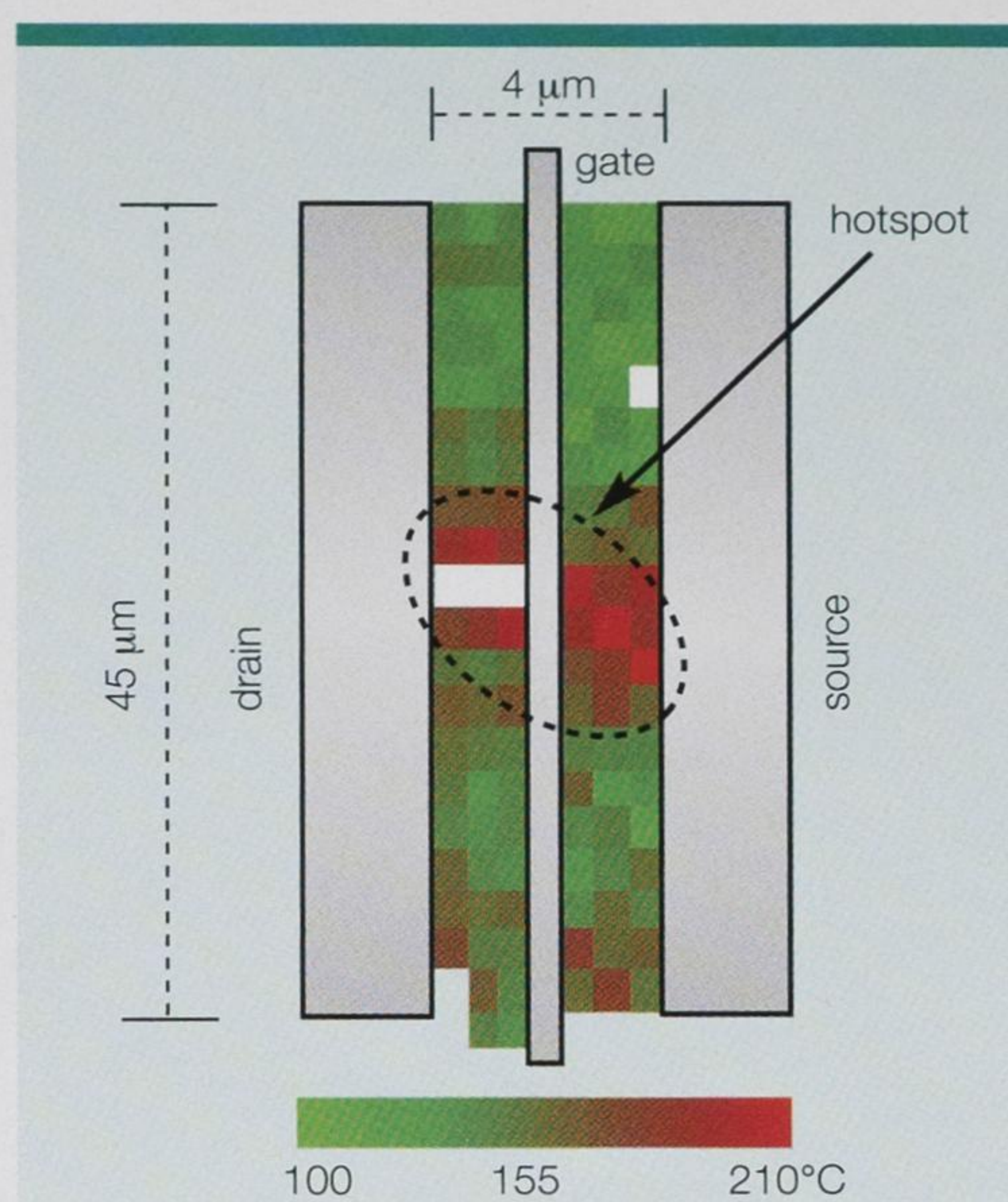


Fig. 4. X-ray mapping of the SiC (1010) reflection across the wafer (above) reveals the substrate's defect density variations. This inhomogeneity causes a spread in the average source-drain temperature measured at the center of single-finger QinetiQ AlGaIn/GaN HFET devices, operating at 18 W/mm DC.

The combined Raman-IR imaging tool will enable GaN manufacturers to optimize device packaging, and to address thermally related reliability and performance issues to an extent that was not previously possible. This will speed the route to real-life applications for GaN microelectronics. The integrated instrument can also be deployed to research the underlying physics of GaN devices, and help address performance issues such as the current collapse phenomenon.

Martin Kuball heads the Applied Spectroscopy Group at the University of Bristol, UK. E-mail: Martin.Kuball@bristol.ac.uk.

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GaN

III-V



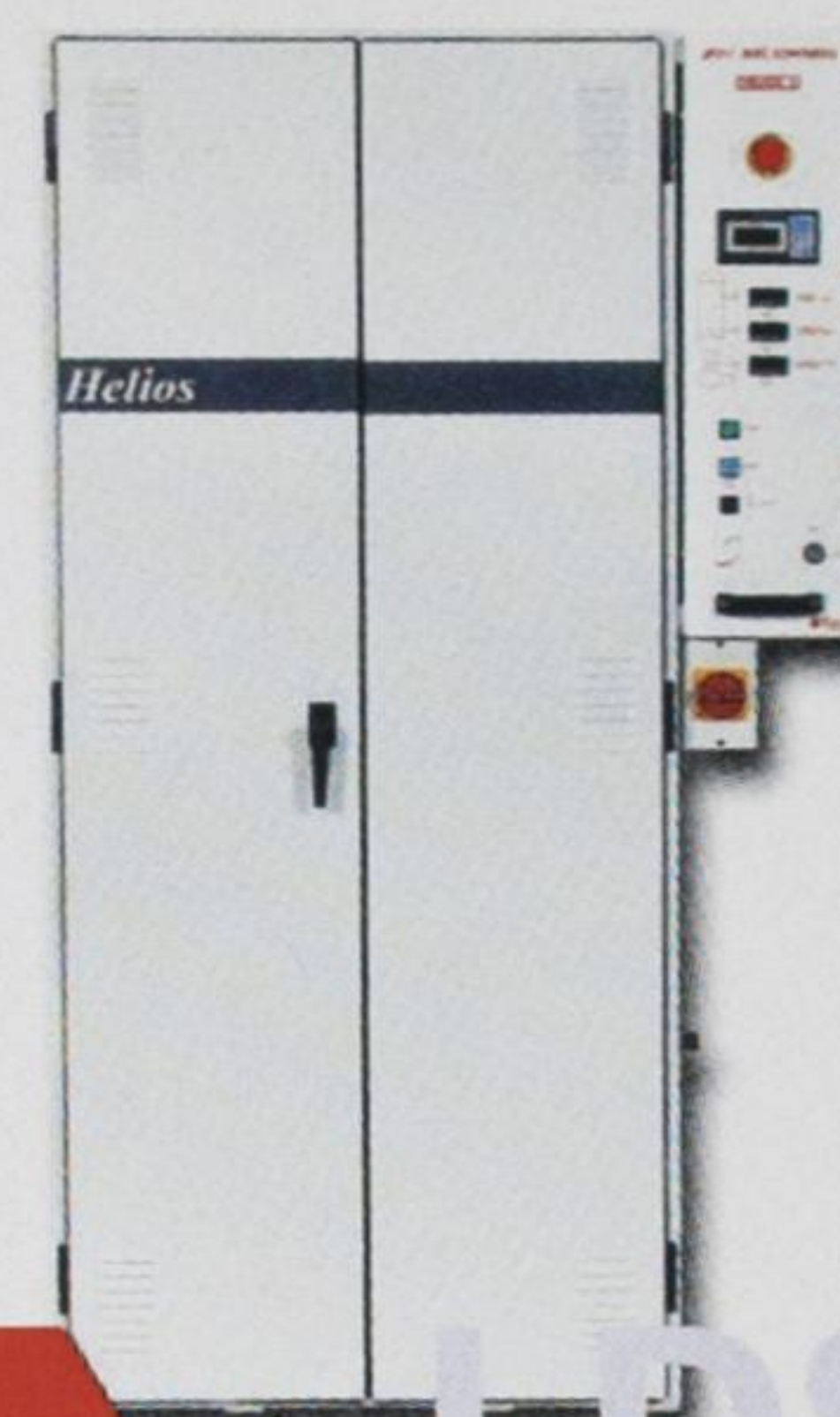
RFICS

Solar

MMIC

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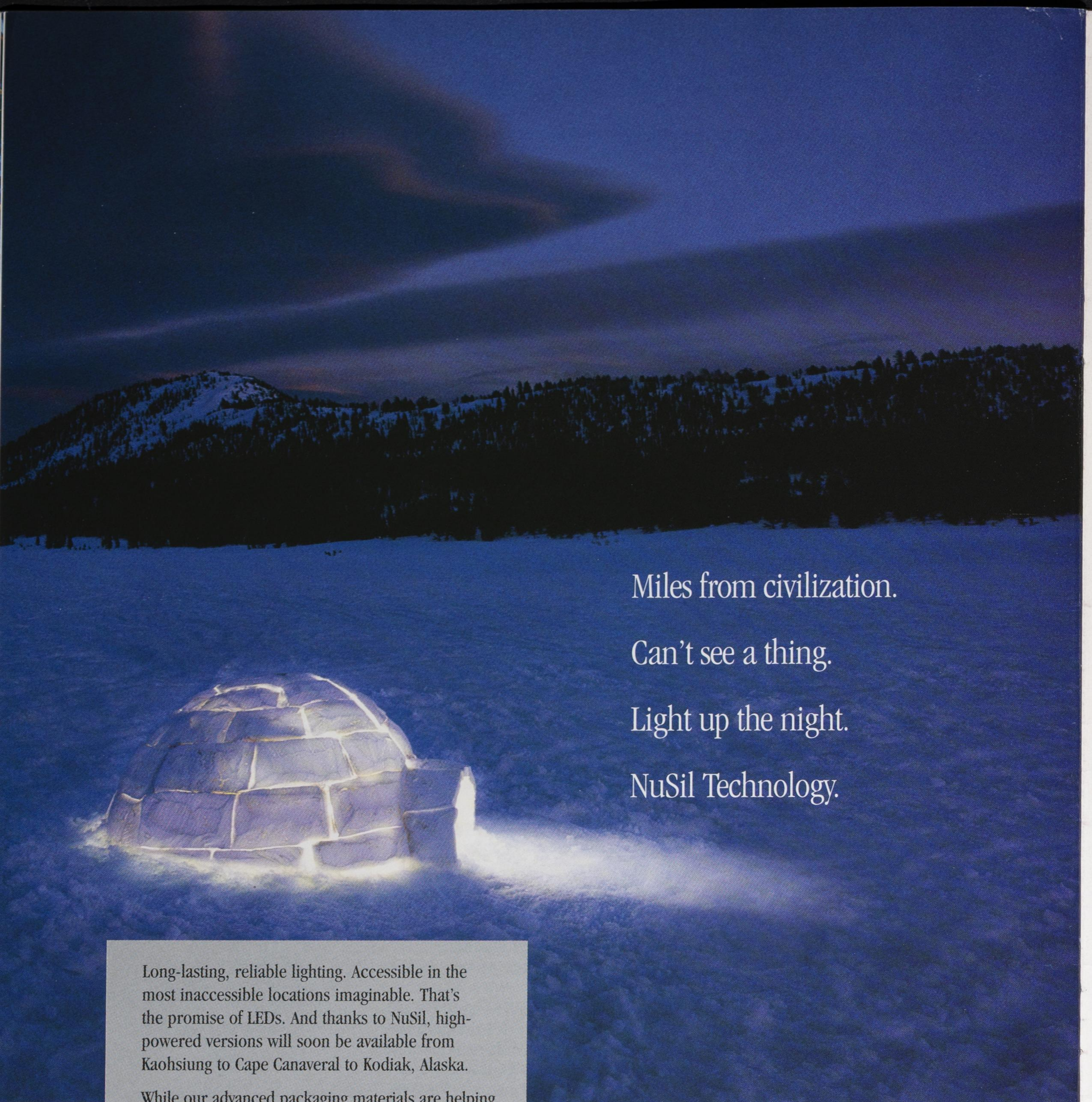
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Megapixel QWIPs deliver multi-color performance

The NASA Jet Propulsion Laboratory's quantum well infrared photodetector (QWIP) program has advanced from fabricating singleband detectors to imagers with multiple spectral bands. **Sarath Gunapala** explains why the latest detectors will benefit weapons detection and remote sensing.

Objects at room temperature have their most intense emission between 8 and 9 μm , which enables infrared cameras operating in this range to deliver detailed images in complete darkness. The best of these cameras can cover a wider spectral band, from 3 to 15 μm , and have focal plane arrays (FPAs) with individual photon detectors. These imagers typically use narrow-bandgap semiconductors. Interband absorption converts the incident light into charged carriers that provide the electric signals that ultimately form the image.

However, difficulties associated with the growth and processing of narrow-bandgap materials reduces the yield of these detectors and increases their cost. These problems provide the motivation to develop artificial, low-effective-bandgap structures containing multiple quantum well (MQW) heterostructures formed from GaAs-based material systems that are easier to grow and process.

Singleband QWIPs

Developments at the Jet Propulsion Laboratory (JPL), CA, have led to the fabrication of megapixel singleband detectors, such as GaAs/AlGaAs-based 1024 $\times$ 1024 pixel long-wavelength infrared (LWIR) QWIP detector arrays, and mid-wavelength infrared (MWIR) arrays that use GaAs/InGaAs/AlGaAs structures to detect shorter wavelengths. The MWIR arrays operate in the 4–5.5 μm spectral range, and their long-wavelength counterparts detect the 8–9 μm band. Both detectors have a 19.5 μm pixel pitch but an actual pixel size of 17.5 $\times$ 17.5 μm . The detectors have been combined with matching silicon read-out integrated circuits (ROICs) using indium bumps to form cameras that operate at a frame rate of 30 Hz.

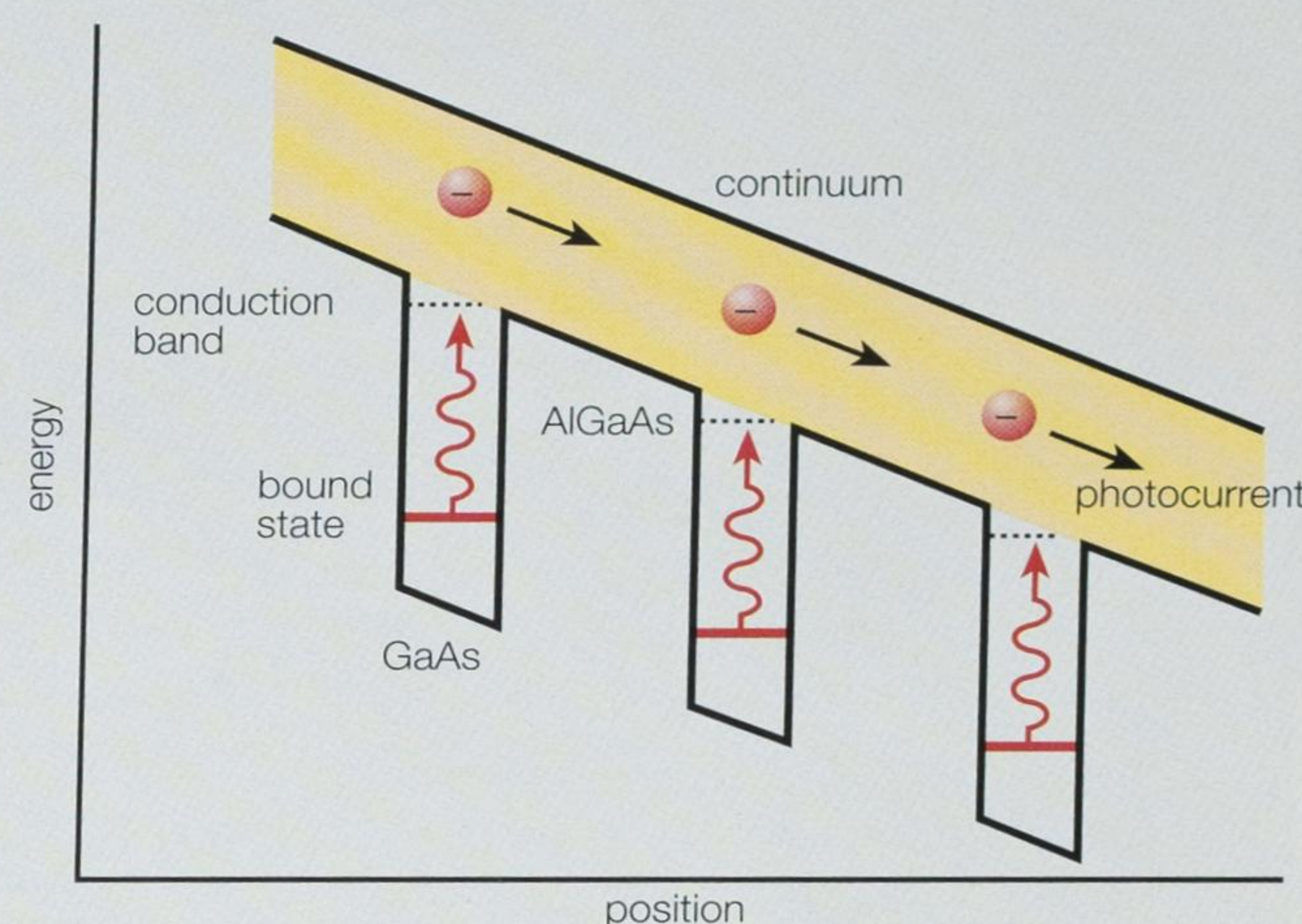
Although singleband QWIPs can deliver infrared images (figure 1), they are inferior to cameras that deliver images containing information from different spectral bands. A num-

How to fabricate a QWIP

The simplest QWIP uses a GaAs/AlGaAs quantum well that accommodates just two states – a ground state deep inside the well, and the first excited state near the top of the well. This creates a detector that has a narrow spectral response; the sharpness is determined by variations in the energy between the excited and ground states.

To alter the detection wavelength, adjustments can be made to the well width, barrier width or well composition. Photoelectrons are formed under constant illumination, and a steady-state photocurrent can be detected by applying a voltage across the active region.

Today JPL uses molecular beam epitaxy to produce QWIP heterostructures with sharp interfaces on substrates that have a diameter of up to 6 inches. Ground-state electrons are introduced by doping the GaAs quantum well with silicon, an n-type



Incident light with energy equal to the difference between the ground state and the first excited state generates photocarriers that provide the electrical signals that subsequently form infrared images.

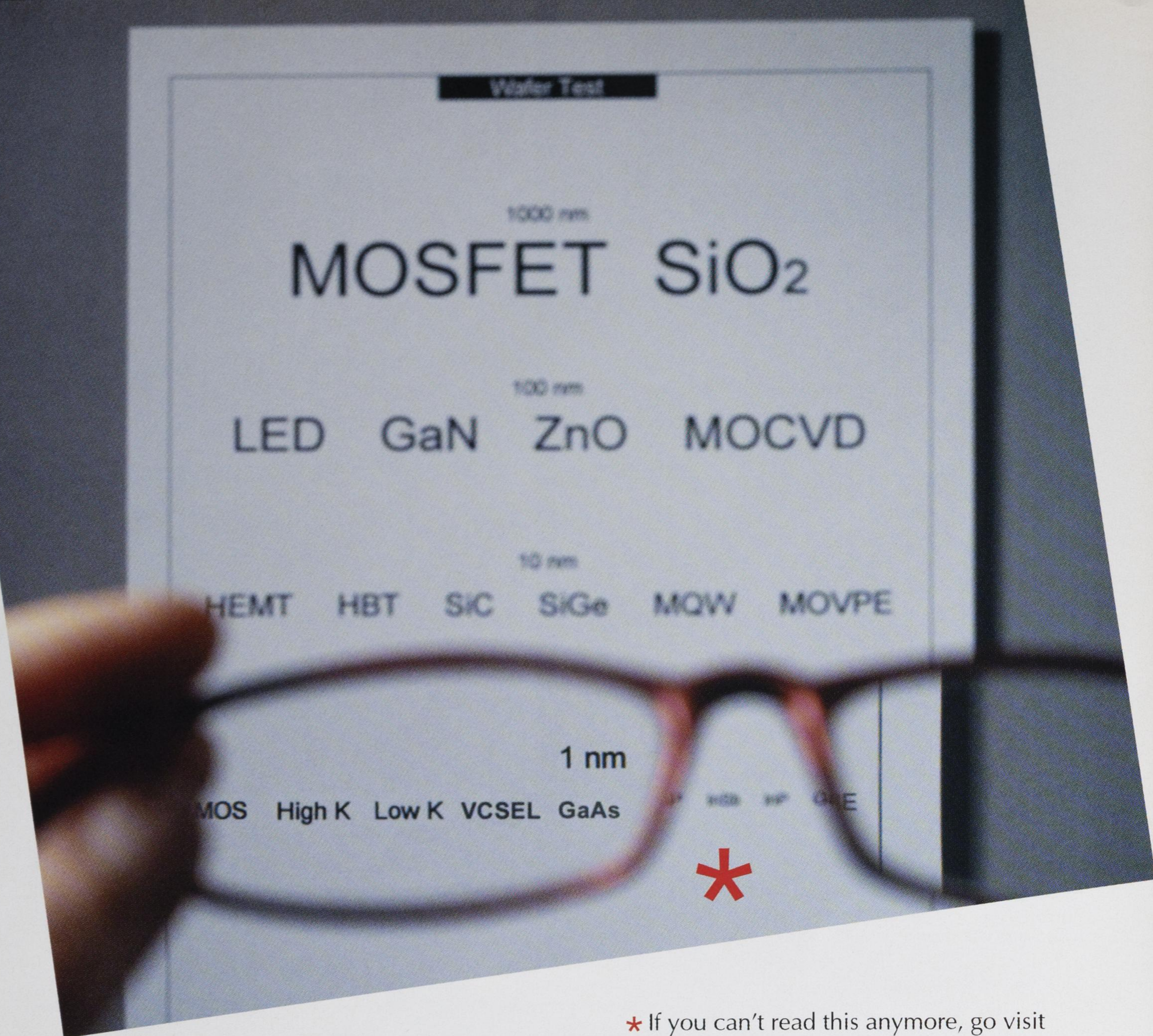
dopant. Although hole photocarriers can also be created by using the p-type dopant beryllium, this approach is avoided because these carriers have inferior transport properties.

For incident light to be absorbed in the quantum well it has to have an electric field component in the growth direction. To prevent light propagating normal to the plane of the substrate

from not being absorbed, two-dimensional gratings are added to the design to diffract the incident light. Lithography is used to define these gratings before isolated pixel detectors are produced by dry etching trenches through the photosensitive GaAs/AlGaAs multi-quantum-well layers into a 0.5 μm -thick, highly doped GaAs bottom contact layer.

ber of years ago JPL fabricated a four-band, spatially-separated QWIP FPA camera in which each band fulfilled a different need. One band detected forest fires, another pollution, a third recorded cloud characteristics, and a fourth monitored weather patterns. This

detector, which had a 640 $\times$ 512 pixel focal plane, also had a unique feature: the four infrared bands were independently and simultaneously readable on a single imaging array. This gave the FPA an advantage over competing broadband detectors, such as HgCdTe,



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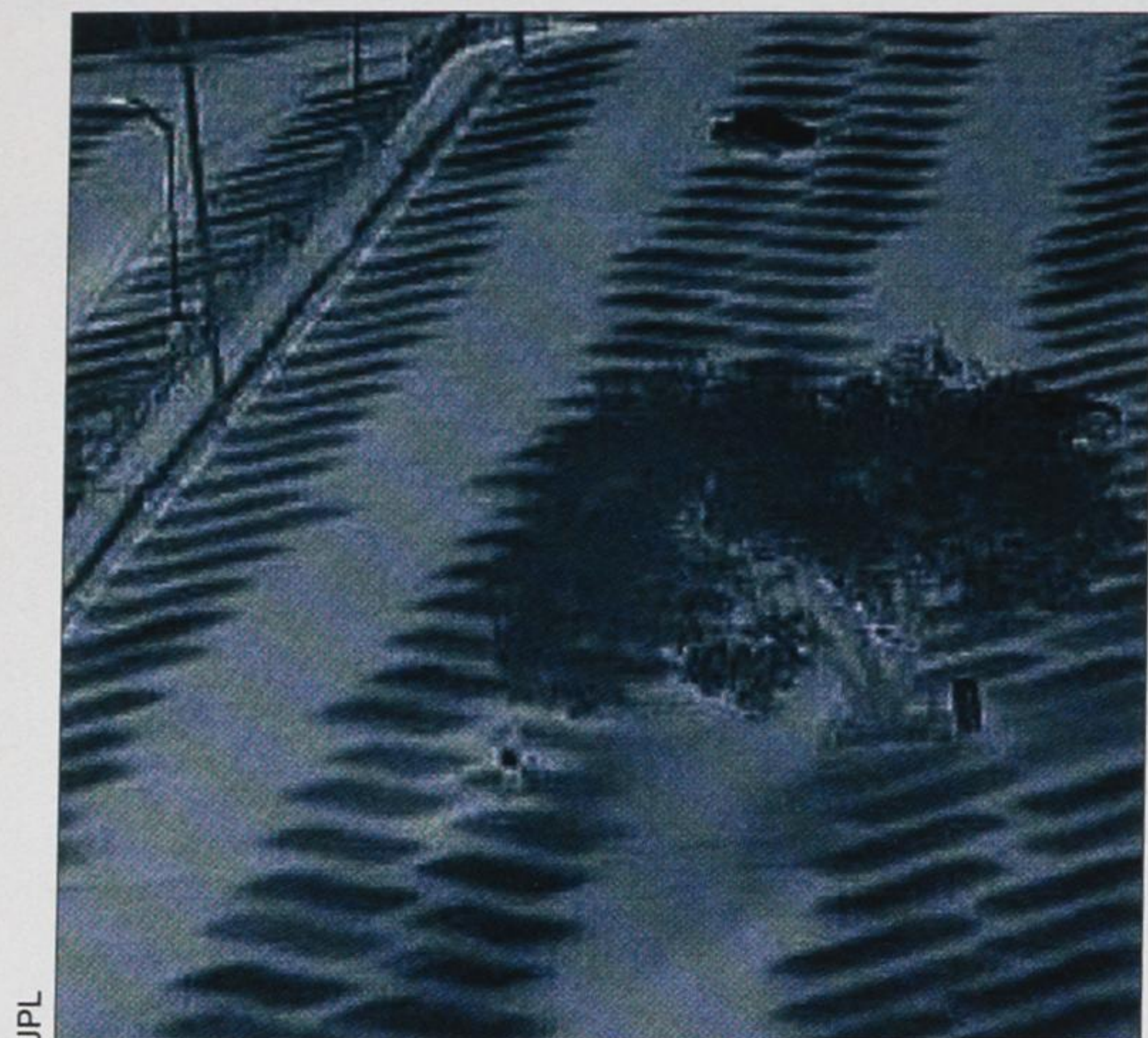


Fig. 1. JPL's singleband camera offers detailed imaging in the dark. This image was taken at midnight with a 640×512 pixel QWIP focal plane array integrated with a 330 mW integral Stirling closed-cycle cooler assembly and installed into an Indigo Phoenix camera body.

that have a relatively narrow spectral response.

Each of the bands that formed the four-band camera detected radiation only in that band, and this enabled the detector to have little or no spectral cross-talk. The design of this detector also enabled simultaneous read mode operation of the array, as opposed to the frame read mode used by other multiband FPAs. These advantages eliminated the need for moving parts, and this reduced the size of the instrument, its weight, mechanical and optical complexity, and power requirements.

The four detector bands were defined by a deep trench etch process, and the unwanted spectral bands were eliminated by electrically shorting the top detectors with gold-coated reflective gratings that provided light coupling to the QWIP stack (figure 2). The FPAs were then combined with 640×512 pixel silicon CMOS ROICs. The imager operated at a bias of -1.5 V, covered the $4\text{--}6\text{ }\mu\text{m}$, $8.5\text{--}10\text{ }\mu\text{m}$, $10\text{--}12\text{ }\mu\text{m}$, and $13\text{--}15\text{ }\mu\text{m}$ spectral bands, and was mounted onto an 84-pin leadless chip carrier. One frame of a video, taken with the camera cooled to 45 K, is shown in figure 3.

This four-band camera has been used to investigate the environmental impact of vegetation burning in Africa, and was modified by NASA's Goddard Space Flight Center to form a hyperspectral infrared camera operating over 209 wavelength bands. Detection over many bands was achieved by covering the array with several narrowband spectral filters that each selected a different spectral range.

Although this form of camera delivers mul-

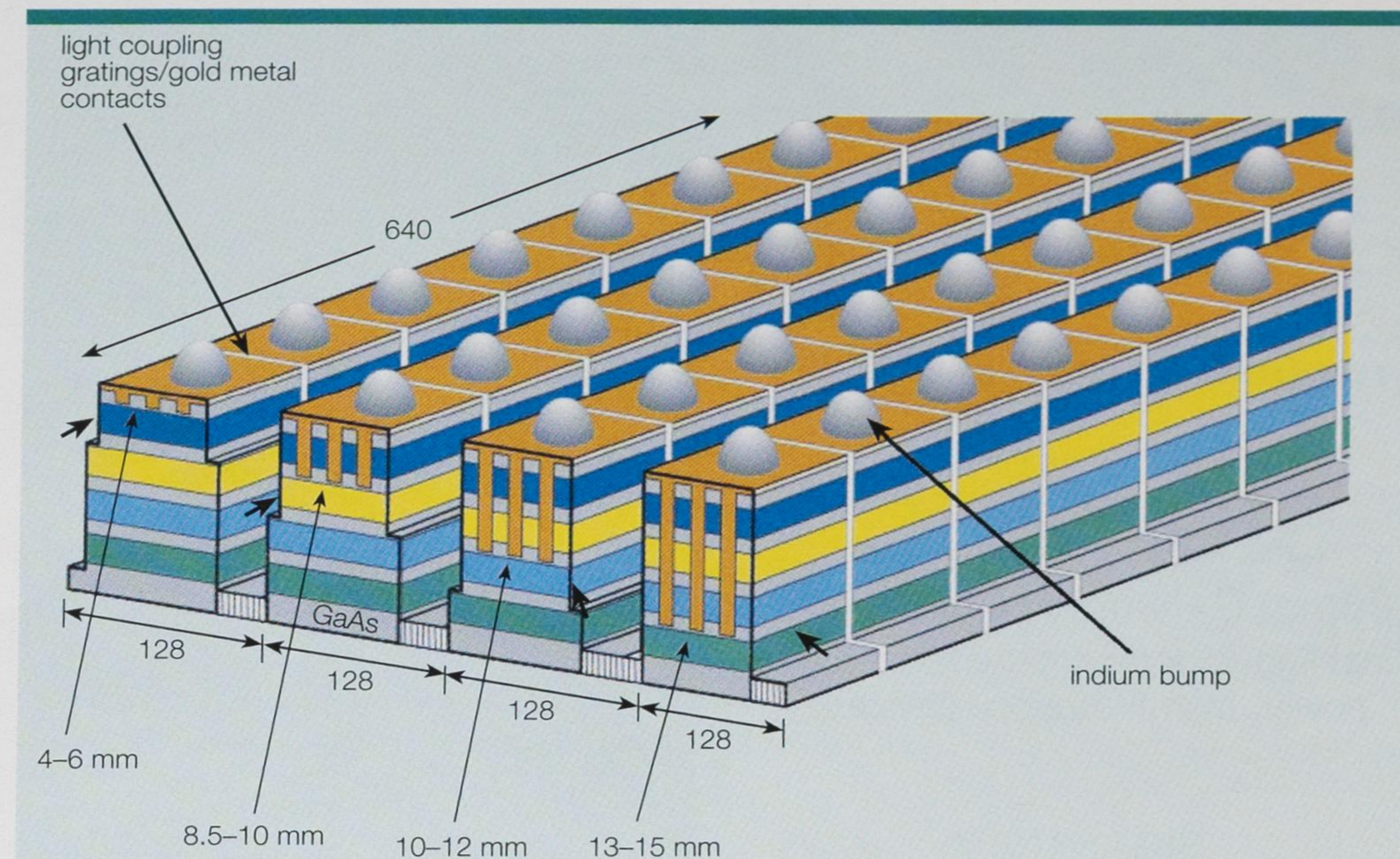


Fig. 2. JPL's fourband QWIP imager, which detects in the $4\text{--}6\text{ }\mu\text{m}$, $8.5\text{--}10\text{ }\mu\text{m}$, $10\text{--}12\text{ }\mu\text{m}$, and $13\text{--}15\text{ }\mu\text{m}$ spectral bands, has assessed the impact of vegetation burning in Africa.

tipleband performance, each pixel detects only a single spectral band. Consequently, these cameras produce images with separate regions corresponding to the intensities at different spectral ranges. This can be seen in the image of the soldering iron in figure 3. To form images that have spectral information for every band at every point in the image requires that several separate pictures are taken with the camera pointing in slightly different directions, before the results are added together. This approach can be used for certain applications, such as imaging pollution from a satellite, but it is clearly advantageous for every pixel in the array to simultaneously detect multiple spectral ranges.

Dualband cameras

JPL is now developing dualband cameras that contain an array of pixels that simultaneously detect light in the MWIR and LWIR spectral regions. These cameras are suitable for many applications. For example, the military can use them to determine the absolute temperature of a target with unknown emissivity and to differentiate between missiles, warheads, and decoys. The imagers can also be used for earth and planetary remote sensing, astronomy, and medical applications. These monolithically integrated pixel-collocated FPAs also eliminate the need for the beam splitters, filters, moving filter wheels, and rigorous optical alignment that are required in dualband systems that use two separate singleband FPAs, or in broadband FPA systems with filters.

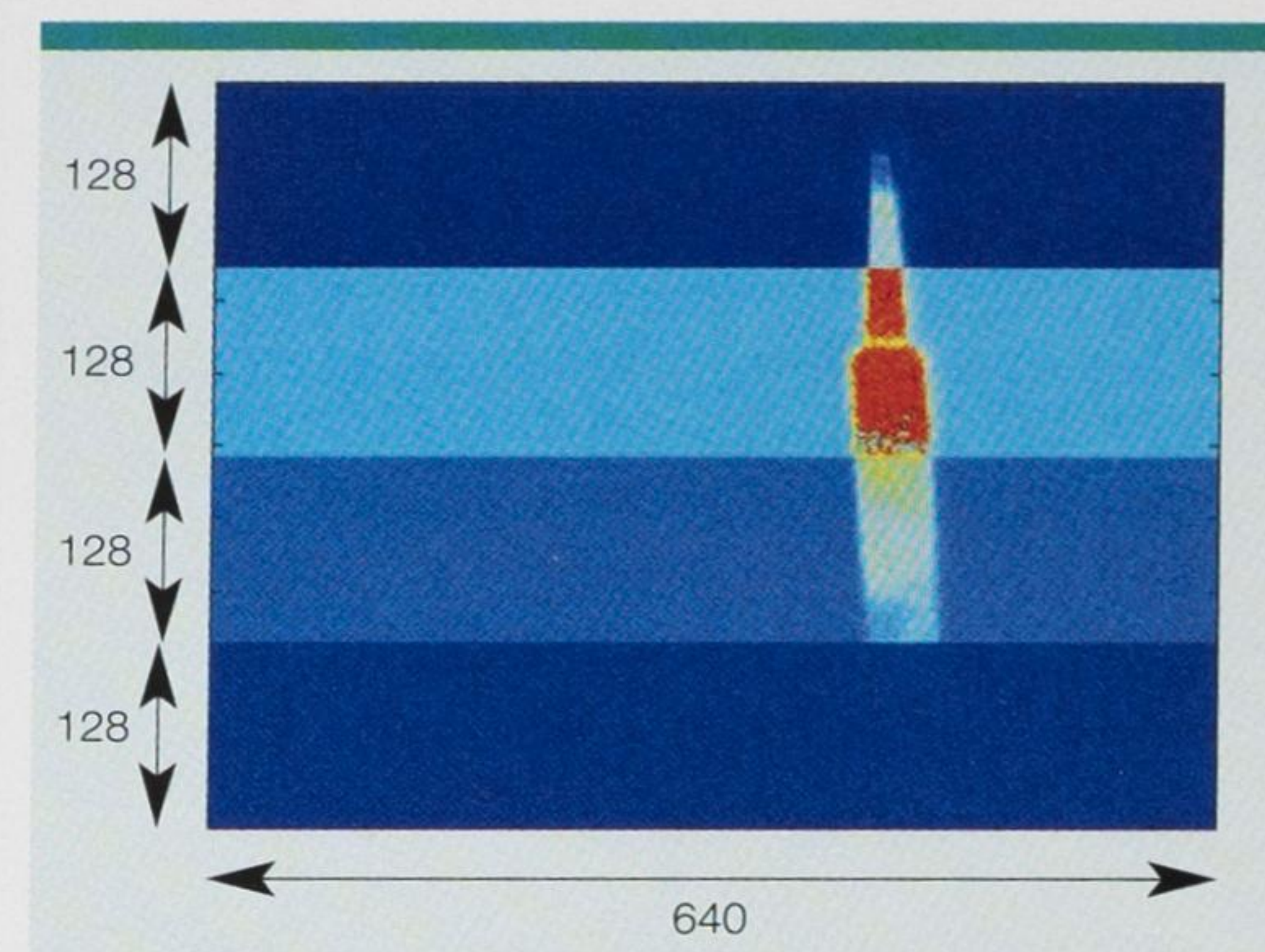


Fig. 3. Images of a soldering iron were taken with JPL's fourband QWIP. The poor optical transmission of a germanium lens coated with an antireflection layer prevented clear imaging in the $13\text{--}15\text{ }\mu\text{m}$ band.

JPL's dualband infrared FPAs use GaAs-based QWIPs, because this technology offers a narrowband response, wavelength selection, and stability. The photosensitive MQW region of each QWIP is transparent to other wavelengths, giving the imager an important advantage over conventional interband detectors. This spectral transparency also enables dualband FPAs using QWIPs to deliver negligible spectral cross-talk.

The 320×256 dualband QWIPs developed by JPL are similar to the singleband devices already described, but the two detectors are separated by an intermediate GaAs layer (figure 4). The device structures and the contact layers were grown *in situ* during a single MBE growth run. Individual pixels for the dualband

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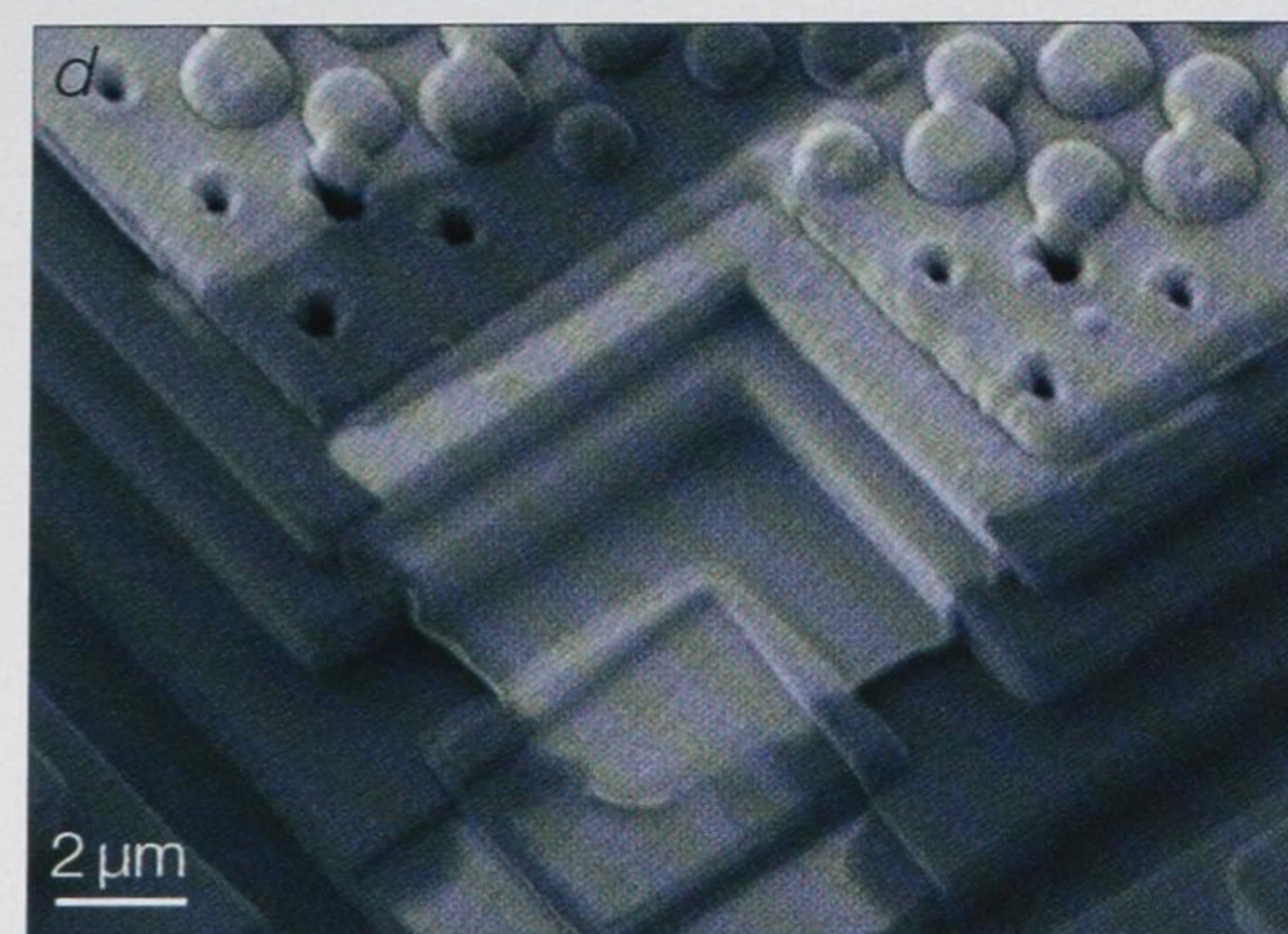
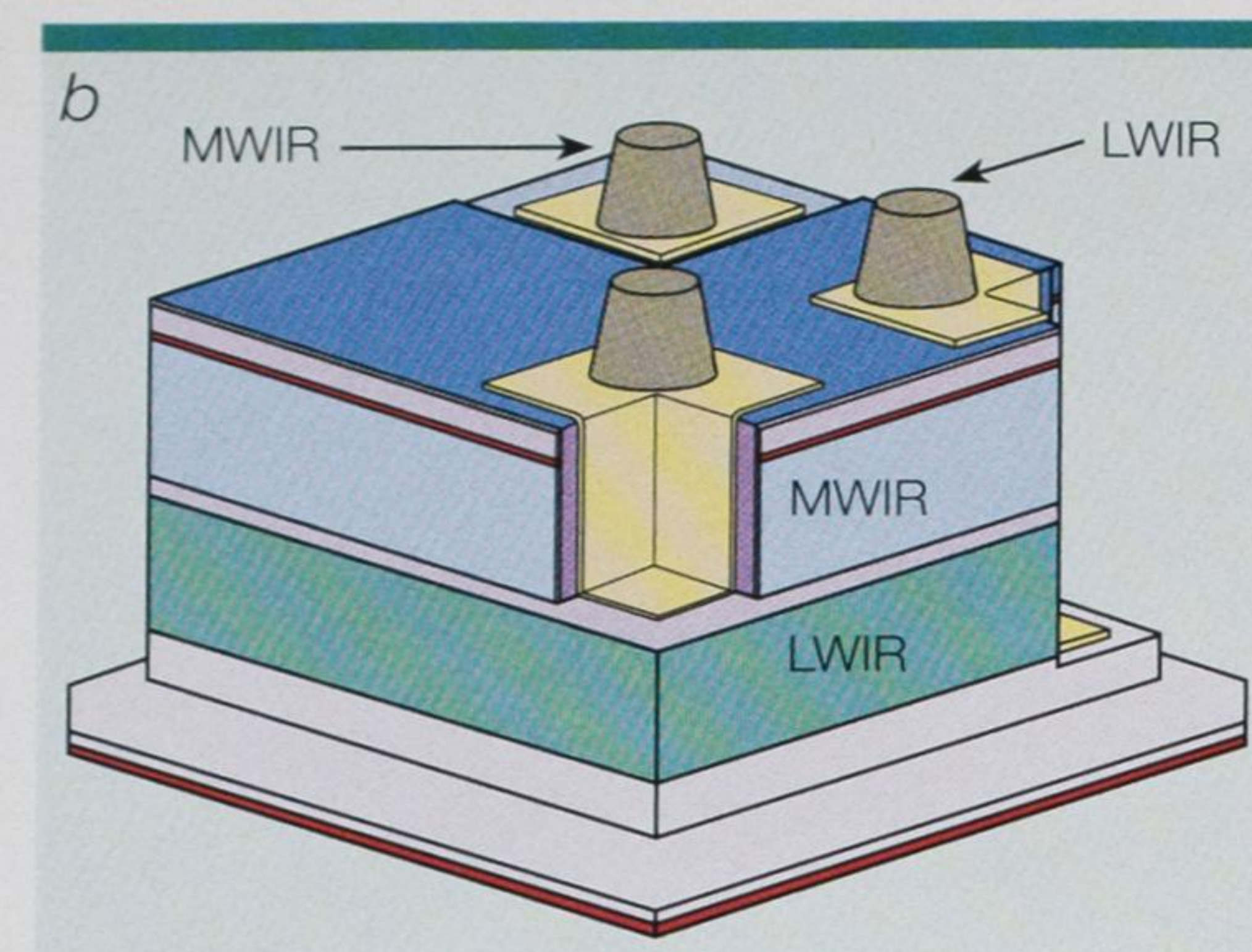
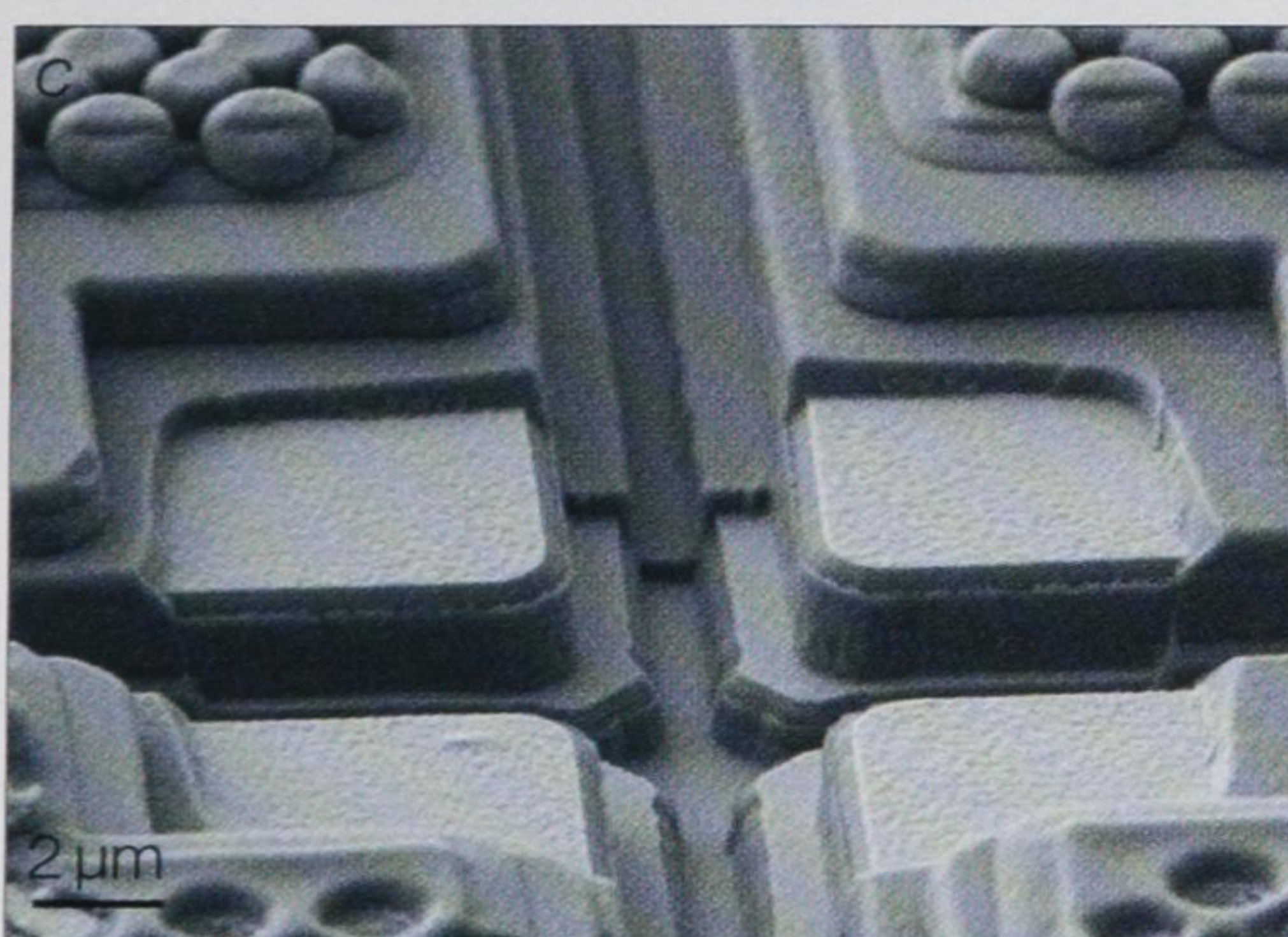
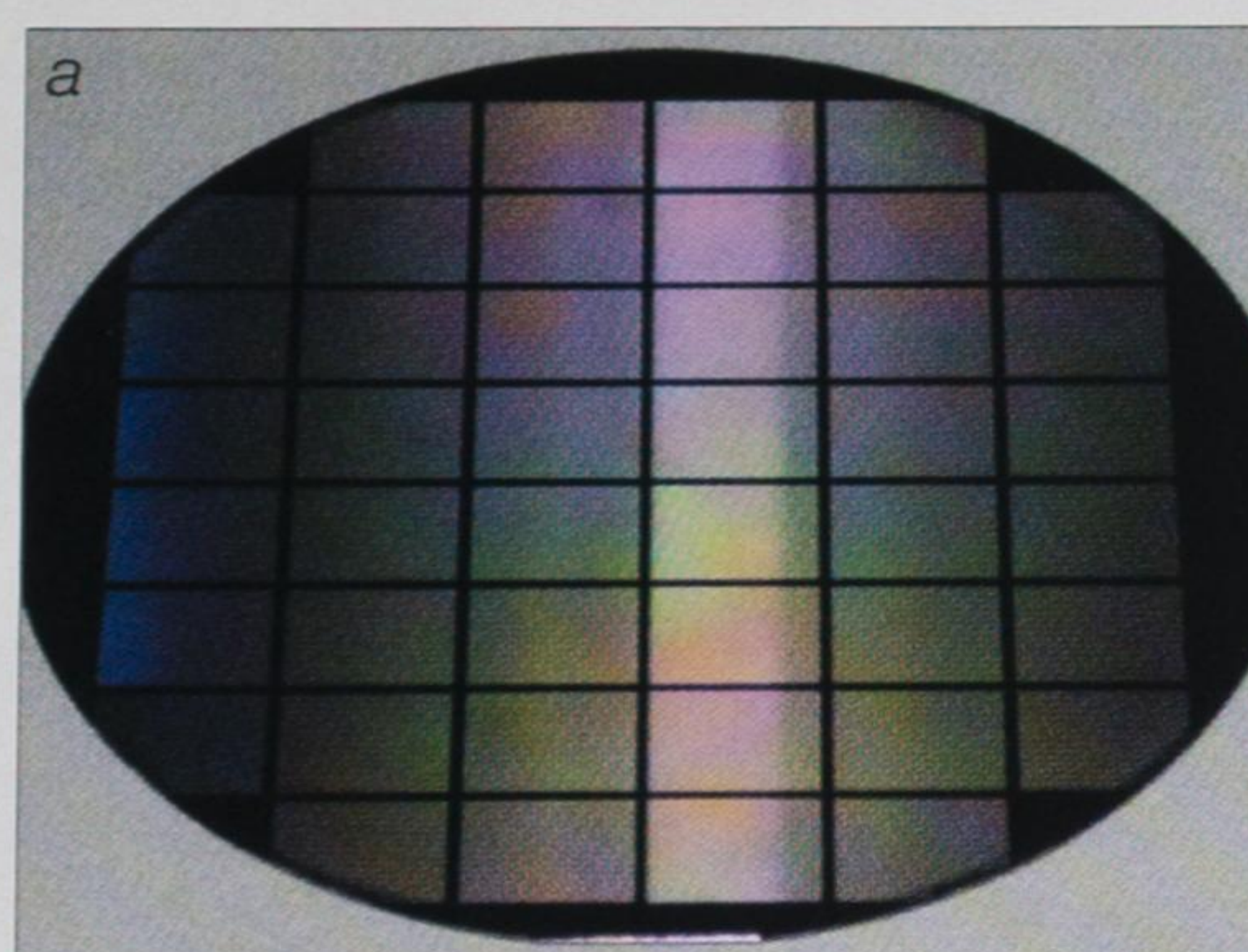


Fig. 4. (a) JPL has used 4 inch wafers to fabricate dualband QWIP devices that have the potential to differentiate between missile targets, warheads, and decoys. (b) The carriers emitted from each MWQ region are collected separately using three contacts, with the middle contact layer acting as the common contact. (c) Electrical connections to this shared contact and the LWIR pixel connection are brought to the top of each pixel using the gold via connections visible in (d).

QWIP detector arrays are fabricated using a process similar to that used for their singleband counterparts, but via holes are added to access the silicon ROIC's electrical connections.

QWIP processing

The process begins by dry etching through the photosensitive GaAs/InGaAs/AlGaAs MQW layers into the 0.5 μm -thick heavily n-type doped GaAs intermediate contact layer. This forms the MWIR 320 $\times$ 256 pixel detector arrays and via holes to access the detector common contact. LWIR pixels are then fabricated along with additional via holes to access these pixels, before a thick insulating layer is deposited and contact windows are opened at the bottom of each via hole and on the top surface. Once this is completed, ohmic contacts are added before excess metal is removed with a lift-off process.

JPL has recently produced 20 dualband detectors, each containing FPAs that have a pitch of 40 μm and an actual pixel size of 38 $\times$ 38 μm on a 4 inch GaAs wafer. The 320 $\times$ 256 pixel detectors were formed by using indium bonding to combine the arrays with CMOS ROICs.

Although the dualband cameras have yet to be tested, JPL's work has shown one route to fabricating detectors that require a single exposure to determine the temperature of an object. This work could lead to imagers that can detect three separate bands on a single pixel. This would improve the accuracy of temperature measurements and consequently the reliability of weather forecasting – a task that will be increasingly important if extreme weather becomes more common.

Further reading

S D Gunapala *et al.* 1999 *Semicond. Sci. Technol.* **20** 473.
A Goldberg *et al.* 2000 *SPIE* **4029** 276.
S D Gunapala *et al.* 2003 *IEEE Trans. Electron Devices* **50** 2353.

Sarath Gunapala is group supervisor of the NASA Jet Propulsion Laboratory's QWIP program. Sarath acknowledges the contributions of colleagues Sumith Bandara, Cory Hill, John Liu, Jason Mumolo and David Ting, and thanks Dr Meimei Tidrow of the Missile Defense Agency, and the NASA Office of Space Science for financial support.

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MEETING HIGHLIGHTS

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Graduate students who are interested in assisting in the symposium rooms during the 2006 MRS Spring Meeting are encouraged to apply for a Symposium Assistant position. By assisting in a minimum of four half-day sessions, students will receive a complimentary student registration, a one-year MRS student membership commencing July 1, 2006, and a stipend to help defray expenses. Applications will be available on our Web site by November 1.

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A Career Center for MRS members and meeting attendees will be offered in Moscone West during the 2006 MRS Spring Meeting.

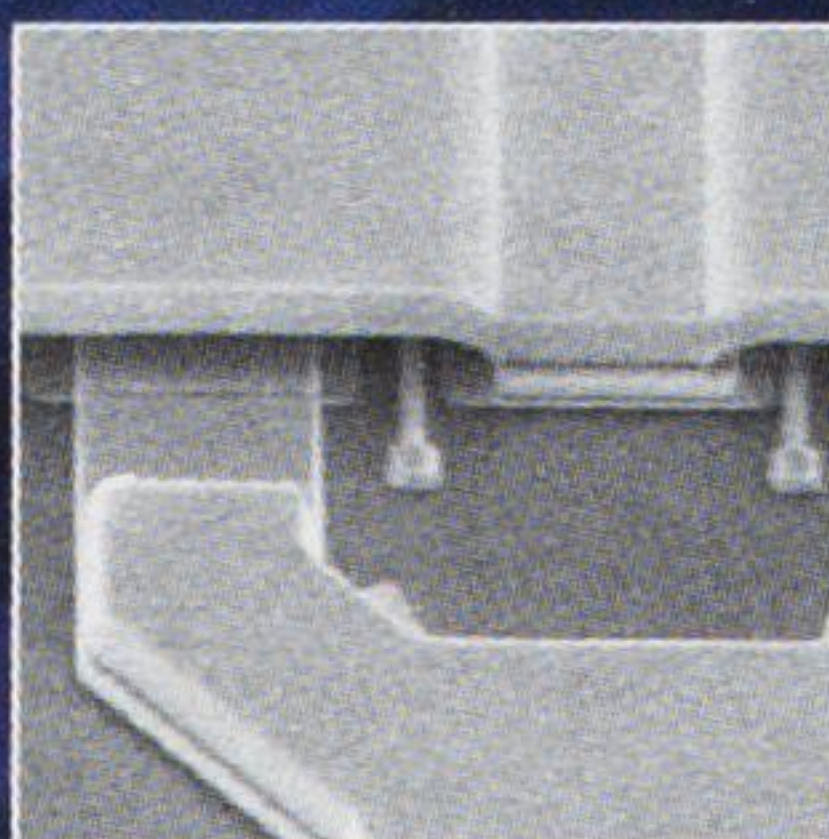
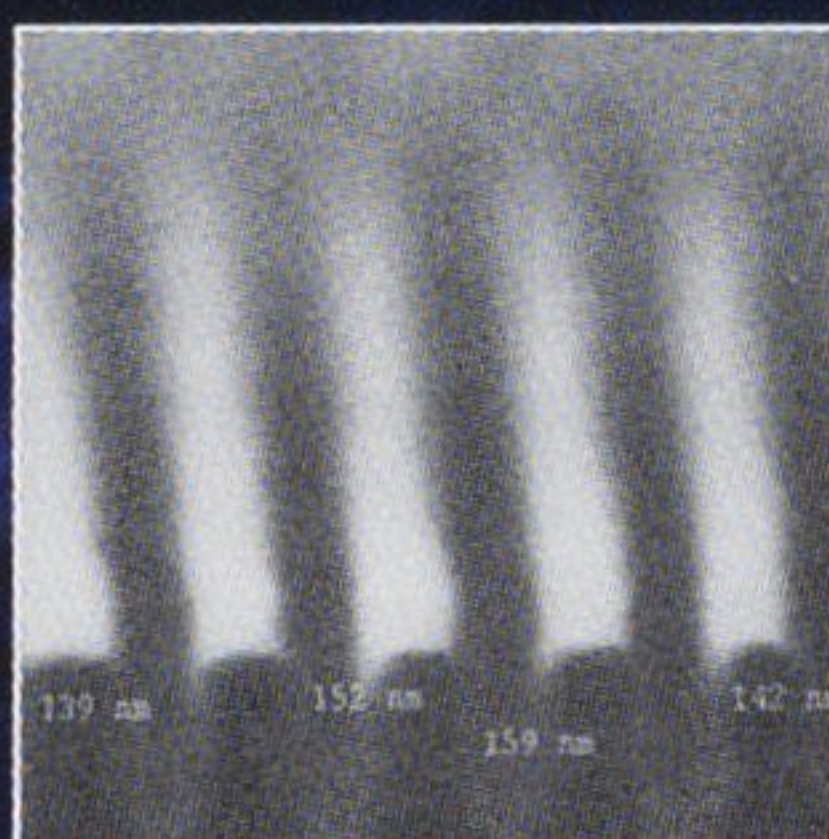
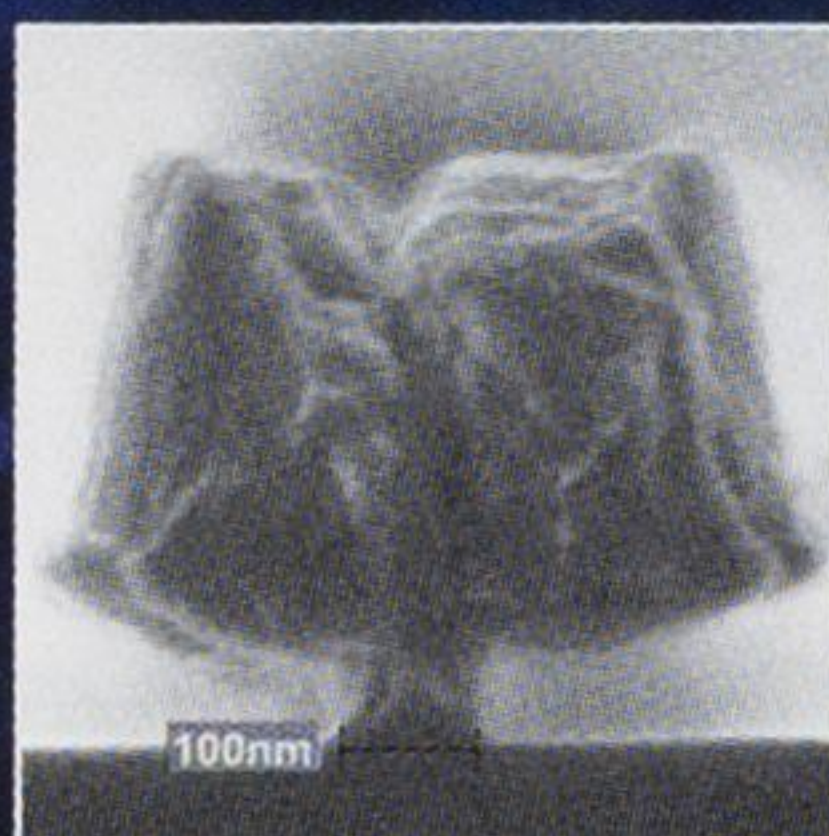
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Consumer diversification aids Finisar's march to profitability

Fiber-optic component manufacturers Finisar and Avanex believe their financial and technological strategies will bear fruit next year in the form of profitability.



Avanex is facing the prospect of being de-listed from the Nasdaq exchange after its stock price bumped along at less than \$1 for 30 consecutive days recently.

As the situation appears to be looking up in the photonic components business, the big question now is this: when will the improving conditions translate into profitability for optoelectronic chip manufacturers?

Two of the major suppliers – Avanex and Finisar – have indicated in recent presentations to the investment community that they expect this to happen in 2006.

Both believe that they will post an operating profit next year as revenues steadily increase and the results of cost-cutting actions coincide on what Finisar CEO Jerry Rawls calls “the march to profitability”.

Finisar certainly seems to be making some decent headway in that direction. As revenue from the Infineon business it acquired early this year kicked in, Finisar’s top line of \$81.7 million in its most recent quarter represented the highest yet recorded in company history. What’s more, its cash balance figures over the past year indicate a near-negligible rate of cash burn (see graph, below). Finisar’s cash reserves have also been boosted by \$12 million resulting from the sale of Sensors Unlimited, in which it held a minority stake, to aerospace giant Goodrich.

An even more promising sign is that Finisar’s operational improvement was largely due to sales from its optics business unit rather than its network tools divi-

sion. In the three months that ended July 31, optics revenue was up 35% on the same period last year. The acquired Infineon product lines contributed around 40% to this increase, indicating a pretty healthy “organic” yearly growth rate of 20%.

One important factor in Finisar’s favor is that it does not rely too heavily on any single customer, with Cisco the only one to represent more than 10% of sales. Rawls now estimates that Finisar is the number-one optical module supplier in the storage area network (SAN) sector and is level with Agilent Technologies in local area networks (LANs). And with Agilent in the hands of a private equity group, there is perhaps an opportunity for Finisar to capitalize.

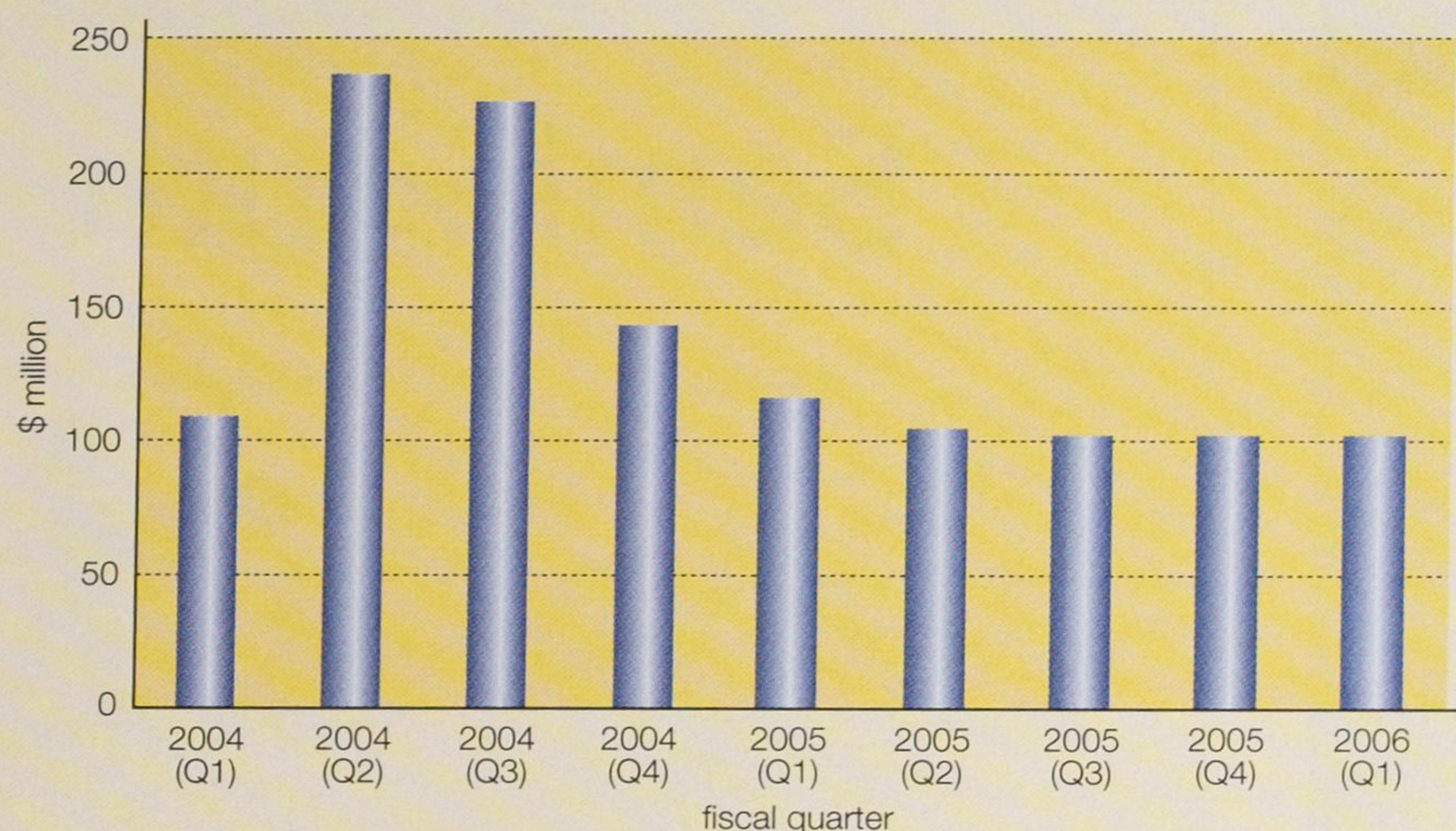
Away from the telecoms arena, Finisar is set to compete with Agilent in the consumer-led world of computer peripherals for the first time. That’s because VCSEL technology acquired by Finisar when it bought Honeywell’s laser diode business is now being exploited in a mouse designed by leading peripherals supplier Logitech – a company that uses Agilent optics in its existing laser-based mouse products.

Mass-production of these new optical mice, featuring VCSELs and an integrated monitor photodiode made by Finisar’s Advanced Optical Components (AOC) division, is scheduled to begin in the final quarter of this calendar year. That should give Finisar penetration into a high-volume consumer market to augment the cyclical telecoms business. The Sunnyvale, CA, company is also hoping to penetrate the automotive datacom market in a further sign of diversification.

Rawls says that the VCSEL structures, which are manufactured at the company’s wafer fab in Texas, could even find volume application in identification devices, printers and mobile phones.

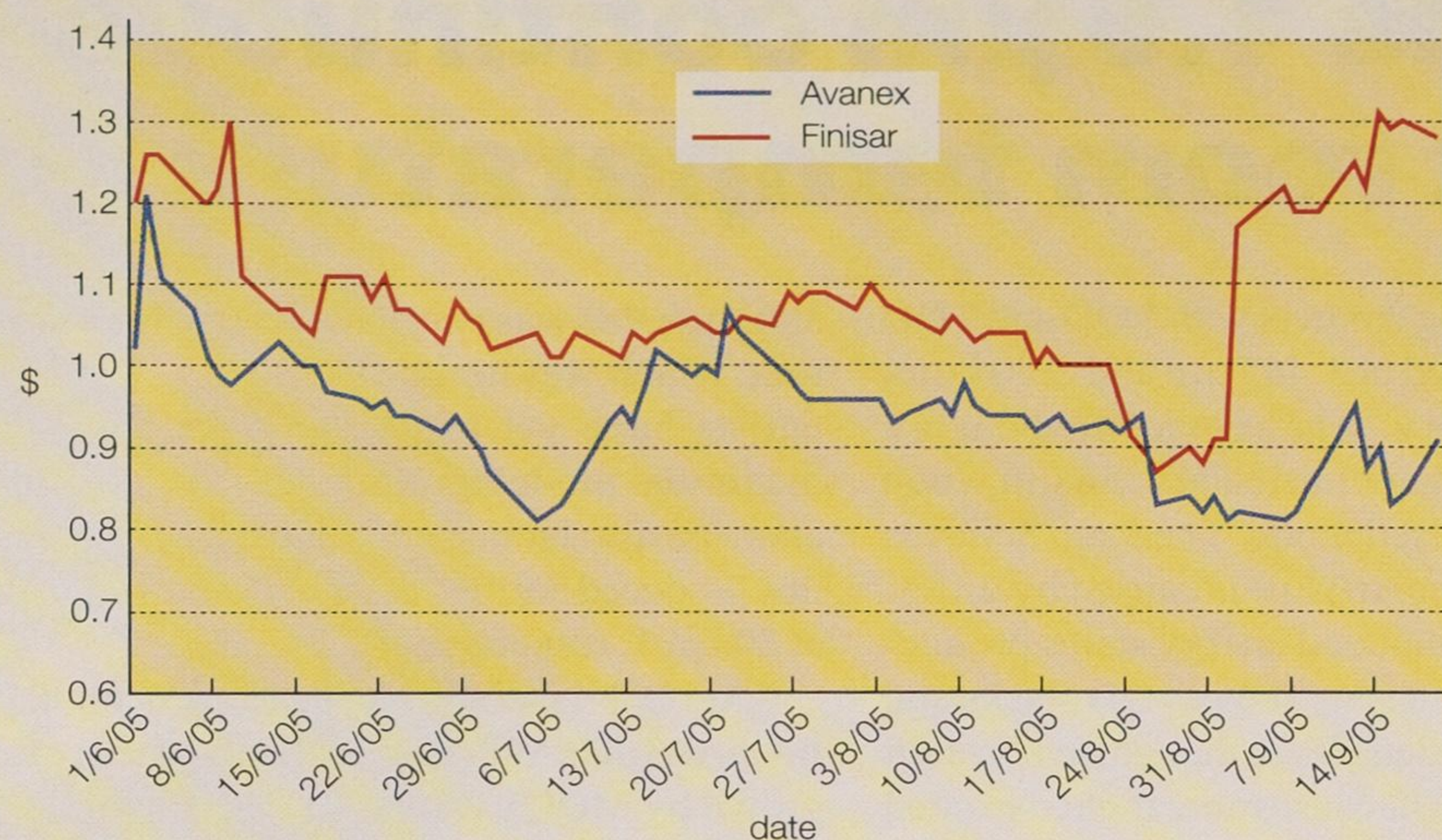
After factoring all of that, as well as a fast-dropping revenue break-even point, into his financial predictions, Rawls estimates that Finisar will be able to post an operating profit in the third quarter of fiscal 2006, which ends in January next year. If he’s right, Finisar will be generating cash flow at that point, with more cost reductions set to follow as chips manufactured at Finisar’s Fremont fab are incorporated into modules that previously featured lasers supplied externally.

“It has been four years since the Internet boom collapsed, forever changing the competitive dynamics of our industry,” remarked the CEO in a recent conference call. “We have reached a point where our highest



Stopping the rot: Finisar has managed to contain its cash burn over the past year, with cash, cash equivalents and short-term investments stabilizing around the \$100 million mark. The company expects to begin generating cash and post an operating profit within the next two quarters.

SOURCE: YAHOO FINANCE



Bumping along: Avanex was threatened with Nasdaq de-listing after its share price traded below \$1 for 30 consecutive business days in the summer. Finisar looked to be heading for a similar warning until investors were encouraged by the company's 2006 first-quarter results and outlook.

priority is our march to profitability.”

As Finisar jostles with JDSU and Agilent for the leading positions in the fiber-optic components market, another local rival in the form of Avanex is also sound-

ing the profitability horn.

Recent downsizing, including a workforce reduction of 60% at its fab in Nozay, France, as well as the completion of a plan to consolidate module manufacturing operations into its Thailand facility, should be almost completed by the end of this year. Excluding costs resulting from that restructuring process, Avanex now says that it will be generating cash by June 2006.

Whether that will convince any would-be investors is not certain, bearing in mind that Avanex is facing the prospect of being de-listed from the Nasdaq exchange after its stock price bumped along at less than \$1 for 30 consecutive days recently. Further worries may result from an audit by Deloitte and Touche, which indicated accounting problems and a need for Avanex to raise more cash to survive. Finisar's stock had been looking set to face a similar fate until a sharp uptick in late August (see graph, left).

Another of Finisar's competitors, Bookham, has been rapidly burning cash for years, but it has made a series of recent moves towards boosting its liquidity. A tax break worth nearly \$12 million and the sale of land in the south of England for \$15 million have had an immediate positive effect, while the company plans to add cash to the balance-sheet through another public offering of stock that could potentially realize a further \$35 million. ●

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InP QD laser yields 1.5 μm continuous-wave emission at room temperature

The first InP-based quantum dot (QD) lasers capable of continuous-wave operation at room temperature have been produced by a collaboration involving Sungkyunkwan University and Chungnam National University in Korea, the University of Southern California, and Korean epiwafer manufacturer NanoEpi Technologies (*Appl. Phys. Lett.* **87** 083110).

The 1.5 μm QD lasers are suitable for telecommunication applications and have the potential to deliver higher-speed operation than today's quantum well lasers by exploiting the device's low chirp characteristics.

The researchers fabricated various QD

lasers, including emitters with 5 QD and 7 QD stacks that lased at 1.445 μm and 1.503 μm , respectively, as well as a device containing a 15 QD stack that emitted at 1.56 μm when operated in pulsed mode. The team believes that the wavelength shift is caused by differences in the quantized energy states producing the gain for lasing. Fewer QD stacks and a shorter cavity length are thought to blueshift the wavelength because more higher-excited states are involved in producing the gain.

Team member Weon Jeong told *Compound Semiconductor* that the 5 QD stack laser could deliver a maximum output power of 7 mW,

although this was restricted by the drive current, which was limited to 100 mA. The scientists have yet to measure the device's maximum modulation speed. The collaboration has also fabricated 7 QD and 3 QD lasers that produced 8.9 mW at 500 mA and 11.8 mW at 200 mA, respectively.

The QD lasers were all based on the InGaAs/InGaAsP/InP material system and grown by MOCVD on (001) InP substrates. The InGaAs QD's composition was used to optimize its optical quality, while the InGaAsP barrier's bandgap was adjusted to maintain the emission wavelength.

Cool GaN-on-silicon growth enables silicon-style processing

Scientists at Arizona State University have developed a very-low-temperature growth method for epitaxial GaN-on-silicon substrates (*Appl. Phys. Lett.* **87** 072107). The technique involves depositing an intermediate ZrBr₂ buffer layer before growing a GaN film using a novel single-precursor gas source.

The researchers claim that the growth process is compatible with low silicon processing temperatures, and unlike the conventional MOCVD technique can be used for direct epitaxy of GaN on ZrBr₂.

The team selected MBE to deposit a 25 nm-thick ZrBr₂ buffer layer onto a silicon (111) substrate using the gas source Zr(BH₄)₄, before growing a GaN film from the perdeuterated gas D₂GaN₃. The GaN film's growth rate increased "substantially" to 3–4 nm/min under photo-excitation by ultraviolet light at 500–550 °C.

This growth process produced smooth layers with a uniform thickness and a surface roughness, determined by atomic force microscopy measurements over a 10 μm $\times$ 10 μm area, of 1–1.5 nm. These measurements sug-

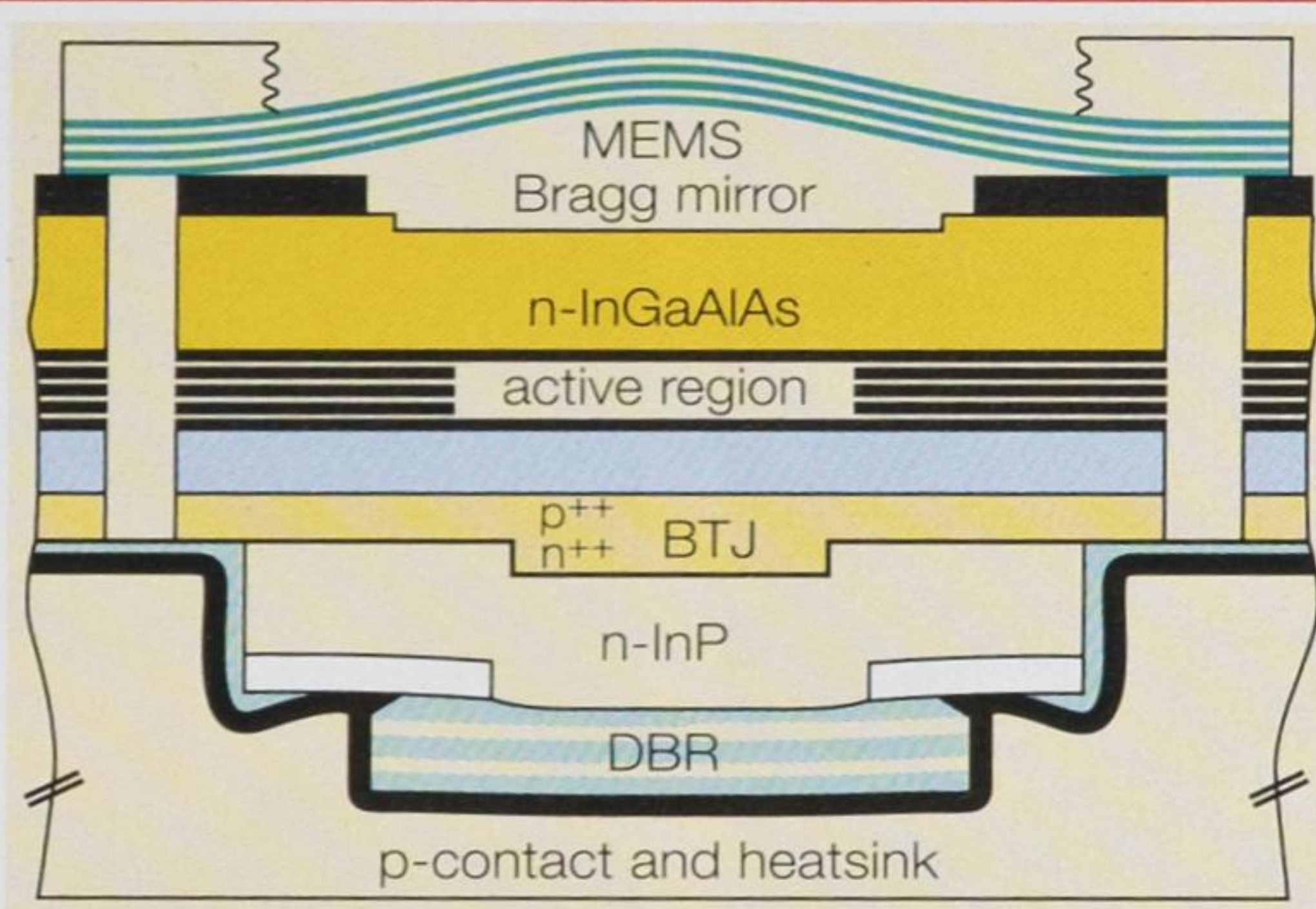
gest that the epitaxial growth process is based on the coalescence of columns that lead to a planar surface morphology.

Team member John Kouvetakis revealed that the researchers are investigating the growth of nitride-based heterostructures and aim to eventually fabricate LEDs. Kouvetakis said that the ZrBr₂ buffer layer is suited to LED growth – the layer is highly reflective, which prevents light loss into the silicon substrate; it is conductive; and it is latticed-matched to Al_{0.2}Ga_{0.8}N layers that feature in LEDs.

Micromirror boosts singlemode VCSEL

Researchers in Germany have fabricated a VCSEL with a micromirror that is claimed to offer the best combination of high output power, sidemode suppression and polarization control (*Elec. Lett.* **41** 966).

Conventional VCSELs that could be used for optical communication deliver singlemode output by using aperture dimensions below 5 μm , but this limits the output power. If larger apertures are used the cavity forms a multimode waveguide, and sophisticated techniques are required to maintain singlemode operation. However, by fabricating a VCSEL with a micro electromechanical (MEM) mirror, the researchers from the universities of Munich and Darmstadt have built a laser with a 12 μm -diameter active region that produces high output powers in the 1.5 μm range.



The micromirror 1560 nm VCSEL, which incorporates a buried tunnel junction (BTJ), delivers record singlemode optical power coupling into single- and multimode fiber.

The laser produces record singlemode coupling into multimode fiber and lensed single-mode fiber of 2.8 mW and 19 mW, respectively. The device produces sidemode suppression greater than 48 dB for the transverse mode, and 34 dB for the polarization mode.

The laser was formed by fabricating an active chip and a MEM Bragg mirror on separate wafers, before bonding two structures together with adhesive. The active device was grown by MBE, and comprises an InGaAlAs multiple quantum well amplifying region, a buried tunnel junction current aperture, an InP current and heat spreading layer, and a thin dielectric distributed Bragg reflector (DBR). The top structure is a 16.5 period GaAs/Al_{0.86}Ga_{0.14}As DBR that incorporates a graded indium content. This causes an intrinsic stress gradient that defines the mirror geometry.

Researcher Benjamin Kögel says that the two-chip concept offers an accelerated technique to independently optimize the active part of the half-VCSEL technology, the MEM Bragg mirror, and the combination of the two chips in various device designs. He added that the team is also developing a monolithic integration approach with inductive coupled plasma CVD growth of the micromirror.



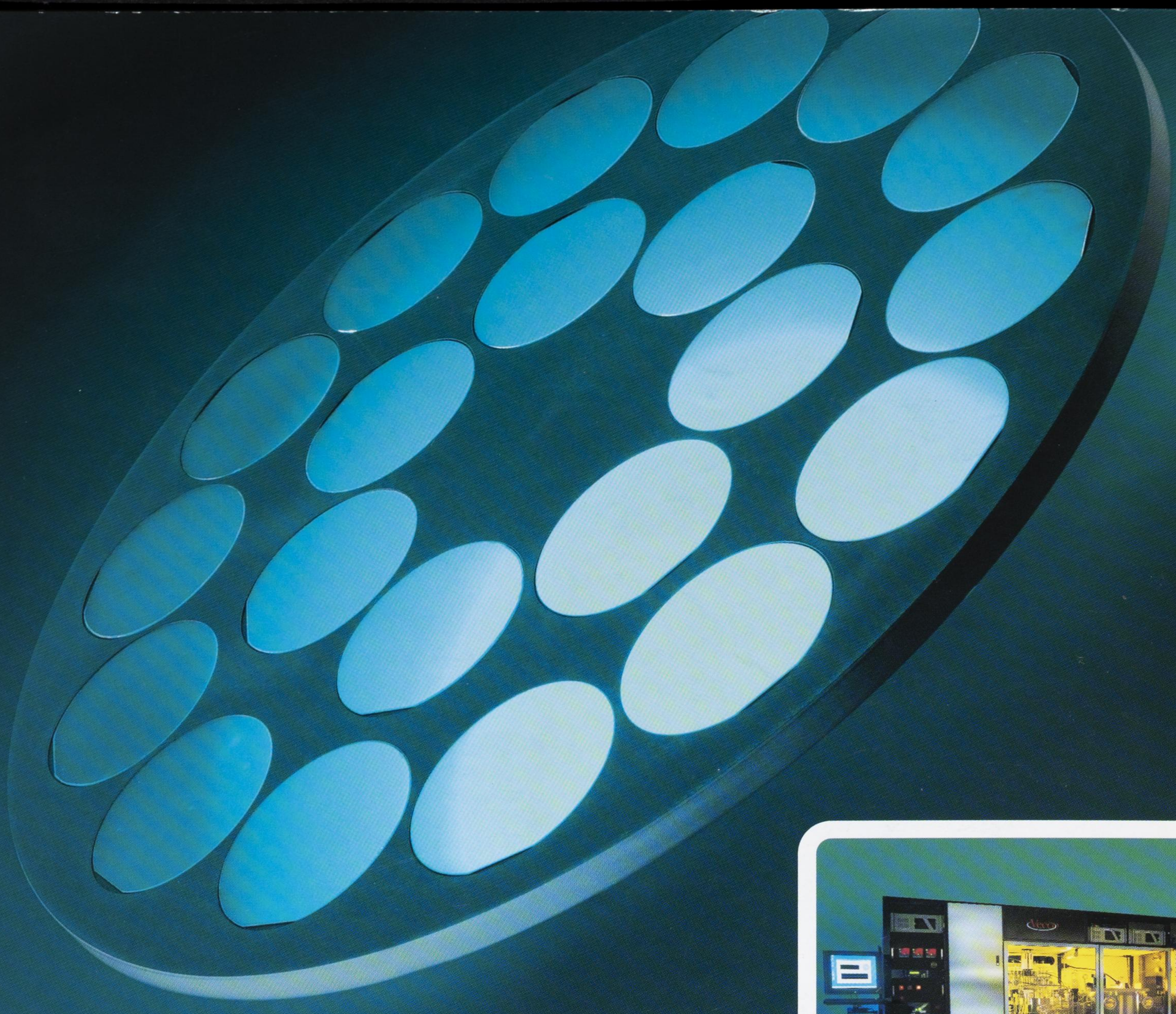
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