

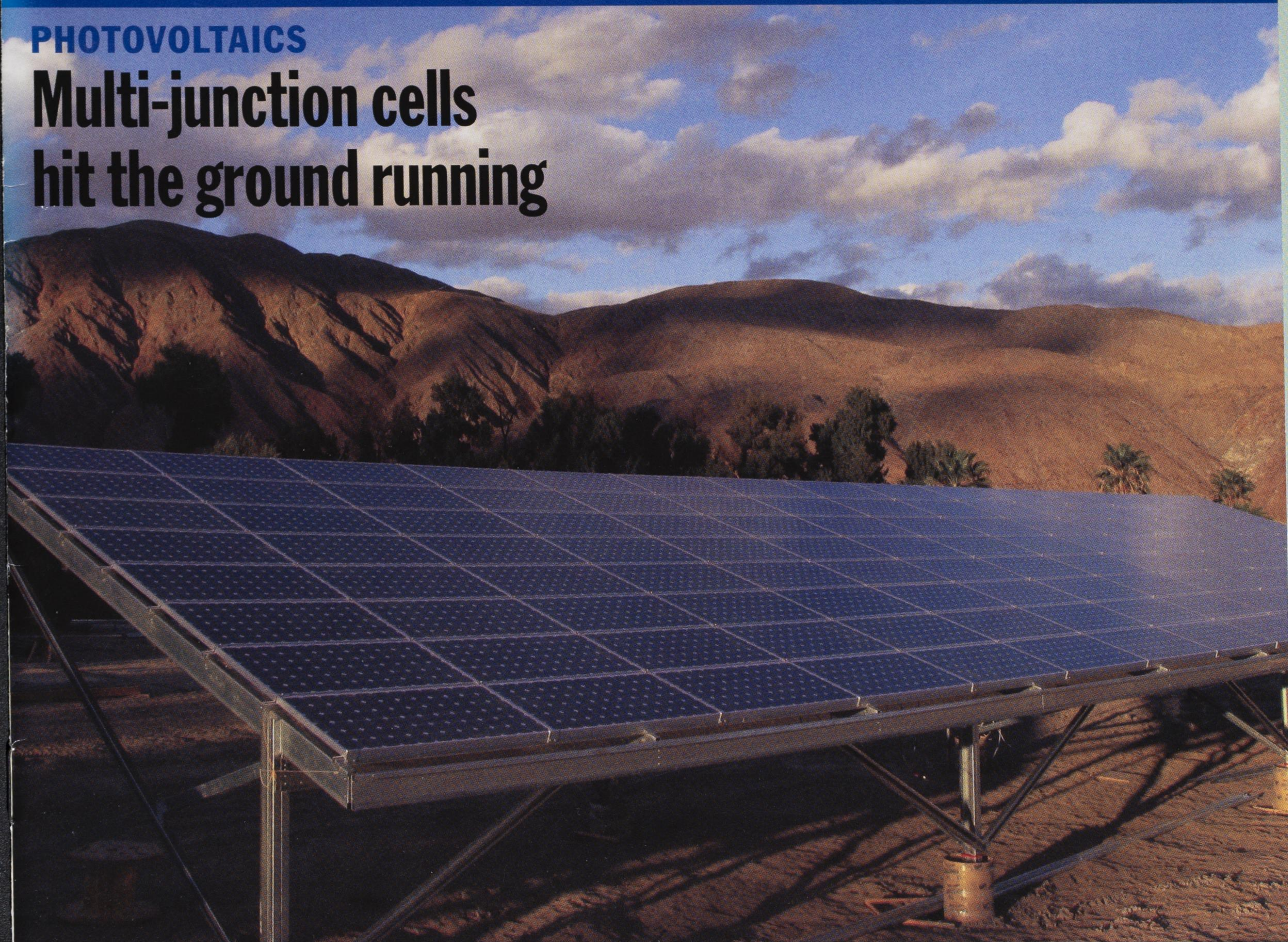
COMPOUND SEMICONDUCTOR

December 2006 Volume 12 Number 11

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

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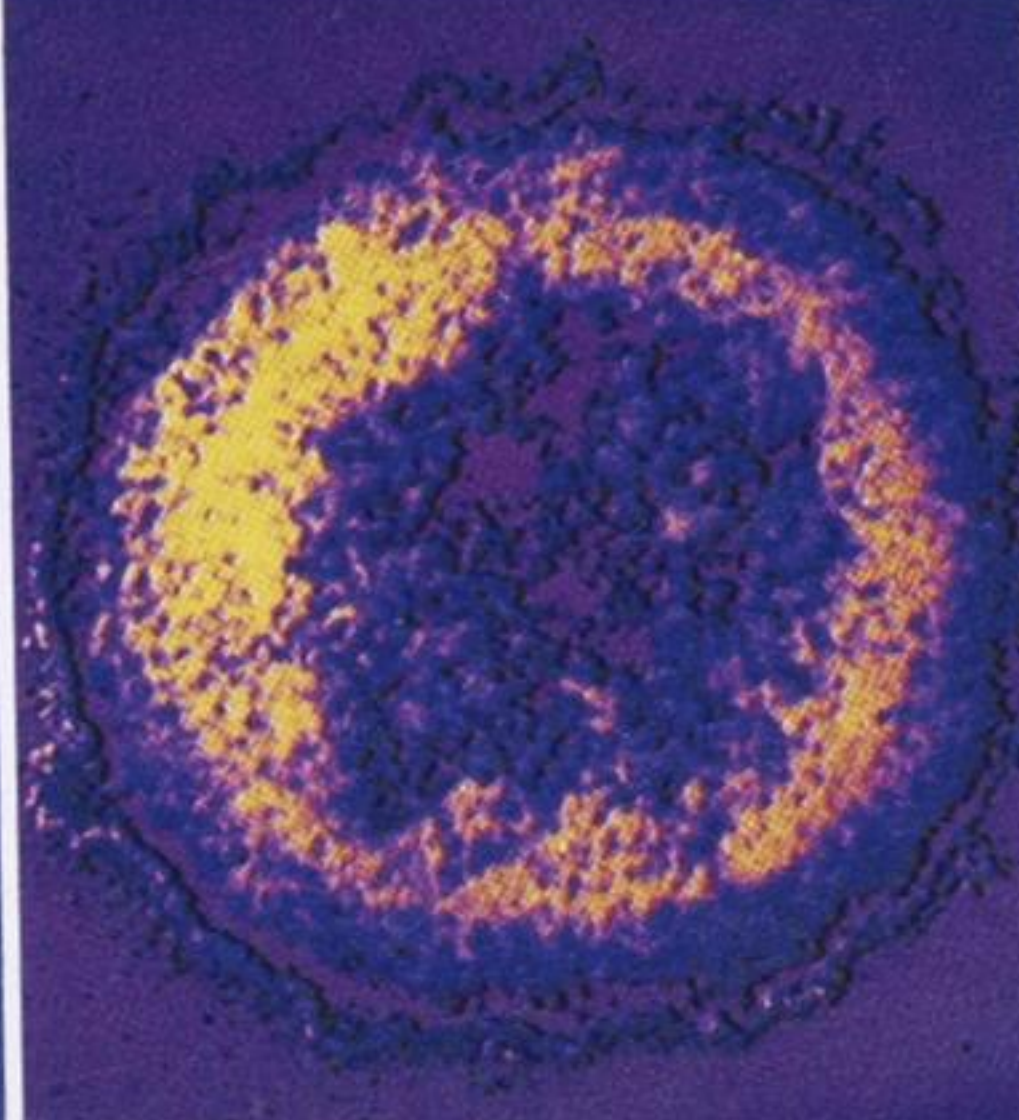
Multi-junction cells hit the ground running



PORTFOLIO

**MOCVD orders
roll in at Veeco
and Aixtron p11**

TECHNOLOGY



Nitrides get medical

A new breed of GaN-based sensors could aid early-stage disease diagnosis. **p24**

INTERVIEW



The military view

Laura Rea reveals a different approach to semiconductor materials research at the US Air Force. **p12**

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Expanding market

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TECHNOLOGY

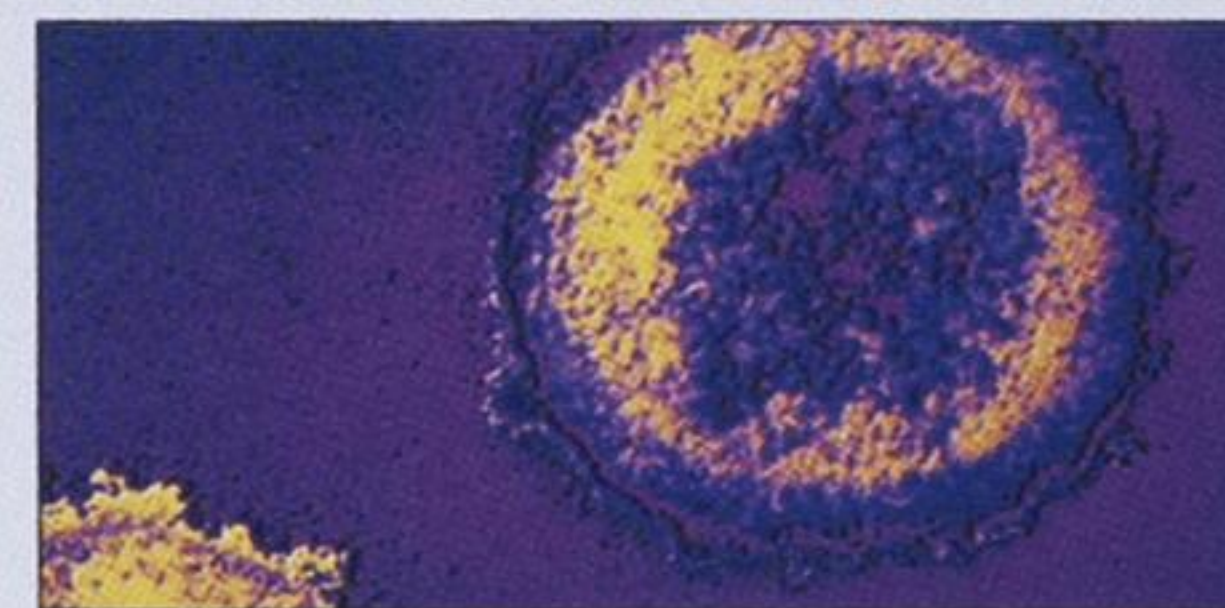
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Medical marvel

GaN-based analytical tools may soon help to detect conditions such as cancer, AIDS and Creutzfeldt-Jakob Disease. **p24**

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Main cover image: Photovoltaics is the current darling of the venture capital community, and compound semiconductor companies are set to benefit. Image courtesy of WorldWater and Power.

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All about Emcore



It's never a problem filling the news pages of *Compound Semiconductor*, in fact it's much more of a struggle trying to squeeze in as many stories as possible. But this month I could have dedicated the entire front half of the magazine to news about Emcore and its various legacies in the compounds industry.

Leaving aside its internal investigations into stock option shenanigans – an issue that must be sending corporate legal teams at publicly-traded firms into meltdown – just take a look at the sphere of influence of this pioneering New Jersey company: Veeco's TurboDisc equipment division, acquired from Emcore in 2003, is witnessing a massive rebound in MOCVD orders (p11); Velox, an Emcore spin-off, has signed a licensing and manufacturing deal with the top-tier silicon house ST Microelectronics (p7); and Gelcore, in which Emcore owned a half-share until a few months ago, has landed a potentially enormous contract with supermarket chain Wal-Mart to install LED-based refrigerator lights (p9).

And there's more. Emcore has just inked two major deals to supply III-V solar cell assemblies – one worth \$41 million in the traditional space market, where its cells will power some 10 individual satellite payloads and another worth “up to” \$100 million for terrestrial applications with World Water and Power (p5). It shows how influential the company, which started off in 1984 with a focus on the core epitaxy techniques of MBE and MOCVD, has become. And it certainly makes me think that wherever Emcore is headed must be a direction that everybody else in the compounds sector should take a very close interest in.

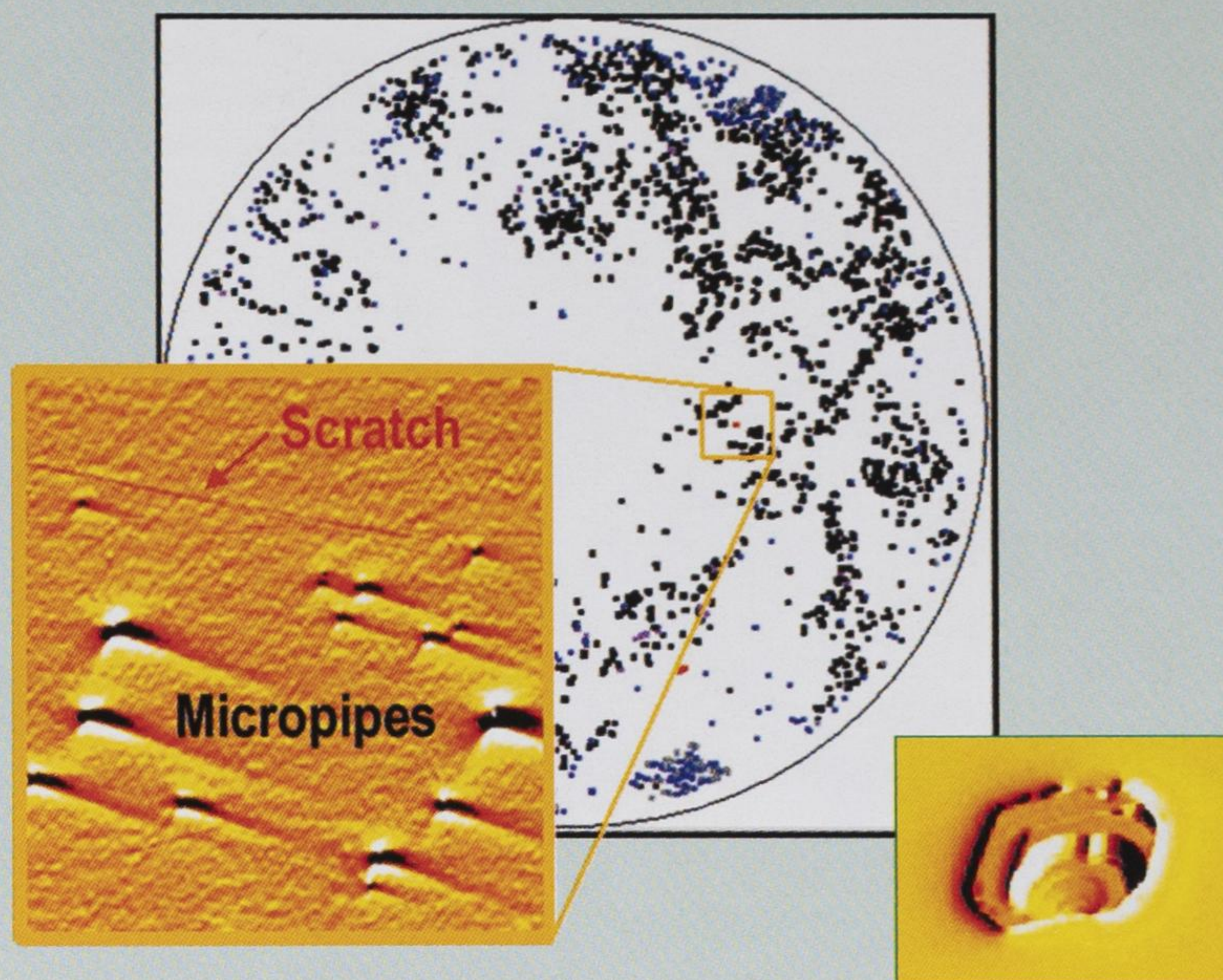
At the moment, that direction is pretty clear – solar energy. Emcore's photovoltaics divisional head has estimated the size of the global market for terrestrial photovoltaic systems at over \$10 billion. Until very recently, precisely none of that sector had been colonized by multi-junction solar cells based on compound semiconductors.

Emcore is betting on that situation changing significantly as the market size grows in swift fashion to around \$30 billion by 2010. Already the new darling of the venture capital community, photovoltaics is also reckoned by some financial analysts to be the fastest-growing industry in the world. Can III-V cells carve out a healthy chunk of that market? Emcore thinks so, and I for one would not want to bet against them being right.

Michael Hatcher *Editor*

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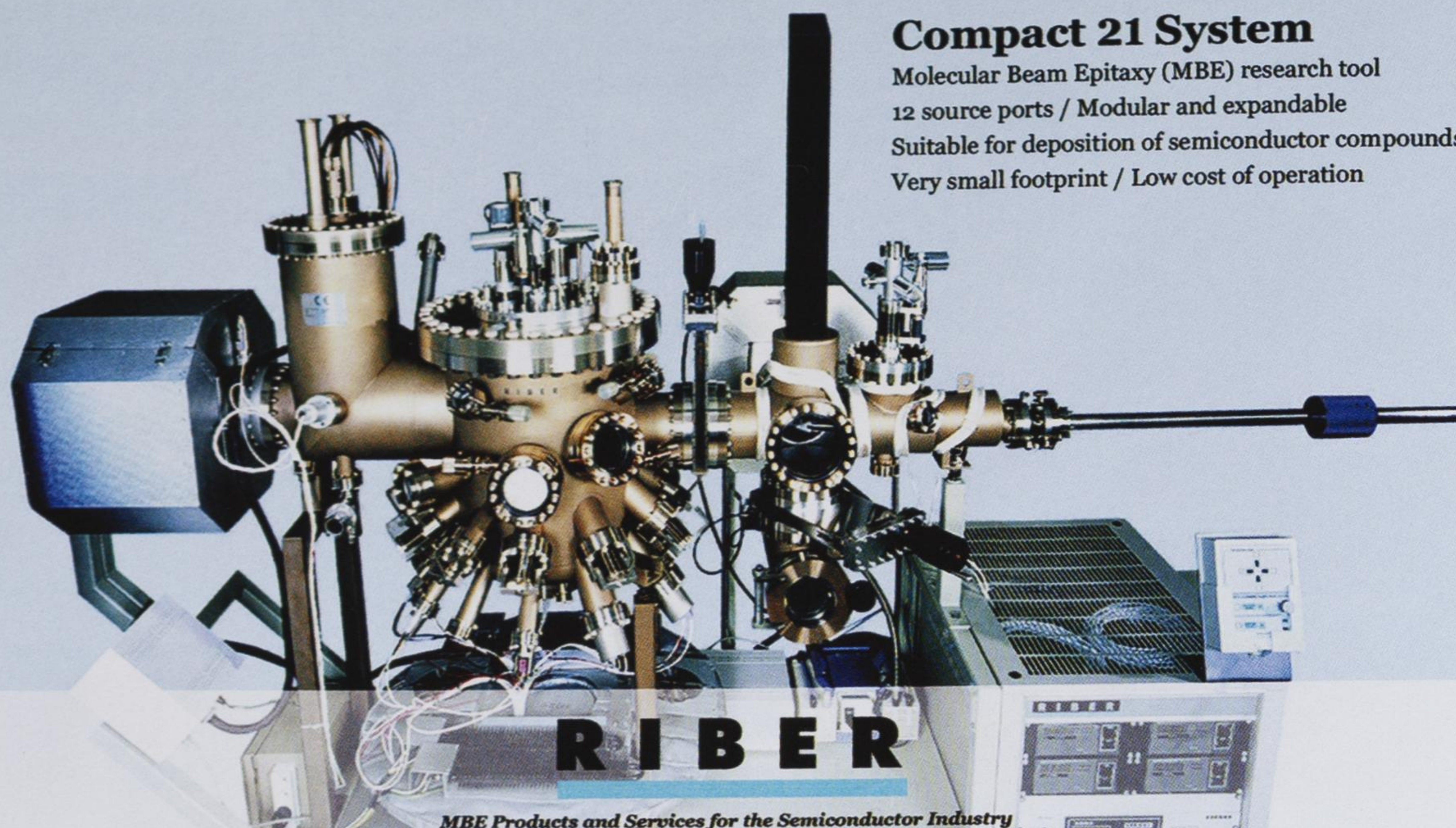
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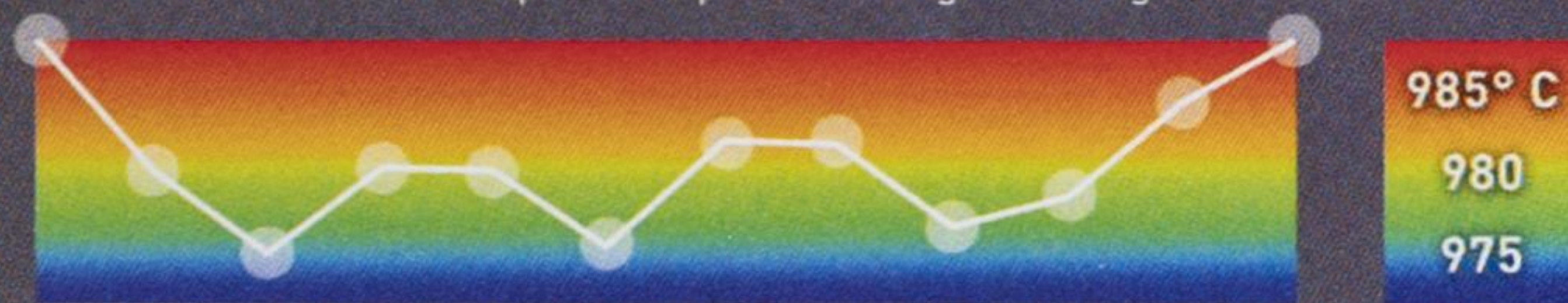
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SOLAR POWER

Emcore splashes \$18 m on solar venture

In a strategic move that will guarantee a lucrative and exclusive customer supply deal for its solar cell division, III-V device manufacturer Emcore is to invest \$18 million in WorldWater and Power Corp.

Based in Pennington, NJ, WorldWater specializes in solar-powered water pump technology. Emcore has already invested \$13.5 million and is expected to provide the \$4.5 million balance before the end of 2006.

That will give Emcore a 31% equity share in WorldWater, while a separate agreement means that Emcore will be its exclusive supplier of high-efficiency multi-junction solar cells, assemblies and concentrator subsystems.

Emcore has valued that contract to be worth "up to" \$100 million over the next three years, a figure that ought to deliver a massive boost to its photovoltaics business unit.

As Emcore CEO Reuben Richards noted, the investment marks an important shift in the company's strategy within the terrestrial solar energy market. "[Emcore] is becoming, with WorldWater, a solution provider rather than just a component supplier."

This movement up the industry food chain has been a feature of Emcore's wider strategy over the past few years, beginning in 2003 when it sold its MOCVD equipment division to Veeco Instruments. Since then, Emcore has



Emcore's semiconductor fab in New Mexico, where the company manufactures its multi-junction solar cells, is filling up fast thanks to major new supply deals for both satellite and terrestrial applications.

sold its RF electronic materials division to epi-wafer foundry IQE and its half-share in the LED joint venture Gelcore to General Electric.

Via the WorldWater supply deal, Emcore solar cells based on GaAs alloys and germanium substrates will be hooked up to customized electrical drives that are used to pump water for utility companies and in other applications such as farmland irrigation.

Richards said that a significant share of the world's electrical consumption is used to run

pumps and motors, and sees this as part of a rapidly expanding opportunity for solar energy systems to replace or augment grid electricity. WorldWater has already begun to make an impact in this area and its annual sales are expected to grow almost ten-fold from \$2 million in 2005 to nearly \$17 million this year.

WorldWater founder Quentin Kelly, who started up the company as long ago as 1984 to supply water and power to developing nations, said of the deal, "Concentrated photovoltaic systems are the keys to reducing the cost per watt of power generated."

"This major financing will enable [us] to increase our core business of blending and/or replacing the electric grid with solar power... whether in the water utility, agricultural or other industrial fields."

● A voluntary review of stock options awarded by Emcore has revealed no intent to profit from false pricing. The company said: "Senior management did not seek to profit from the issuance of the option grants at the expense of [Emcore] or its shareholders."

However, the company has admitted that because of "inadequate" financial controls, there were some instances where the exercise prices of granted stock options, usually those awarded to new employees, appeared to have been selected with the benefit of hindsight.

POWER AMPLIFIERS

Cell-phone semiconductor market report says predicted wave of CMOS PAs is 'several years off'

By Michael Hatcher in San Antonio, Texas

Improved silicon CMOS power amplifiers (PAs) capable of displacing GaAs from cellular handsets on a wide scale will not reach the market until beyond 2010, according to a review of the cell-phone semiconductor market conducted by Strategy Analytics.

Speaking at *Compound Semiconductor Week* in San Antonio, TX, in November, Asif Anwar from the firm said that the much-predicted wave of CMOS PAs is "several years off".

Instead, Anwar believes, the increasing complexity of multi-band, multi-mode handsets and the likely lack of any common architecture for future generations of handsets will hold back CMOS PAs. These trends will also push out most of the remaining PA slots still captured by silicon LDMOS technology and drive a significant increase in the overall amount of GaAs deployed in cell-phones.

With 1 billion mobile phones expected to ship in 2006, Anwar estimated that handset makers have needed 1.33 billion PAs – equivalent to market revenue of \$1.6 billion. GaAs-based PAs now fill 90% of all the available PA slots in handsets, with the rest mostly captured by silicon LDMOS. "CMOS PAs from Silicon Labs and Axiom will capture less than half of 1% of the market in 2006," said the analyst.

When coupled with other applications, this means that the total market for GaAs devices will exceed \$3 billion this year. Thanks to the strong relationships between handset makers and their front-end radio suppliers, and the inability of silicon CMOS to match GaAs linearity and efficiency performance in the fast-growing EDGE and wideband-EDGE wireless protocols, the GaAs market will expand at a healthy rate for the rest of the decade.

Anwar estimated compound annual growth

of 7%, which would mean a market expansion to nearly \$4 billion in 2010 if correct. By then, EDGE and W-EDGE handsets are expected to account for three-quarters of annual shipments.

In 2006, this market penetration figure is closer to one-in-five. These newer phones have more complex functions and this will fuel an increase in the GaAs "real estate" required.

"As EDGE and wideband-CDMA become the main focus for RF chip suppliers over the next 24 months, front-end module suppliers will espouse their specialist capabilities against competitors looking to offer the complete radio," Anwar said. The particular challenges of EDGE designs could play into the hands of complete radio solution providers, such as RF Micro Devices, Skyworks and Freescale, but second-tier GaAs players partnering with leading transceiver makers like Qualcomm will also remain competitive, Anwar added.

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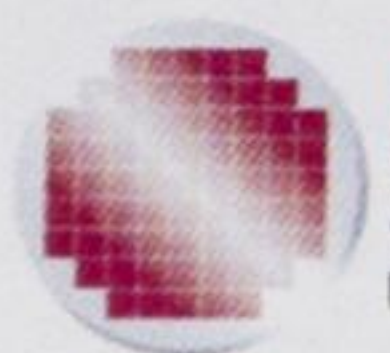
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INDUSTRY THE MONTH IN RFICS

APPLICATIONS

TriQuint trains sights on high-speed Bluetooth

TriQuint Semiconductor has launched its first GaAs-based power amplifier (PA) product designed specifically for high-speed Bluetooth wireless connectivity.

Although the Oregon-based company already sells filter devices for Bluetooth applications, these components are based on surface acoustic wave technology rather than compound semiconductors.

Bluetooth, which is mostly used for short-range connectivity like hooking up a cell phone to a speaker headset or a wireless mouse to a PC, already represents a huge market. The market research firm Strategy Analytics expects 420 million Bluetooth devices to ship in 2006.

However, the PA stages used in Bluetooth devices have typically been dominated by low-cost silicon technology, which is suitable for low-data-rate, short-range connectivity at the 2.4–2.5 GHz frequency used.

RF Micro Devices launched a GaAs-based Bluetooth product back in 2000, for example, although its latest offerings are manufactured using a single-chip silicon CMOS process.

But now it appears that consumers are beginning to demand longer-range Bluetooth connectivity, while transfer rates are becoming an issue for data-intensive applications like data transfer for high-quality wireless headphones. And it is this market for high-end Bluetooth, also known as "Class 1 operation", that TriQuint hopes to penetrate with its InGaP

HBT amplifier designs.

"Class 1 Bluetooth systems allow up to 100 m ranges and provide for high data rates," said TriQuint's marketing manager Berry Leonard, adding that Class 1 systems will make up roughly 45% of the projected total future market for Bluetooth.

Using a GaAs-based technology in the PA stage allows a far more compact system design, thanks to the smaller die size that is needed compared with silicon, as well as a simplified circuit board and a reduced external part count.

In particular, TriQuint's new PA is said to be the first to meet enhanced data rate specifications for operation at up to 3 Mbit/s.

The high power-added efficiency and linearity rating of GaAs-based power amplifiers also means that high data rates and long-range communication can be supported with a reduced drain on battery power compared with systems that use silicon amplifiers.

TriQuint told *Compound Semiconductor* that, when bundled together with an extra switch and a bandpass filter, the 2 × 2 mm amplifiers were easily able to slot into lower-specification Class 2 or Class 3 Bluetooth systems and provide an instant design "upgrade" to Class 1 operation.

The company has already sampled to lead customers and is now finalizing its plans for volume manufacturing. Although no dates for this have been fixed, the chips will be made at its 6 inch wafer facility in Hillsboro, OR.

MANUFACTURING

WJ Communications to close GaAs wafer manufacturing facility in strategic move

WJ Communications, which currently makes RFICs primarily for wireless infrastructure applications, is to close its GaAs wafer manufacturing facility in early 2007.

The San Jose, CA, firm acquired the GaAs fab in nearby Fremont when it bought EiC Corporation's wireless infrastructure business in June 2004, but has decided to go fabless in a move that should reduce its annual costs.

WJ Communications has been working with Global Communication Semiconductors (GCS), the pure-play compound wafer foundry company, since March 2006. GCS acts as a second source for WJ Communications to provide InGaP HBT and GaAs material, but will now become its primary supplier.

WJ's CEO Bruce Diamond said of the new strategy: "As a result of our successful qualification and production ramp [with GCS], we have solidified a restructuring plan, resulting

in the planned closure of our wafer manufacturing facility during the first quarter of 2007."

Closing the 4 inch GaAs fab will cost WJ an estimated \$1.5 million, although some of that could be recouped through the sale of manufacturing equipment. However, the leaner cost structure should ultimately benefit the company to the tune of \$5 million per year.

WJ Communications is following in the footsteps of former GaAs chip maker Mimix Broadband, which decided to become fabless in early 2006, as well as Hittite Microwave, the Chelmsford, MA, firm that has proved how profitable this business model can be.

WJ has also reported improving sales, and posted revenue of \$12.7 million – up 57% on last year – for the financial quarter that ended on October 1. It made a net loss of \$1.2 million, suggesting that financial break-even should be possible after the GaAs wafer plant closes.

SCHOTTKY DIODES

Velox and ST team up on high-voltage GaN

US-based GaN transistor specialist Velox Semiconductor and European semiconductor giant STMicroelectronics (ST) have decided to jointly launch high-voltage GaN Schottky diode products. The partnership is also aiming to establish the two companies as dual-source suppliers of the devices.

Emcore spin-off Velox and ST believe that these diodes can deliver benefits in terms of cost, efficiency and size in switch mode power supplies used in computers, consumer applications and industrial products that currently employ silicon electronics.

Velox, which claims that its GaN devices offer "SiC performance without the SiC price tag" is now in the final stages of development of its 600 V GaN Schottky diodes and will soon start production. ST will help to complete this development and then qualify, market and dis-

tribute the diodes under the Velox brand name. Eventually, Velox and ST expect to become dual sources for all products.

To enable this second-source supply, Velox is currently licensing its technology to ST and the two companies are working together to synchronize production. Although these efforts could delay the start-date of production at Velox, it is also expected to lead to an agile and consistent supply of GaN devices.

"The deal with Velox enables ST to introduce a new and fast growing product line, quickly, and with the minimum of research and development and capital investment," said Ricardo de Sa Earp, general manager of ST's application-specific discretes division.

ST has previously developed SiC Schottky diodes, which share many of the attributes of the new GaN devices, for similar applications.



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...Shareholders OK Freescale sell

Shareholders in semiconductor manufacturing giant Freescale have approved the sale of the company to a private equity consortium.

The Blackstone Group, which is leading the proposed buy-out along with The Carlyle Group, Permira Funds and Texas Pacific Group, has offered stockholders \$40 per share.

Those voting in favor of the buy-out represented around 73% of the total number of eligible shares. The transaction remains subject to other closing conditions but is now expected to be completed by the end of this year.

...Young retires from AXT

Morris Young, the founder and former CEO of substrate supplier AXT, is to retire in December. Young served as CEO for 15 years until 2004, when he was replaced by current CEO Phil Yin in a management reshuffle and moved to the CTO position. Young will continue to serve as an advisor on the AXT board of directors.

Meanwhile, AXT has said that changes to tax laws in China, where the firm's manufacturing operations are located, will not materially affect its earnings as had been feared previously.

...RFMD samples more GaN

Best known for its GaAs-based power amplifiers (PAs), RF Micro Devices has released a family of GaN-on-SiC products for WiMAX, cellular infrastructure and Public Mobile Radio services.

The Greensboro, NC, firm, which faces

competition in the emerging sector from local rivals Nitronex and Cree, as well as a number of Japanese firms, has converted part of its 4 inch GaAs wafer fab into a line suited for GaN device production on 3 inch SiC wafers.

...Soitec's composites suit RF

Compound semiconductor substrate specialist Picogiga, France, says that initial characterization of GaN epilayers deposited on engineered composite substrates have shown "excellent" results. Working under a European research project called HYPHEN, GaN was deposited by both MBE and MOCVD onto two different materials: silicon-on-polycrystalline SiC (SopSiC); and SiC on polycrystalline SiC (SiCopSiC).

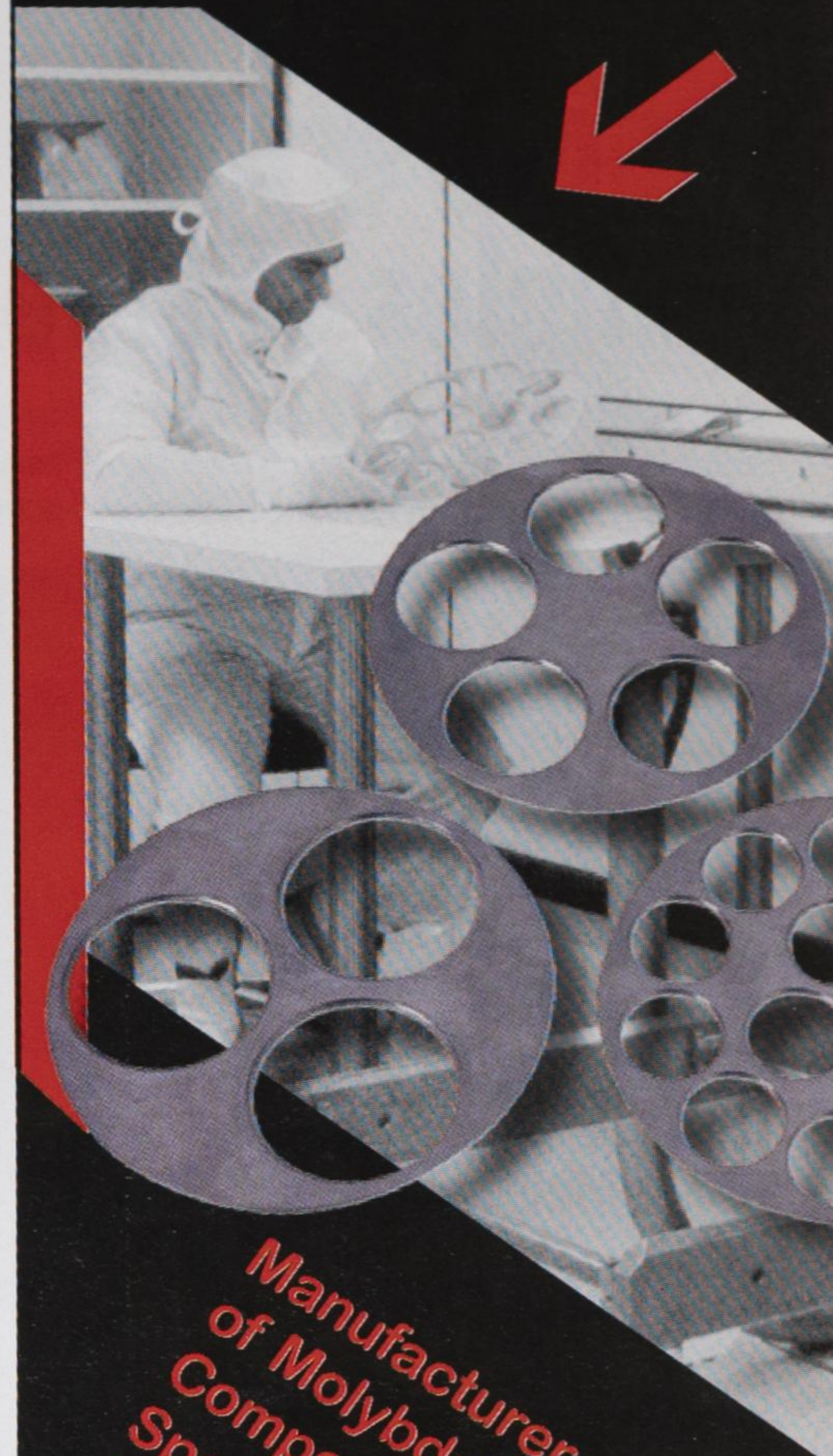
According to preliminary, unpublished results, GaN HEMT epitaxy on the SopSiC material shows high reliability and good pilot production yield. The next phase of the project will focus on HEMT device processing.

...Toshiba touts X-band FET power

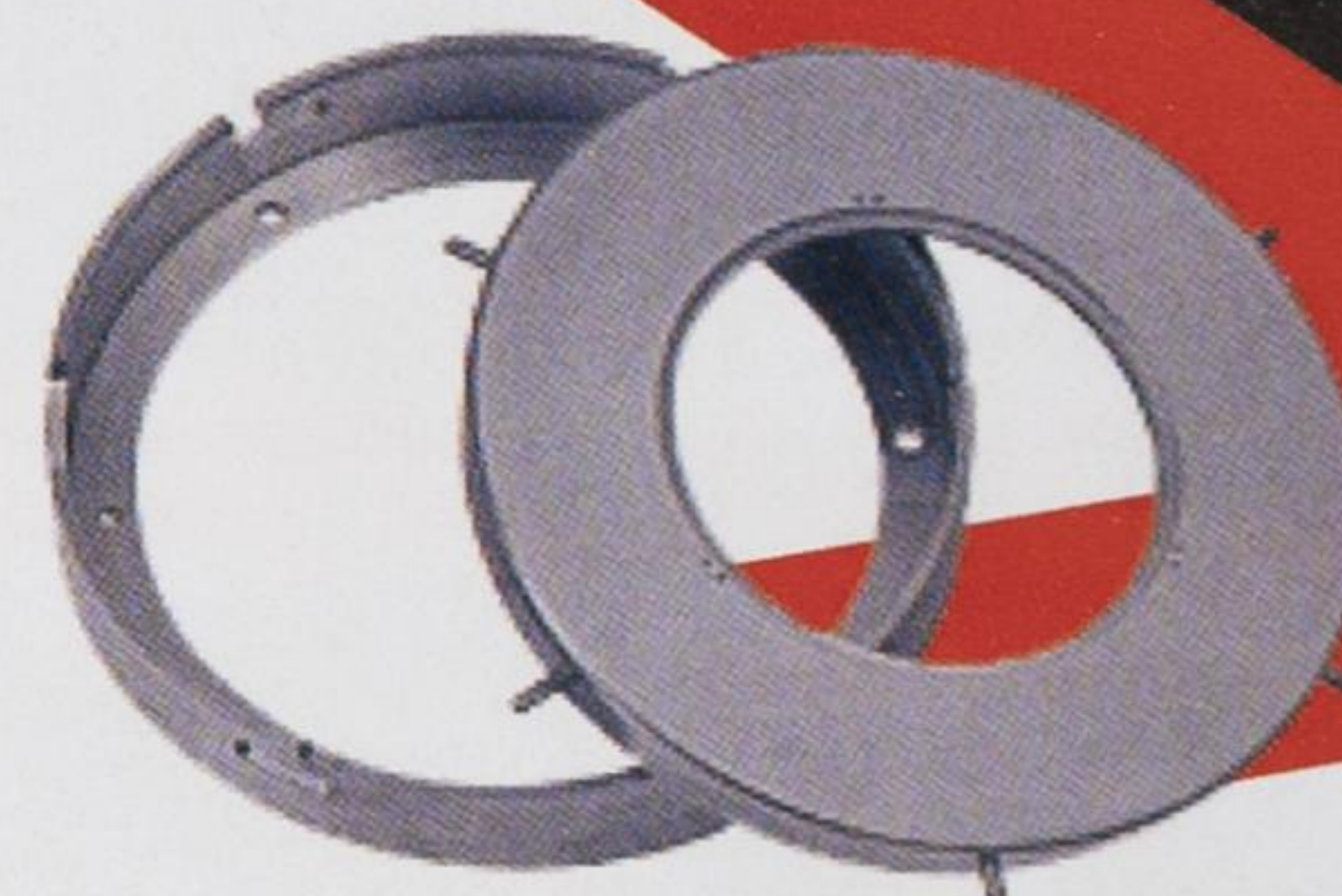
Japanese electronics giant Toshiba claims that it has broken the output power record for a GaN field effect transistor (FET) operating in the X-band (8 GHz–12 GHz).

The record-breaking chip delivered 81.3 W at 9.5 GHz and operated at a power density six times greater than that of a GaAs FET. Toshiba is now releasing sample devices rated at 50 W and plans to begin mass-production within six months.

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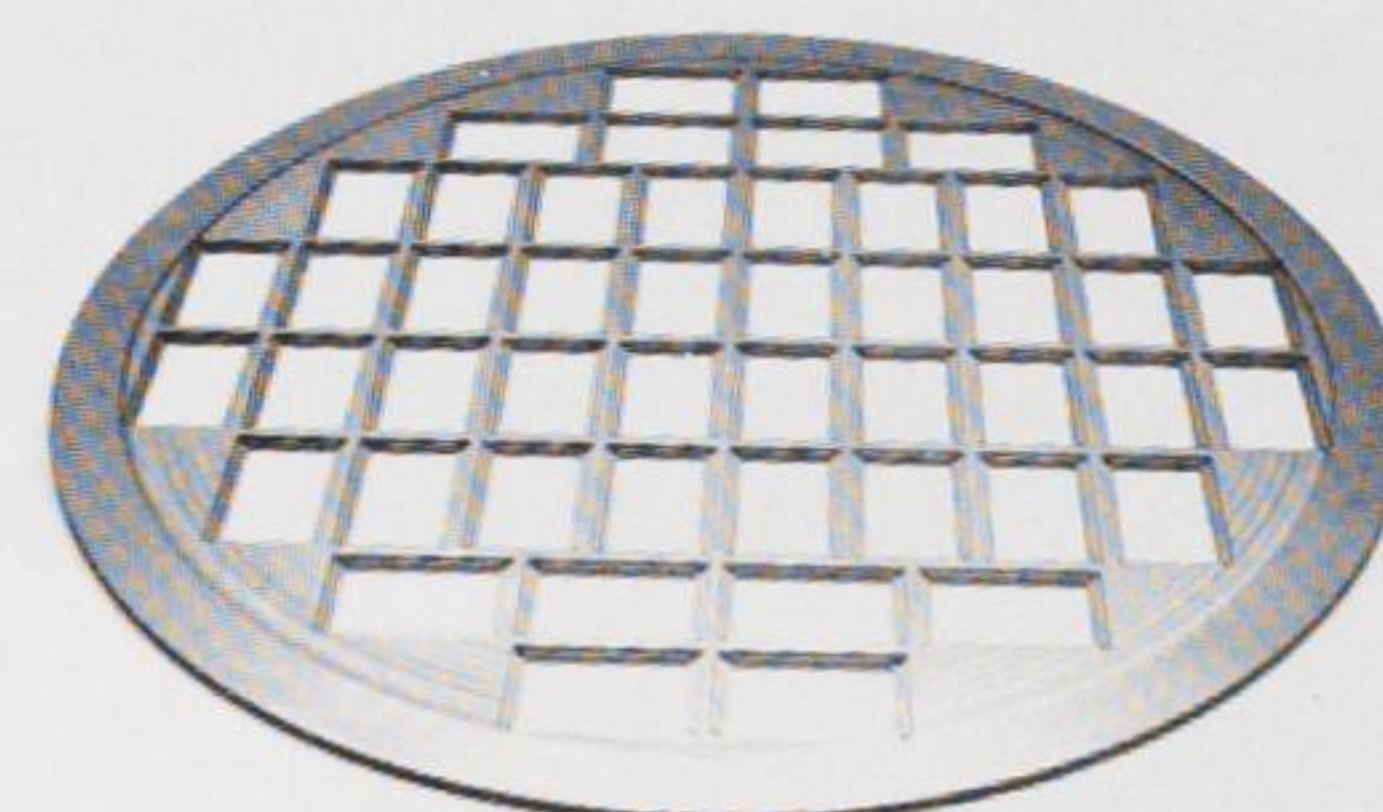


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BLUE LEDS

Japanese start-up Shimei Semiconductor to ship samples of blue LED using GaN-on-silicon epitaxy

Shimei Semiconductor, a start-up firm based in Kyoto, Japan, is reported to have developed a blue LED using GaN-on-silicon epitaxy.

According to reports at both *Nikkei.net* and *EE Times*, Shimei is planning to begin shipping samples of the technology in April 2007.

Because native nitride substrates aren't yet available in large diameters, blue LEDs are normally fabricated on either SiC or sapphire wafers for volume applications such as cell phone keypad backlights.

Although silicon would provide a cheaper, conducting, non-native substrate and be available in very large diameters, the problem is that

it is opaque in the blue spectrum.

To overcome this, the Shimei team, led by co-founder and CTO Hirofumi Yamamoto, have developed a way to deposit a reflecting layer within the device structure so that all of the light is emitted from the top of the LED.

Unlike sapphire substrates, doped silicon is conductive, so the bottom electrode of the chip can sit below the silicon and eliminate the need to etch down from the top of the device.

According to the *Nikkei.net* report, Shimei is readying a production system capable of manufacturing 3 million units per month. It adds that the LEDs can deliver up to 2 cd of

450 nm light when driven at 20 mA.

Shimei's is not the only research team to have worked on silicon as a substrate for blue LEDs. Alois Krost's group at the Otto von Guericke University, Magdeburg, Germany, reported a similar device at the 5th European Conference on Silicon Carbide and Related Materials, held in Italy in 2004 (see *Compound Semiconductor* November 2004 p21).

Krost said that although the different thermal expansion coefficients of GaN and silicon could result in cracks throughout the structure, monitoring the strain in the devices as they are grown allows crack-free epitaxy.

MOCVD REACTORS

Epitech scales up with 4 inch AlGaInP LED mass-production

Epitaxy equipment vendor Aixtron has sold three more production-scale MOCVD reactors to Taiwan-based LED epiwafer and chip manufacturer Epitech.

The order is another sign of the growing market for high-brightness LED manufacturing equipment, thanks to which both Aixtron and its US rival Veeco Instruments are currently seeing a very strong increase in orders.

Epitech, which is involved in a double-merger plan with LED manufacturers Epistar and Highlink Technology, will use the AIX 2600G3 machines to mass-produce red, orange

and yellow AlGaInP LEDs at its epiwafer plant in the Tainan Science-based Industrial Park.

The reactors will be supplied in a 12 x 4 inch multi-wafer configuration. AlGaInP LEDs are usually produced on smaller substrates and Epitech normally works with 3 inch material.

The merger between Epitech, Epistar and Highlink Technology will create a Taiwanese LED chip making firm to rival the established leaders: Nichia, Cree, Philips Lumileds, Toyoda Gosei and Osram Opto Semiconductors.

Epistar is regarded as the biggest AlGaInP-based red, yellow and orange LED producer.



GaN-based LED headlamps that match the brightness of halogen lamps are to be qualified by automotive standards authorities, claims LED manufacturer Osram Opto Semiconductors.

The German firm's headlamps are based on its O-star LEDs, consisting of five tightly-packed

ThinGaN chips. At a forward current of 700 mA, the "O-star Headlamp" produces 250 lm, while the higher-performance "O-star Headlamp Hot Spot" product delivers up to 350 lm.

Osram adds that the LED sources will improve driver visibility and therefore road safety because of the high color temperature that they emit. At 5600 K, this white color is closer to natural daylight than conventional headlamp sources. Osram says that this is useful because the human eye is better at perceiving objects in "daylight white" than other color temperatures.

Along with large-area display backlights and solid-state lighting, automotive headlamps are regarded as one of the crucial applications that are set to drive future growth of the high-brightness LED market.



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...Seoul claims AC-LED breakthrough

Seoul Semiconductor, the Korean company that specializes in LED products, says that it is now in a position to mass-produce solid-state lamps that can plug directly into 110 V or 220 V electrical sockets.

Launching the "Acriche" AC-LEDs at the electronica show in mid-November in Munich, Germany, Seoul CEO Lee Jung-Hoon said: "LED applications are no longer limited to cell phones, computers or cars, but can expand to general lighting applications as well."

Conventional LEDs are only compatible with DC power, but thanks to a new patented chip packaging process developed by its subsidiary Seoul Optodevice, the parent firm says that the need for a DC converter has been eliminated.

The firm expects to sell KRW 20 billion (\$20 million) worth of Acriche products next year, rising rapidly to KRW 300 billion (\$300 million) in 2009.

...Cree shoots with Arrow

LED chip manufacturer Cree has entered into a global distribution agreement with US-based Arrow Electronics. "With this agreement, Cree is aligning itself with one of the top electronics components distributors in the world to drive the LED lighting revolution," remarked Bob Pollock, Cree's senior vice-president of sales.

The products available through Arrow include the XLamp 7090 XR-E, which according to Cree is the first-ever 160 lm white power LED.

GENERAL LIGHTING APPLICATIONS

Wal-Mart goes green with Gelcore chips



Going green: Retail giant Wal-Mart reckons that by kitting out refrigerators in 500 stores with LED lighting, it will save \$2.6 million on its annual electricity bill.

US retail giant Wal-Mart has announced plans to launch itself as an early adopter of LEDs for general lighting applications and is set to update 500 of its stores by installing LED-based lighting.

Instead of using conventional fluorescent illumination, the company will install LED-based lighting developed by Gelcore in many of its refrigerator display units.

According to Wal-Mart, the installation will help to cut energy usage by up to 66% in stores where the LEDs are installed, aiding the company's initiative to reduce its overall energy consumption by 30%.

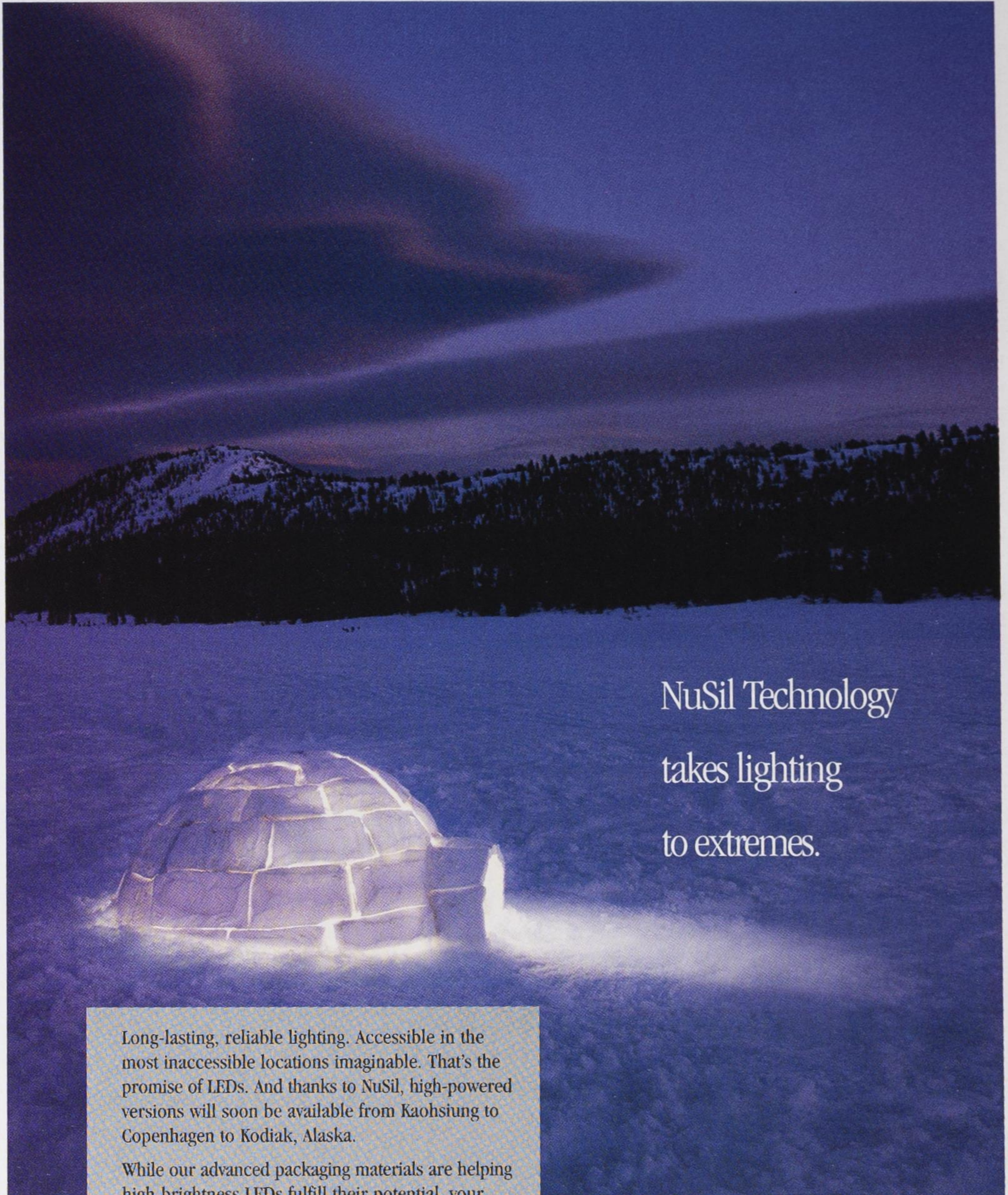
Energy cost savings across the 500 stores where the LEDs are used should amount to \$2.6 million annually, although that figure is something of a drop in the ocean when compared with Wal-Mart's latest quarterly profit of nearly \$3 billion.

Until recently, Gelcore was half-owned by compound semiconductor device manufacturer Emcore, but in August joint-venture partner General Electric (GE) purchased its stake for \$100 million in cash. GE has also announced that it is entering into a "strategic alliance" agreement with Japanese GaN LED manufacturer Nichia.

The LED initiative should extend well beyond the 500-store plan. Wal-Mart owns more than 6500 shops worldwide, including the UK chain Asda, and claims to be committed to investing "up to" \$500 million annually

on energy-efficient technology.

"It's our hope that one day all of our reach-in refrigerated display case lighting will use energy-efficient LEDs," explained Wal-Mart vice-president Charles Zimmerman.



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PHOTOVOLTAICS

Spectrolab closes in on efficiency record

US-based Spectrolab is on the verge of developing a triple-junction solar cell with a record 40% power conversion efficiency.

The Boeing subsidiary reported a 39.3% terrestrial concentrator cell earlier this year, and expects to pass 40% by January 2007. The increase in conversion efficiency should help the company to penetrate the emerging market for terrestrial III-V photovoltaics, for which power conversion is a key metric.

Speaking at last month's Key Conference in San Antonio, TX, Spectrolab's Hojun Yoon predicted that higher-efficiency converters would reach to at least 45% by 2009. "A 40–50% efficient cell could make the [terrestrial] market explode," he said.

Meanwhile, the drive towards terrestrial deployment of III-V solar cells received a further boost with Sharp, the world's leading maker of solar cells, now expected to begin selling concentrator systems featuring compound semiconductor technology next year. The systems are set to ship to customers in Europe, where solar power enjoys a large subsidy from the European Union.

Until now, Sharp has focused on silicon-based systems in the commercial solar energy

sector. However, the Japanese electronics company has also been developing multi-junction technology in its laboratories for some time.

As well as utility-scale photovoltaic systems, Sharp is also working on rooftop converters featuring III-V materials that could be suitable for powering high-density housing in locations where sunlight is abundant. In collaboration with Daido Steel, Sharp has built a small 3 kW rooftop system that operates at 500× solar concentration.

And at the World Conference on Photovoltaic Energy Conversion in Hawaii earlier this year, Takashi Tomita confirmed Sharp's backing for III-V concentrator systems when he presented the outline of the company's future vision of photovoltaics.

Tomita, a corporate executive director at Sharp, said that concentrator systems would play a key role in the energy industry, particularly in areas where skies are typically very clear and sunny. He identified areas such as the Mediterranean coast in Europe, north Africa, southern Australia and the south-western US as some of the best geographies for concentrator systems.

Citing figures based on tests in Arizona,

Tomita said that a concentrator system tracking sunlight throughout the day would generate 40% more electricity than a comparable system based on crystalline silicon.

And if concentrator systems were used widely in these sunny regions, they could produce phenomenal amounts of clean electricity. Tomita estimated that widespread deployment in Nevada, Arizona and New Mexico could generate as much as 2.6 TW hours of electricity annually.

To put that figure in context, 2.6 TW hours would be equivalent to more than 40% of the predicted total electricity generation in the US for the year 2030.

"This calculation is based on our achieved technology right now," Tomita said. Although the cost of concentrator systems for utility-scale electricity generation is currently very high, Tomita indicated that this could change quickly with a manufacturing scale-up.

"In regards to the system cost, the portion of cell cost is relatively small [for concentrator systems]," he claimed in his paper from the Hawaii conference. "It means that there is a big potential for the system cost to be reduced by economies of scale in the near future."

INFRARED DETECTORS

Sofradir to double production output with MBE kit

Sofradir, the French company that makes high-performance infrared detectors, will nearly double its production capacity when it opens a new semiconductor fab in late 2007.

The €9 million (\$11.5 million) facility will be located near Grenoble. There, Sofradir will use MBE to manufacture 4-inch wafer material for its "third-generation" focal planar array HgCdTe detectors.

Sofradir claims to be the first European manufacturer to produce these specific infrared detectors using MBE on an industrial scale.

MBE is, however, widely used for mass-

production of GaAs-based epiwafers for RF transistor applications, and also to make laser diodes for optical data storage. Meanwhile, the Polish firm VIGO System manufactures so-called first-generation HgCdTe detectors, based on single elements rather than arrays, using an MOCVD reactor supplied by Aixtron.

Sofradir's new fab in Grenoble will measure 9000 m² in total, one third of which will be dedicated cleanroom space.

According to the French firm, users of infrared detectors, such as the US Army, defense contractors Thales and Selex, and the

European Space Agency, are demanding larger, more complex products with new features like dual-band or laser imaging.

By switching to MBE production and the larger wafer format, Sofradir should be able to respond to these demands while reducing the cost of its products.

Sofradir's products include quantum-well and microbolometer detectors, and HgCdTe semiconductors, and cover the infrared spectrum from 1–16 μm. Among other uses, they are used for thermal imaging, missile detection and surveillance applications.

VENTURE FINANCE

BinOptics funding round raises \$6 million

BinOptics, a US manufacturer of monolithically integrated laser chips featuring etched-facet technology, has closed a Series C round of venture funding that has raised \$6 million. The new funding was led by a new investor, STIC International, the US arm of the Korean

venture-capital and financial-equity group STIC Investments.

The Ithaca, NY, company – a spin-off of Cornell University – says that the cash will increase the production capacity of 10 Gbit/s lasers that can operate over a wide temperature range for telecom and datacom applications, and accelerate product development of etched-facet blue lasers for optical data storage.

"The demand for competitively priced lasers that can operate reliably at high temperatures, speeds and powers is now growing at a rapid

rate," said BinOptics CEO Alex Behfar.

"Our unique manufacturing approach has allowed us to meet these requirements in the key material systems, and we are now ready to move to the next stage in production and product development," he added.

BinOptics' products include proprietary 1310 nm and 1550 nm horizontal-cavity surface-emitting lasers (HCSELs). These emitters feature a chip technology that integrates a horizontal laser cavity with a 45° etched reflecting mirror that directs the beam vertically.



EPITAXY EQUIPMENT

Dramatic increase in MOCVD orders

A widespread move among manufacturers of LEDs to prepare for the next big wave of applications means that the order books of **Veeco Instruments** and **Aixtron** are bulging, and prospects look set to improve.

Over the past few years, suppliers of epitaxy equipment have had it tough. Now, it seems, the worm has turned. LED manufacturers are tooling up with new reactors to make improved LEDs that will meet the requirements of the next big application wave – display backlights for televisions and PC desktop monitors.

Veeco Instruments and Aixtron are the two leading vendors of MOCVD equipment for LED production, and although the drawn-out sales process means that revenues are yet to really kick in, the order books at those two firms are suddenly looking very healthy. Given Aixtron's caution when booking orders for MOCVD equipment – it has a strict internal policy and only records an order after a committed delivery date from a customer is received – the German company's backlog is a good measure of demand within the industry.

By early November, Aixtron already had enough MOCVD equipment orders to prompt a €10 million upgrade of its full-year revenue expectations for 2006 and it will take a very healthy backlog into the start of 2007. All €98.3 million (\$127 million) in equipment orders on the books in early November were scheduled for delivery by the end of 2007.

Veeco is seeing a similar picture. It is forecasting 2006 revenue from its epitaxy division (which includes sales of both MBE and MOCVD equipment) to reach \$85 million, up strongly on the 2005 figure of \$63 million.

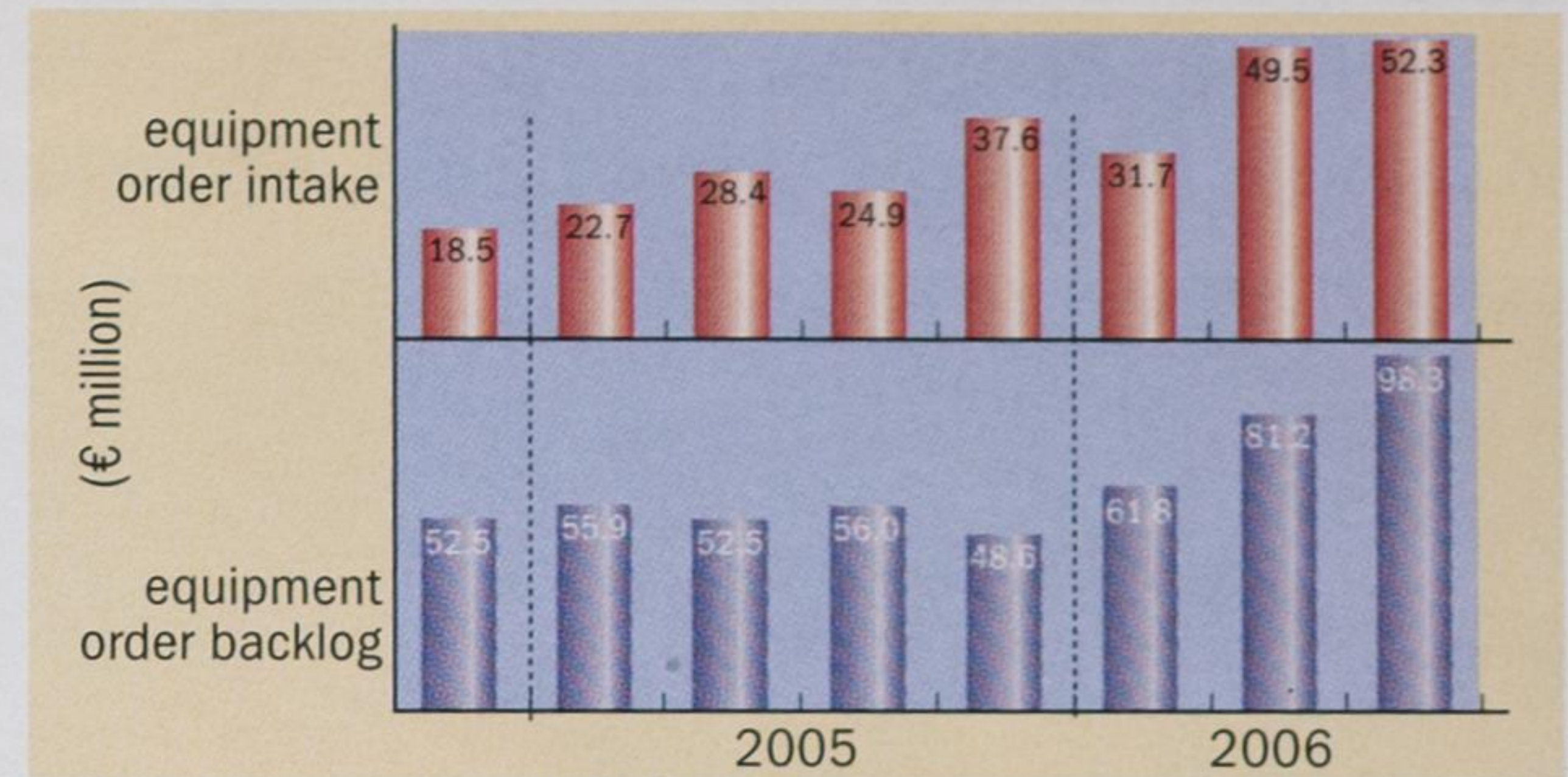
Like Aixtron, Veeco's order book is also brimming, again thanks to major orders from LED makers. In the firm's late-October earnings call, Veeco CEO Ed Braun said that orders for MOCVD equipment alone had surpassed \$20 million in recent quarters. And although the hard-disk data storage sector remains the number-one market for Veeco's overall business, an analysis of its latest orders shows that the break-out of 2007 sales will be much more influenced by III-V device makers.

Of the 15 leading customers who placed orders with Veeco in the third quarter of 2006, seven were III-V companies. The top four customers were all major hard-disk firms like Seagate and Hitachi, but in fifth place was the epiwafer foundry Bandwidth Semiconductor, followed by the Chinese firm Nanjing Guosheng Electronics, Osram Opto Semiconductors and Taiwan-based Arima Opto.

With three other Korean and Chinese chip makers ranking in the top 15, it is already clear where Veeco's revenue is coming from next year. Once they have received their new MOCVD reactors, those LED chip vendors will set to work refining new processes, some using larger-diameter substrates, and begin attacking the new market for large-scale display backlighting.

DisplaySearch predicts that some 308 million backlighting units for flat-panel displays will ship in 2007. Of those, just 3.5%, or 10.8 million units, are expected to be illuminated by high-quality LEDs, but this will still represent a huge increase on the forecast 2006 market penetration of only 2.6 million units.

As a result, Veeco is reckoning on a 30% rise in epi-



In good order: Aixtron's order intake has near-doubled from last year, while its order backlog is higher than at any time in the past two years. Source: Aixtron.

taxy equipment sales to compound semiconductor firms next year, to about \$115 million. And it won't stop there – the US firm says that in 2009 it expects to generate sales of \$175 million as LED-based backlights become firmly established, with in excess of 50 million unit shipments, and applications in more general illumination begin to drive demand for next-generation equipment.

Predictions aside, there are some signs that this is starting to happen. Samsung recently began selling an LED-based monitor for high-specification applications like desktop publishing and ultimately the Korean firm plans to use LED backlights in all of its LCD displays.

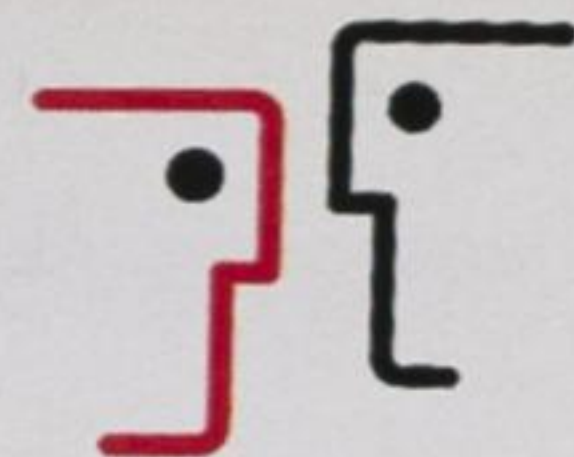
For LED manufacturers, the performance requirements demanded for flat-panel TVs and monitors are extremely high. This means that the central wavelength or specific color emitted by each LED made must conform to strict guidelines. Veeco says that its customers have found that this color distribution is much tighter for chips made with its latest GaNzilla II equipment, with more good die produced per wafer and better yields.

The focus on higher-quality die production means that Veeco and Aixtron are selling more of their newest reactors. This has an added benefit for their finances, since the latest equipment is the most profitable to sell. This much was clear from Aixtron's latest financial results, which indicated a rapid improvement in profit margins. The trend is set to continue, since more than 20% of Aixtron's third-quarter orders were for these latest systems. Aixtron says that 2006 will now deliver a €3 million profit, rather than merely breaking even.

Aixtron CEO Paul Hyland is certainly in a more confident mood than he was at the start of 2006, when he described the market for MOCVD equipment as "cautious". In the firm's latest conference call for investors, Hyland was even bullish about the longer-term prospects for solid-state lighting applications, saying that they will likely begin to emerge sooner than had been expected.

"2007 and 2008 will be a very interesting couple of years for LEDs," Hyland said, although there is likely to be a leveling-off in orders for MOCVD reactors as LED makers concentrate more on reducing the costs of their new equipment and honing their new processes.

"Veeco expects to generate sales of \$175 million in 2009, as LED-based backlights become firmly established."



FUTURE TRENDS

US military plays the integration game

Quizzing the Air Force Research Laboratory's **Laura Rea** about the US military's technology roadmap, **Bob Metzger** hears how a dramatic shift in strategic thinking will affect the role of compound semiconductors.



AFRL/DOO

Laura Rea: the CV

1985: Graduates from Wright State University with a BS in materials engineering.

1990: Receives MS in materials engineering. Becomes program manager for Microwave and Microelectronic Materials Program.

1994: Grows ML budget to \$12 million.

1998: Serves one-year assignment at the Pentagon as a staff member for the director of research.

1999: Returns to AFRL/ML as technology development lead at the Electronic and Optical Materials Branch.

2004: Becomes acting branch chief at MLPS.

September 2006: Returns to technology development lead position at AFRL.

A critical driver in the development of compound semiconductors in the US has been the US Department of Defense's (DoD) need for next-generation communications, radar and power systems. The Army, Navy and Air Force, along with the Defense Advanced Research Projects Agency (DARPA), often require the DoD to sponsor the research and development work needed to build these systems.

Once those technologies have been developed for military needs they inevitably make their way into the commercial sector, opening up whole new industries. A prime example of this phenomenon was the development of GaAs through the DoD's Microwave and Millimeter Wave Monolithic Integrated Circuit Program in the 1980s and 1990s, leading to the creation of a wide spectrum of commercial GaAs companies that are now key players in the ever expanding wireless marketplace.

More recent DoD programs have used InP, SiC and GaN, and devices based on these material systems are starting to make a commercial impact. Therefore, if you want to get a peek of the new technologies and capabilities that will be developed in the compound semiconductor arena, history has shown what a good indicator the DoD's future programs and applications can be.

The military driver

Laura Rea is the technology development lead of the Electronic and Optical Materials (EOM) branch within the Air Force Research Laboratory's (AFRL) Materials and Manufacturing Directorate, located at Wright-Patterson Air Force Base in Dayton, Ohio. Not only is

Rea involved in DARPA's current wide-bandgap semiconductor technology initiative (see web link at the end of this article), but her branch is one of several military research and development offices that will help shape the type of compound semiconductor solutions sought to fulfill the Air Force's future mission. But just what is the mission of the Air Force's EOM branch?

Rea responds in no uncertain terms: "Complete and total domination of the electromagnetic spectrum for Air Force requirements." Her branch's role in that mission addresses the needs of three primary DoD customer communities: "First the intelligence, surveillance and reconnaissance community – where electrons and photons play a critical role," she says, "second, the communications and computations community where we must move 'decision-quality' information quickly and effectively and get it in the hands of operators in real time. And third, the emerging area of directed energy."

With similar directness, Rea explains the approach used to meet the Air Force's need for next-generation semiconductor-based devices and systems: "Bulk and epi," is how she characterizes the DoD's historical examination of a new material system, looking at features such as breakdown voltages, carrier mobilities and thermal conductivities. If those characteristics led to electronic and photonic devices with the sort of enhanced performance that the DoD needed for its next-generation systems, it would initiate a development program focused on developing those solutions.

The GaAs materials research program outlined above is a good example: what was first considered as an exploratory research program evolved into a Defense Production Act Title III program, aimed at improving the quality and increasing the diameter of GaAs substrates. Sandwiched between these programs was DARPA's MMIC effort, where epitaxy developments resulted in the fabrication of advanced MES-FET, HEMT and HBT devices. This is the traditional "bulk and epi" technique that Rea refers to and this model has since been repeated with other material systems – the most recent being GaN.

"We are talking about a component that can see, talk and think."

Laura Rea, AFRL

Multifunctional approach

So, after GaN, which new material system will enable the Air Force to "dominate the electromagnetic spectrum," as Rea puts it? The antimonides, ZnO or perhaps diamond could be considered as candidates. The reality shows a sea-change in the DoD's thinking, however. While Rea says that advanced material systems such as these will be investigated, she believes that there will not be a single next-generation material system *per se*.

In fact, she sees a paradigm shift occurring not only within the Air Force but also within the other services

and DARPA. The approach will no longer be the tried-and-tested bulk and epi, explains Rea. “We are very clearly headed into the realm of multifunction, integrated, miniaturized components.” Rather than one single material, this means different materials and different devices folded into a single component.

What might this component look like? “We need products that can carry out some level of silicon-like processing, and are able to communicate and execute some level of sensing,” says Rea. “In other words, we are talking about a component that that can see, talk and think.”

While she feels that this goal requires some form of materials integration, Rea says that it is not yet clear which path will best achieve this. “Will it be wafer bonding, direct-write epitaxy or will it be...” Rea hesitates because she is about to mention a much-discussed and forever promised buzzword, “system-on-a-chip?” In all likelihood, she admits, different approaches will be adopted for different materials, devices and applications.

New approaches to solve old problems

These approaches may ring of “been there, done that”, and resurrect images of the multiple failed attempts at GaAs-on-silicon, which often showed promise but were unable to make the jump to either military- or commercial-grade devices because of defect-related reliability issues. However, as Rea points out, things are different today. “Materials technology has advanced and we need to bear in mind that new approaches may solve old problems.”

Reassuringly, Rea is also quick to point out that the Air Force is not moving away from the wide-bandgap approach, rather that its development program will evolve toward multifunctional materials research. Future programs will look to integrate the best devices, using the optimum materials to maximize performance, as well as new materials and processes – not all of them traditional semiconductor approaches – into “all-seeing”, next-generation products.

“There are other classes of materials that we are also exploring, including biological materials and processes. For example, we are starting to explore the integration of DNA-based photonic devices with inorganic semiconductor technology,” says Rea.

Much like the term itself, some might characterize the DoD’s paradigm shift as “everything that is old is new again”. But this would be unfair; Rea is a firm believer in the wisdom of the poet-philosopher George Santayana – that those who forget the past are condemned to repeat it. In her world, that would mean wasting too many precious research dollars reinventing the wheel. “Besides, it’s one of the perks of being an old timer – a form of job security!” she laughs.

Web link

DARPA’s wide-bandgap programs (SiC and GaN development aimed at both RF/microwave/millimeter-wave technology and high-power electronics): www.darpa.mil/mto/wbg/.

“We are starting to explore the integration of DNA-based photonic devices with inorganic semiconductor technology.”

Laura Rea
AFRL

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STM images quantum dot epitax

Markus Pristovsek from the Technical University of Berlin describes his team's modifications to an STM instrument that have led to the first *in situ* images within an MOCVD reactor.

Everyone working in the compound semiconductor community has heard of the atomic force microscope (AFM), a desktop instrument that can routinely analyze the surface morphology of epitaxial layers. Its importance can be gauged from its rapid adoption: still a prototype in the 1980s, less than a decade later it had been widely deployed in fabs and research centers across the globe. Before it was available, imaging of samples with a high spatial resolution had to be carried out by transmission electron microscopy (TEM), a technique that requires time consuming sample preparation and experience. Now that it is widely available, *ex situ* measurements of epiwafers can be carried out without any sample preparation and just by following the simple instructions provided in the manual.

Although *ex situ* measurements with an AFM are now routine, it would be great to use this instrument *in situ* and (with an atomic resolution) produce images of epitaxial processes like the growth of quantum dots. It is an aim that is still to be fulfilled.

However, Bert Voigtländer and André Zinner from the Institute for Thin Films and Interfaces at the Research Centre Jülich, Germany, have used a related technique, scanning tunneling microscopy (see box "How an STM works"), to image SiGe material in an MBE reactor. Transferring this technique to an MOCVD reactor is not easy and over a decade has passed since that work before our research team at the Technical University of Berlin produced the first STM images in this harsher environment earlier this year.

Tough environments

An MOCVD chamber is a hot hydrogen atmosphere at near atmospheric pressure that is excellent at conducting heat and sound vibrations. Consequently, it is a poor environment for STM measurements, which require vibrations of less than 0.1 nm between the tip and sample at frequencies of above 1 Hz. This means that the sample and the STM tip must be connected together rigidly, and that the instrument must be isolated from the vibrations of the MOCVD reactor's pump and other external sources. These criteria have been met by mounting the pump on a separate plate and feeding all of the connections through sand boxes. The remaining vibrations of the susceptor-STM unit are then reduced by suspending the system with springs.

The temperature in the growth chamber also hampers STM imaging. This is because the piezoelectric

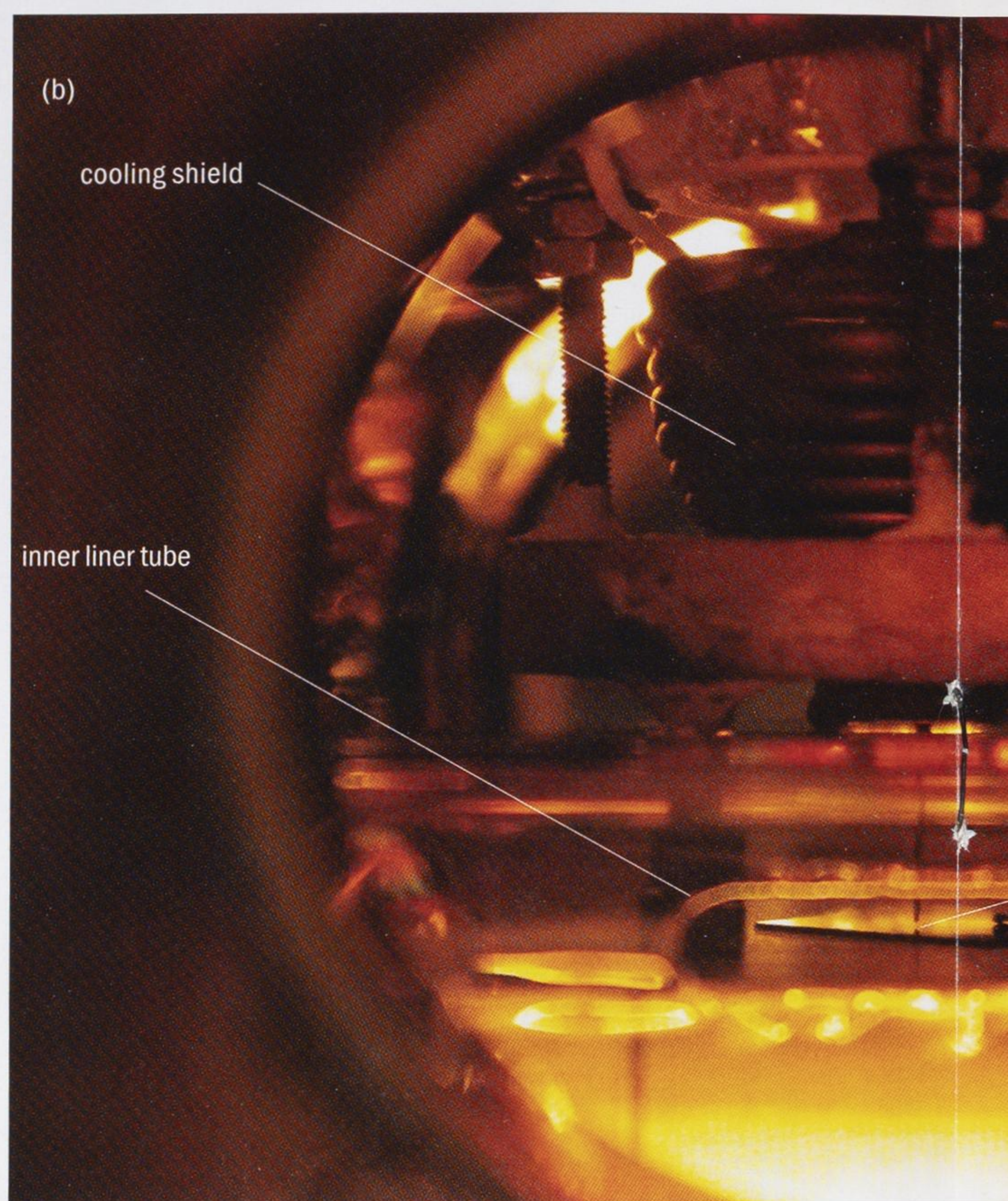
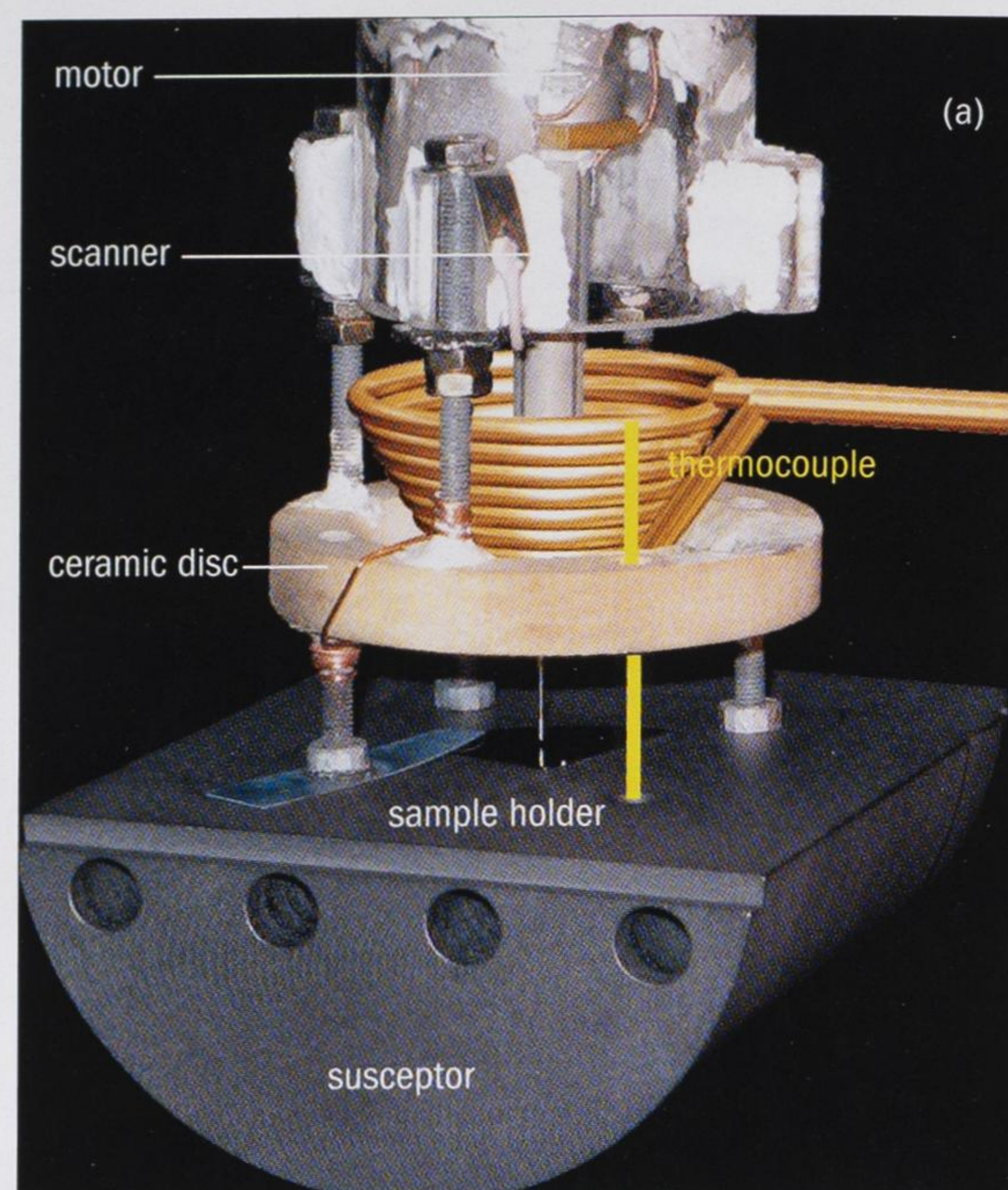


Fig. 1. We have modified the standard STM instrument by adding an active cooling shield through a side window in the horizontal MOCVD reactor enables the STM's metallic tip to

How an STM works

The STM, which was invented by Gerd Binnig and Heinrich Rohrer in the early 1980s, is used to image surfaces with atomic resolution (see figure, right). It works by measuring the tunneling current between the STM tip and the sample. This current is sensitive to the distance between the tip and the sample, allowing the STM to map the surface topography. The scanning process provides horizontal resolution of 2–5 µm. A coarse approach provides a precision of (typically 100 nm).

Galaxy inside an MOCVD chamber

STM works

which was invented by Gerd Binnig and Heinrich Rohrer at IBM in the 1980s, images sample surfaces with a metallic tip that is held at a constant distance of the sample (see Fig. 1). A bias voltage is applied between the sample and tip, leading to quantum mechanical tunneling of electrons between the probe and the sample. This tunneling current, which has an exponential dependence on the tip-sample distance, is used to adjust the height of the probe above the sample. By maintaining the tunnel current at a set value, which fixes the tip-sample distance, the surface can be profiled by raster-scanning the probe over the sample. Scanning is carried out using a piezoelectric scan tube that can be actuated with atomic precision by applying high voltages. This tube provides horizontal translation of 10–25 μm and vertical adjustments of $\pm 10 \mu\text{m}$. A coarse approach stage, which has a travel of several millimeters and resolution of a few nanometers, is used to bring the tip into close proximity (within 100 nm) with the sample.

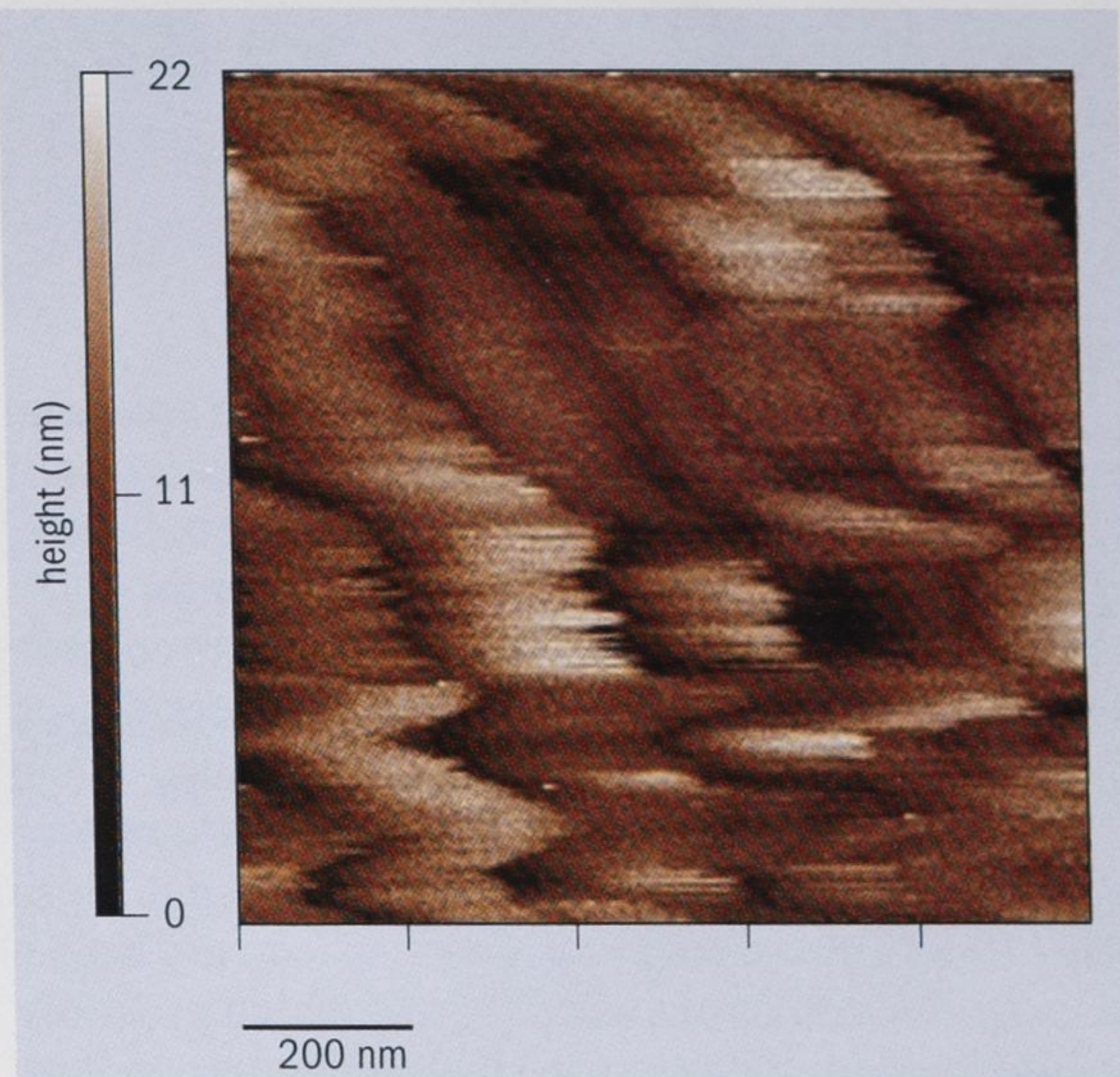
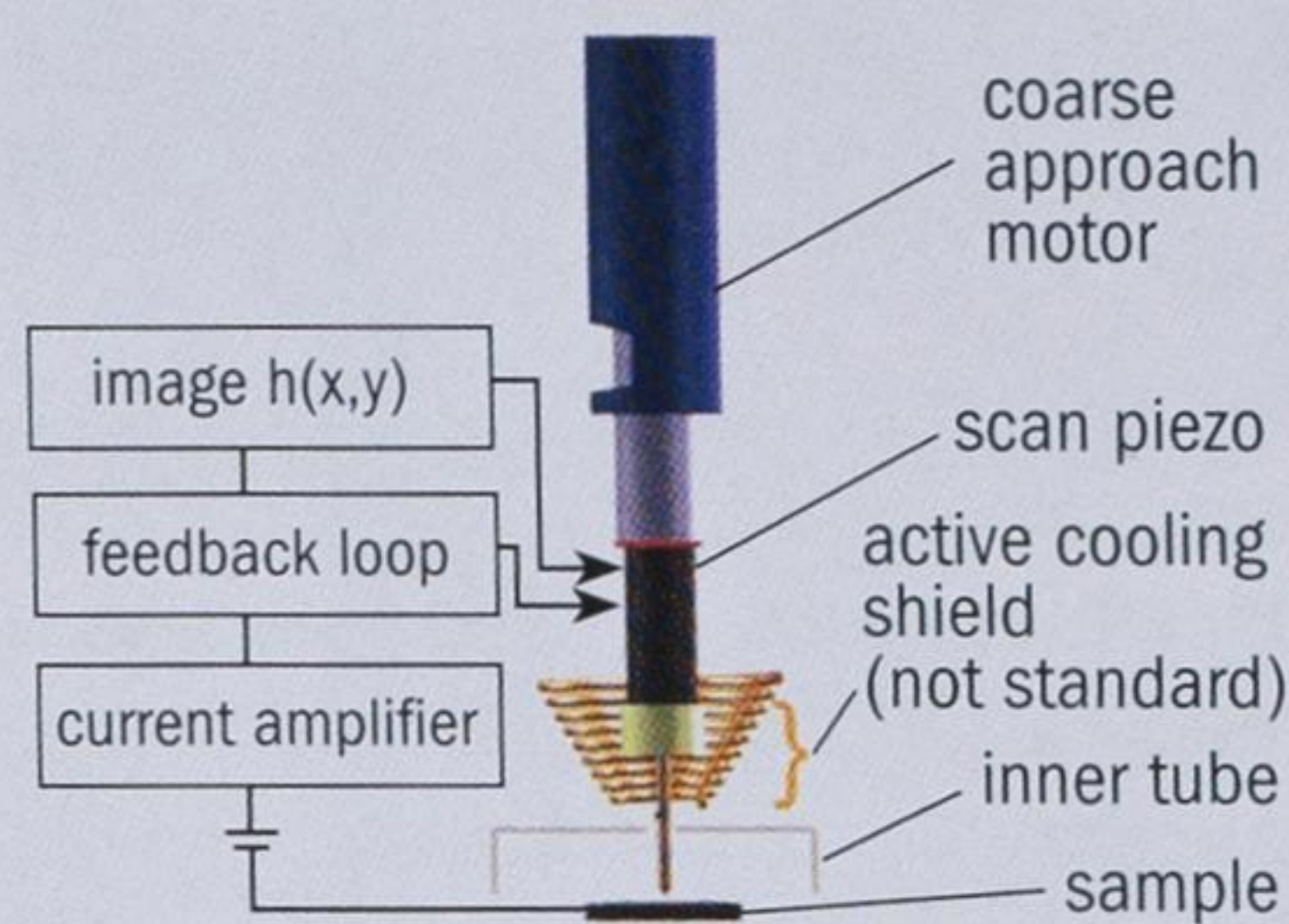
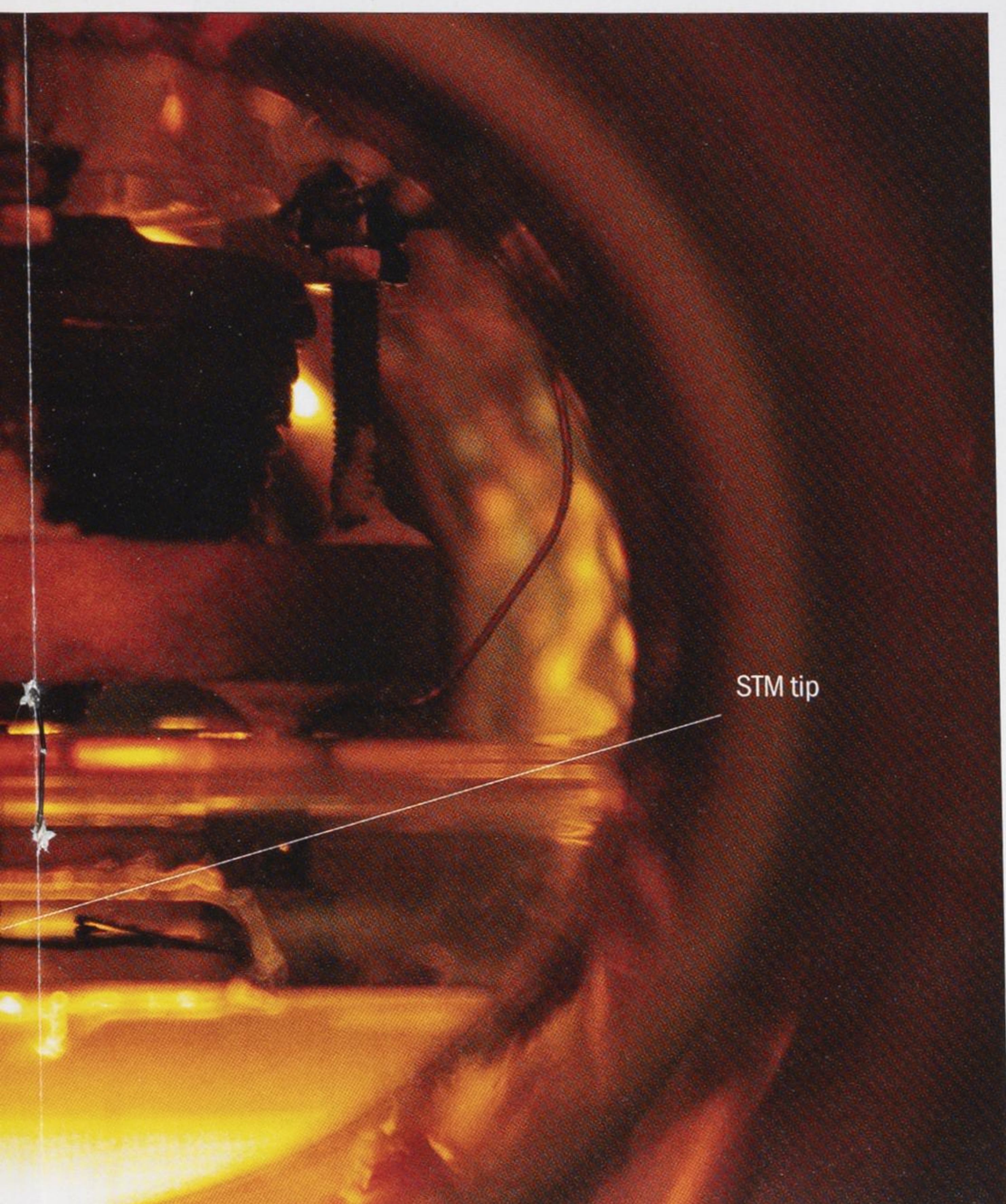


Fig. 2. This is the first ever *in situ* STM image taken inside an MOCVD reactor with an atomic resolution. It reveals atomic steps on a GaAs (001) surface, and was taken after buffer growth.



Active cooling shield that prevents the piezoelectric tube from getting too hot (a). Looking through the quartz tube, the metallic tip to be brought in close proximity to the sample surface in a controlled manner.

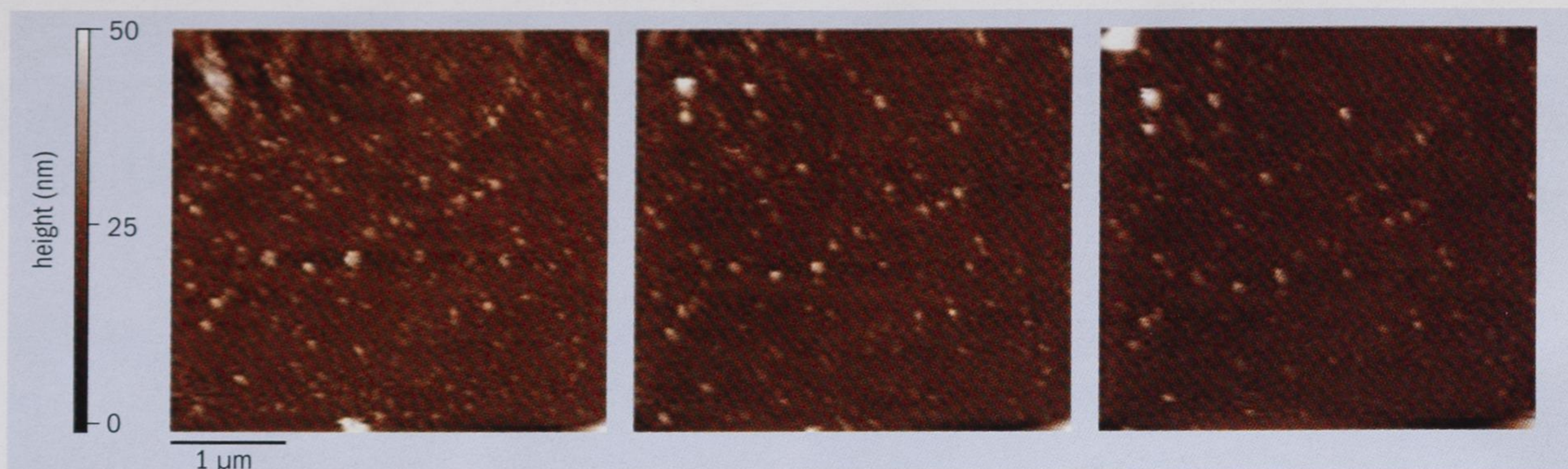
scan tube, which provides the scanning needed to generate images, cannot operate above 150 °C due to depolarization effects and so a cooling mechanism is required. In vacuum and MBE environments, the cooling mechanism is not too demanding because the hot surfaces are small and heat transfer only occurs by radiation. In MOCVD reactor, however, the hot surfaces are much bigger and the piezoelectric tube can also be heated by conduction and convection.

We have prevented depolarization of the scan tube by adding an active cooling shield. We investigated various different designs and cooling agents before settling for a cone-shaped tube supplied with gaseous nitrogen at about 80 K (–190 °C). The latest version enables STM imaging at growth temperatures of up to 650 °C by providing a heat differential of over 400 °C across 10 mm (see figure 1a).

The MOCVD growth chamber also suffers from electrical noise. This is an obstacle to STM imaging, which requires maintaining a fixed tunneling current between the tip and the sample of typically 1–5 nA. Our reactor, which is a forerunner of Aixtron's AIX200 horizontal reactor, uses an inner liner quartz glass tube surrounded by a second quartz tube and provides no electrical shielding. However, we have managed to introduce some shielding by adding a thin wire mesh and we have replaced the heater's noisy power supply with a quieter DC version.

Arsenic material growth has caused us an additional problem because amorphous arsenic is a relatively good electrical conductor and can short-circuit the piezoelectric scan tube and the tunnel contact. Our solution is to balance the fluxes inside and outside the reactor's liner tube, while preventing any precursors from

Fig. 3. This sequence of three images of InAs quantum dots, which were taken directly after growth stopped, shows Ostwald ripening – the increase in size of larger quantum dots at the expense of smaller ones. Care was required taking these images so that we did not influence the sample. There was no intentional delay between each of the scans and each image took 258 s to produce. This involved using low scan rates, which all reduce the likelihood of atoms sticking to the STM tip and electro-migration effects. However, this technique is still in its infancy and we have much to learn about tip-sample interactions in reactive environments.



escaping out of the tube.

The *in situ* STM must not influence the epitaxial process. To ensure this, we have restricted the parts of the instrument reaching into the liner tube to the tip, the three support rods that hold the susceptor and a thermocouple for the susceptor's temperature control. The cooling shield and main STM parts are kept outside this tube and even the tip can be retracted to this region.

We tested this approach by comparing the quantum dot growth with and without the STM present. Both sets of dots were very similar and revealed a difference in growth temperature of only 5 °C, which probably resulted from variations in the thermocouple position.

Addressing all of these issues associated with *in situ* measurements has taken us six years and three design iterations (see figure 1 for our latest instrument). The main challenges have been designing a cooling shield and developing a compact set-up for bringing the STM tip and sample together. We have chosen a piezo motor that can travel up to 25 mm with a 4 nm resolution. The whole system is now relatively easy to maintain, can operate at reactor growth temperatures of up to 700 °C, does not influence growth and can resolve variations in surface height on an atomic scale.

Seeing quantum dots evolve

Our *in situ* STM does not affect either the sample preparation or the growth recipes. The only change we have made is employing tertiarybutyl arsine for quantum dot growth, as this reduces arsenic contamination. Our imaging, which is undertaken after buffer growth, requires a tip with a single atom at its apex. This is produced by cooling the reactor to room-temperature before scanning at higher currents, which removes oxides and amorphous deposits from the tip and sharpens it. Depending on luck and previous treatments, this process can take from one hour to three days.

Once we have a good tip, we can heat the reactor and start to grow and image various structures, including atomic steps on GaAs epilayers (see figure 2) and InAs quantum dots (see figure 3). Monitoring quantum dot growth is not easy because the tip is colder than the surface and it picks up indium atoms, which then reduce the local growth rate. These fluctuations strongly influence the dot, which can change shape with the growth of layers just one-tenth of a monolayer thick.

To avoid these issues we have instead studied Ostwald ripening, the formation of bigger dots at the expense of

smaller ones once growth has stopped. The process was observed by taking several images of the InAs quantum dots, which were grown on a GaAs substrate at 475 °C, directly after growth had ceased (see figure 3). These images reveal that the number of InAs quantum dots strongly reduces with time and those that remain increase in size. This process cannot be observed quantitatively by any other method. *Ex situ* methods are not suitable because the Ostwald ripening continues as the sample cools, while optical *in situ* methods cannot resolve the dimensions of nanometer-sized features.

Our STM development is ongoing and although we have managed to reduce preparation times from days to hours we are still spending too much time conditioning our tips. This could be avoided by using an AFM instead of an STM and we have already developed an AFM-scan head using a piezo oscillating at 3 MHz. This instrument features a laser-sharpened glass-fiber tip that can be oscillated with an amplitude of 5–10 nm and provides a height resolution of 1–3 nm.

The ultimate *in situ* sensor would provide chemical data and topographical information. This is possible when STMs are operated in a scanning tunneling spectroscopy mode, which measures the bandgap across the wafer's surface. With this method, local composition of ternary and quaternary alloys can be measured.

The road ahead

Although the *in situ* STM holds a great promise and has already provided a unique insight into quantum dot evolution, we do not expect it to become a routine production monitoring tool. This is mainly because it is unlikely that the technique could ever be applied to growth in multi-wafer planetary and vertical reactors. *In situ* STM is probably also incompatible with investigations of GaN material growth because this involves reactor temperatures of at least 800 °C and probably prevent the use of piezoelectric materials. For both of these these applications we believe that engineers should instead continue to use the range of optical techniques that are already on the market.

However, we believe that a commercial STM, which could be available within five years, may have a place in the research environment. This instrument could provide a unique view of the critical steps of processes like the overgrowth of trenches, quantum dots or related problems that require a lateral resolution in the nanometer range and can fulfil the needs of a niche market. ●

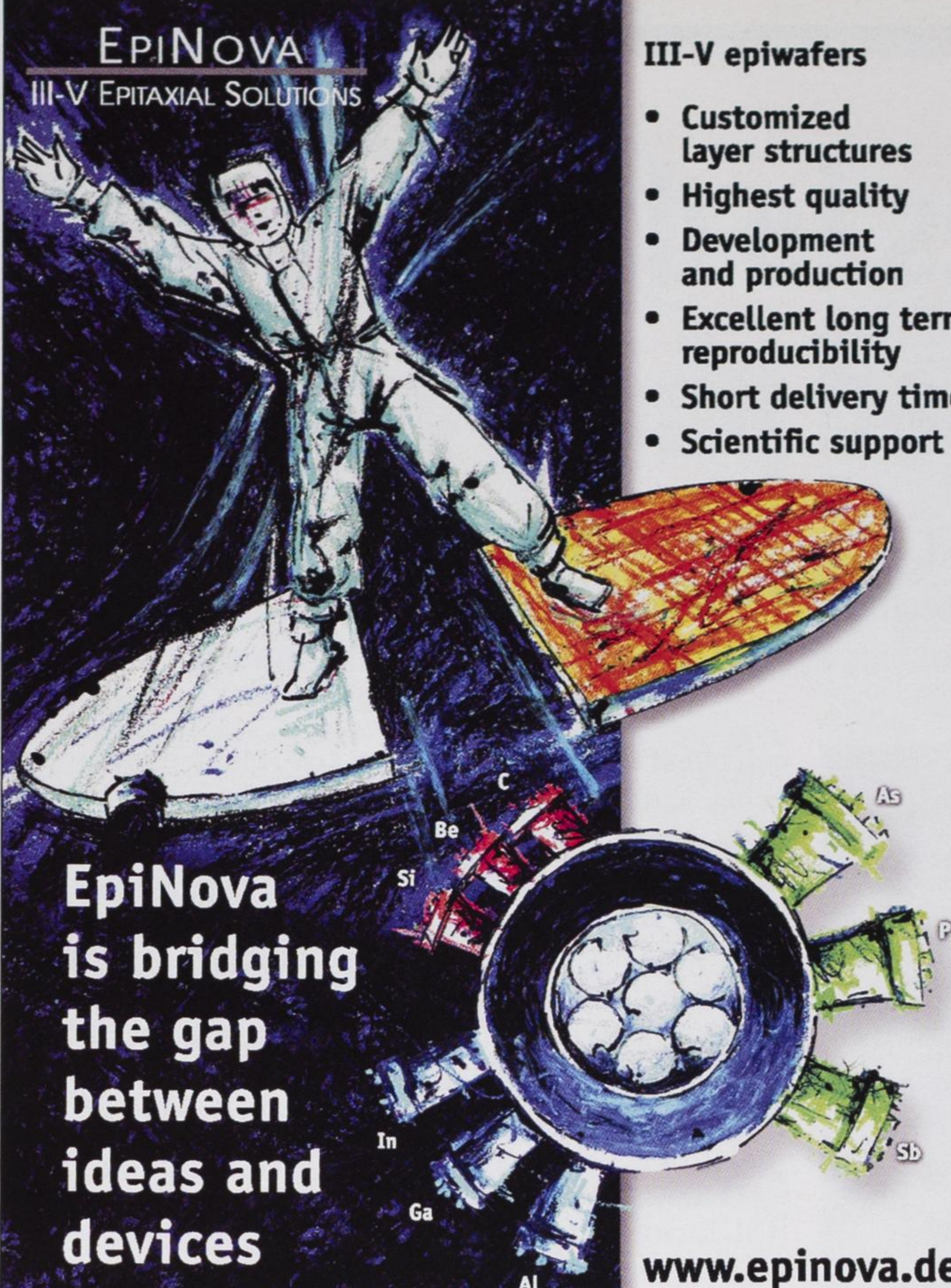


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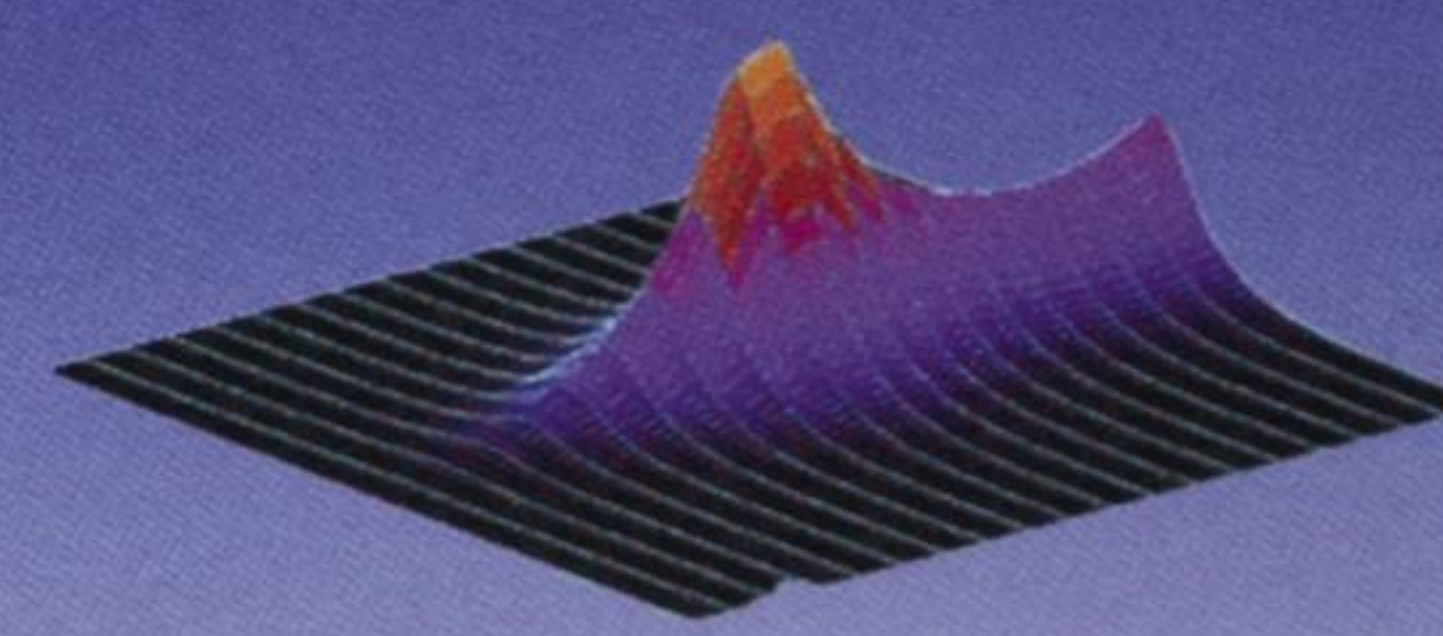
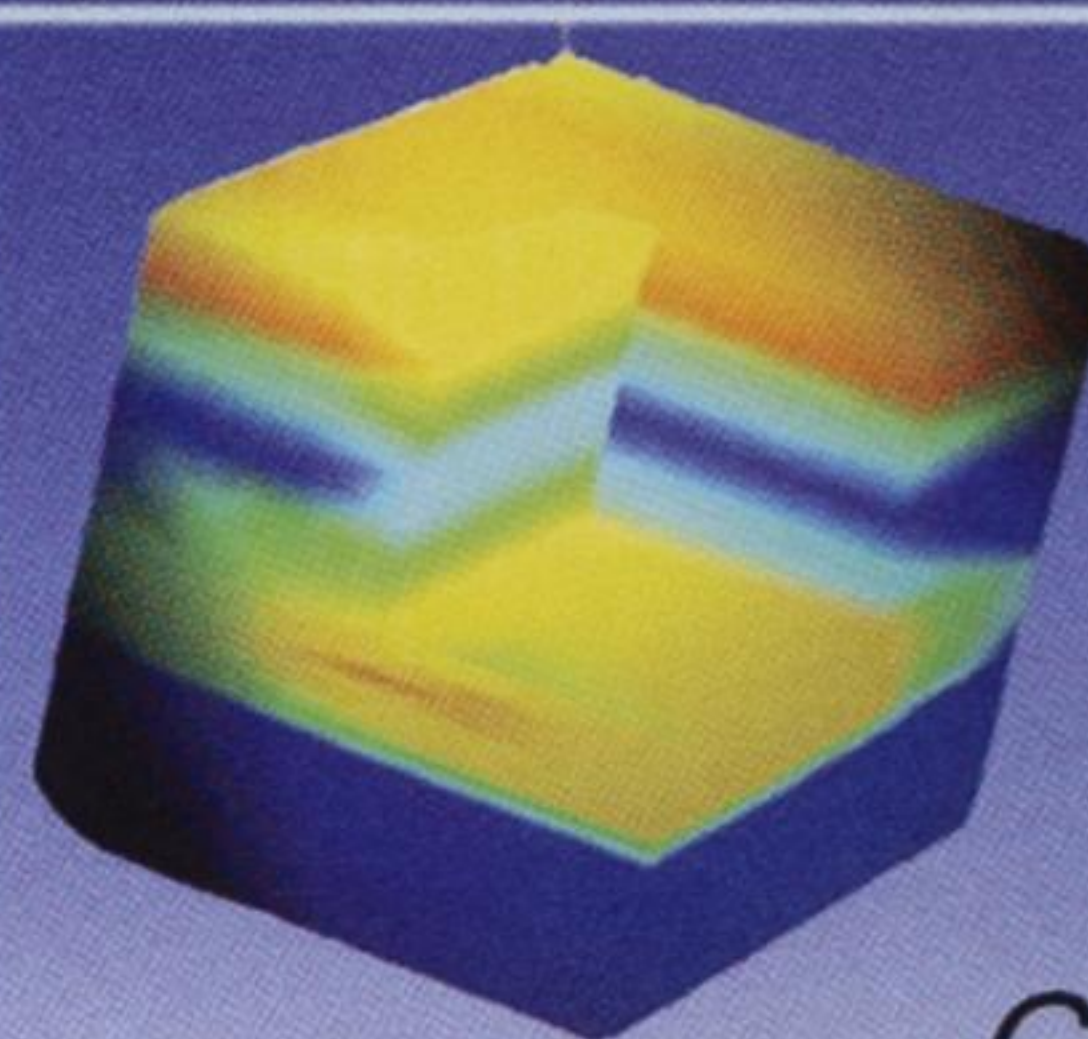
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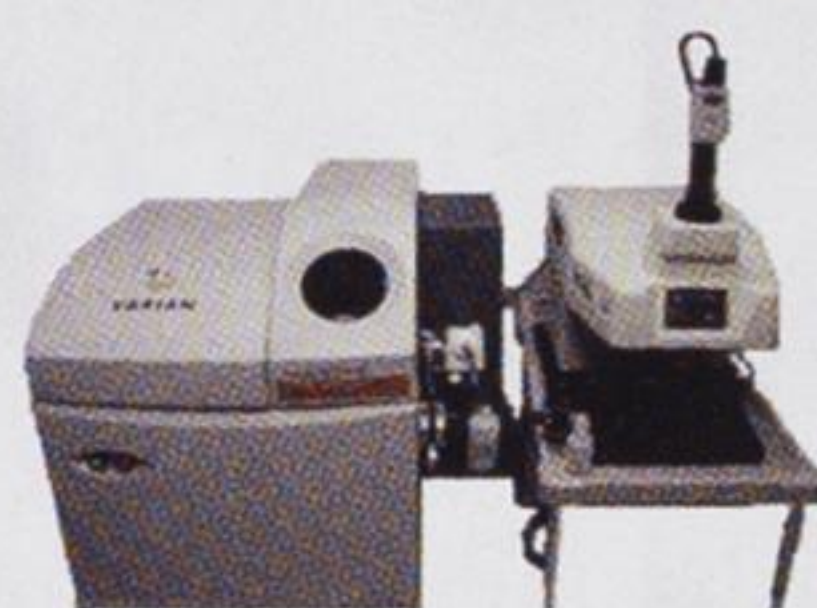
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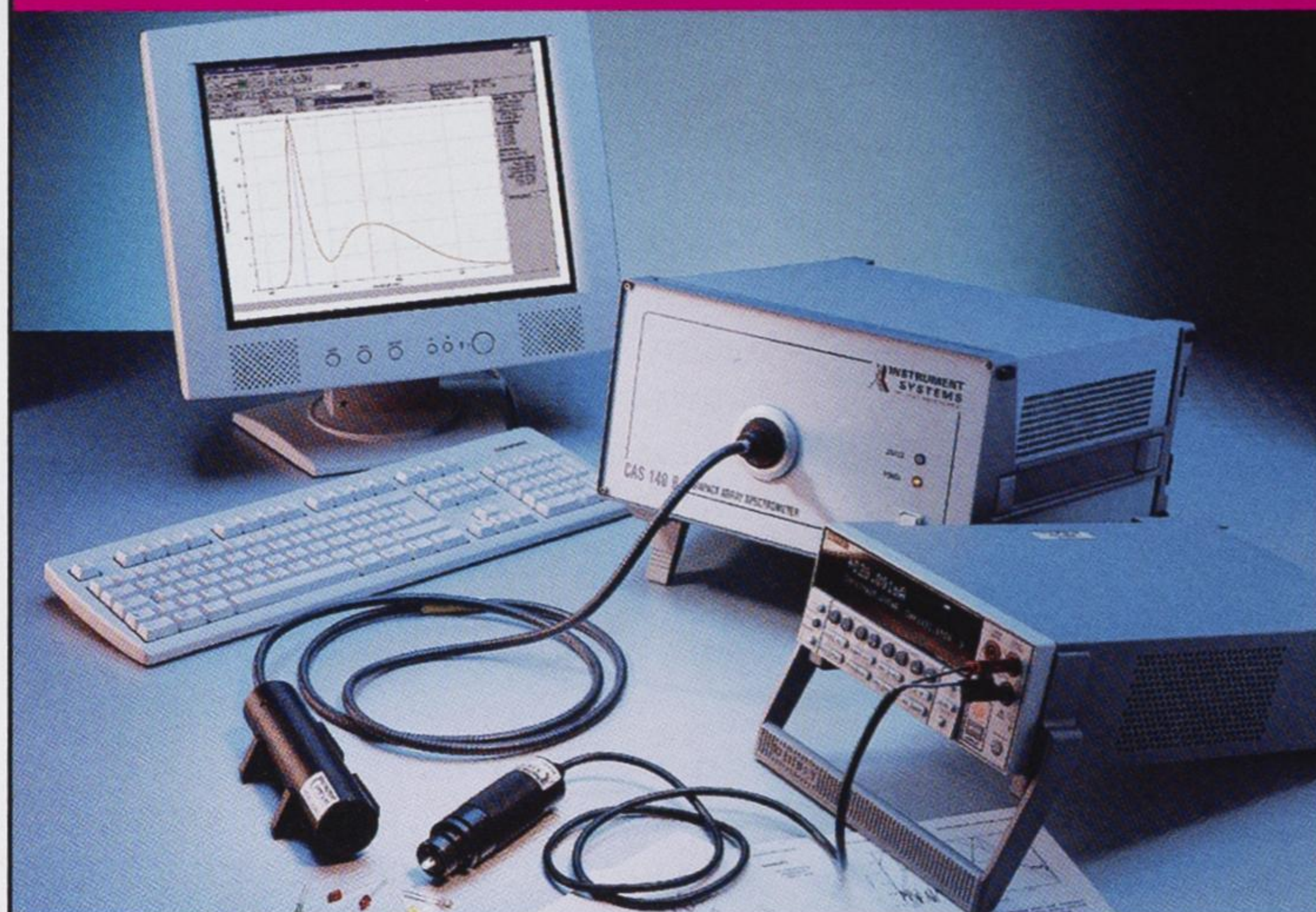
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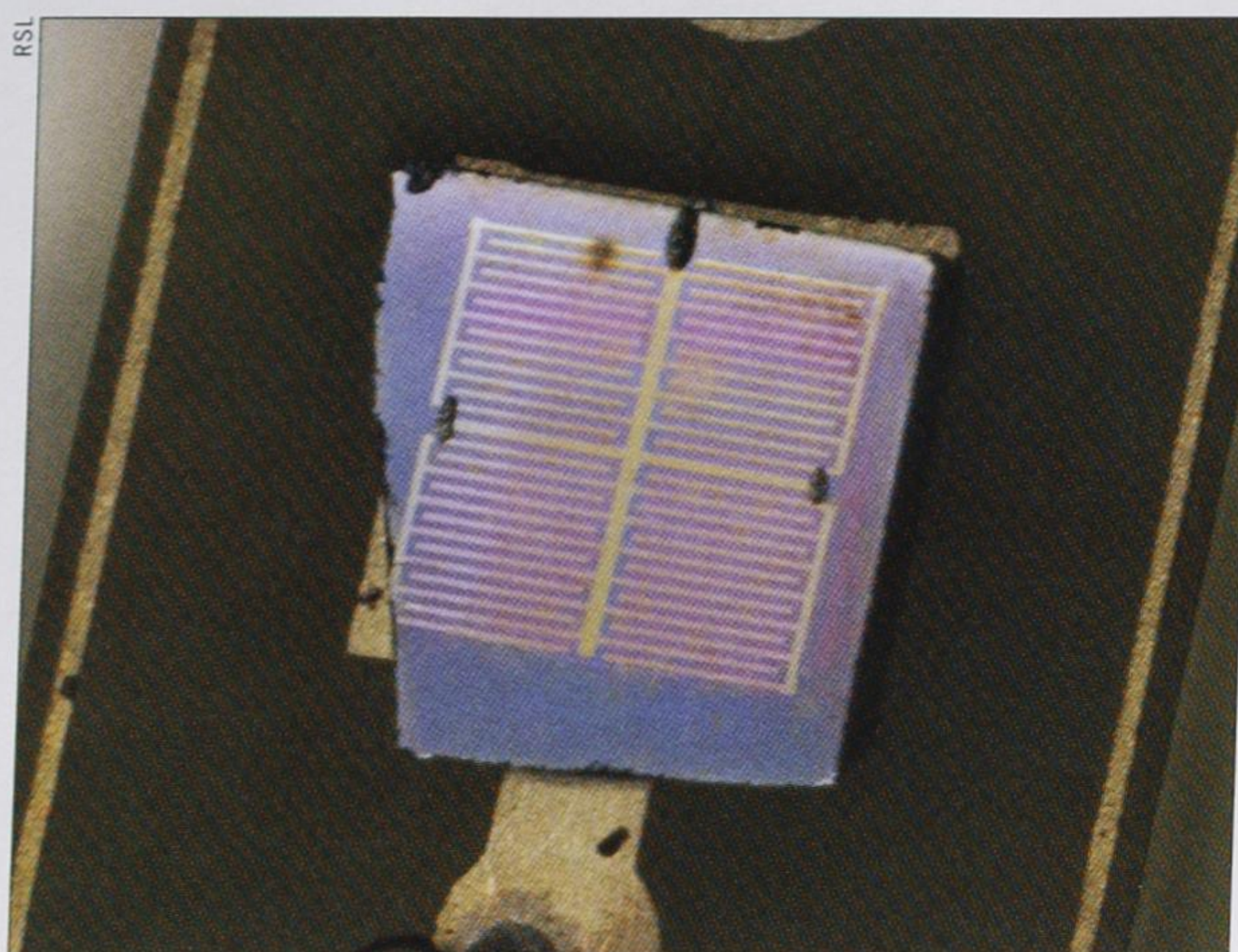
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SOLAR CELLS

RSL Energy promises to deliver on multi-band ZnTe-based photovoltaics

If we are going to harness the true extent of the Sun's energy, multi-junction solar cells are one option. But as **Jon Cartwright** reports, we could do it with multi-band cells — a new technology that RSL Energy promises will deliver the power conversion efficiency of triple-junction GaAs-based photovoltaics at the same price as single-junction devices.



RSL is now producing the first prototypes of its multi-band photovoltaic cells for field testing in 2008.

There aren't many plausible contenders for large-scale renewable energy sources. Solar power is one of them, but to make it practical in regions other than those with the sunniest climates it needs to be efficient and, perhaps more important, cheap. Silicon solar cells, the most readily produced photovoltaic devices by far, satisfy the latter of these criteria. But their poor power conversion from sunlight to electricity means it is unlikely that they will instigate any widespread adoption to solar power — at the time of writing, the silicon record lies at 24.7%.

Unfortunately, even if silicon devices were perfect they wouldn't get much past 30%. The reason is that no single bandgap can absorb all of the Sun's useful radiation, which includes potentially exploitable energy across the infrared, visible and ultraviolet.

Compound semiconductors such as GaAs have overcome this limitation by employing different alloys stacked in series, one on top of another, to cater for particular portions of the spectrum. But while these multi-junction cells have now attained efficiencies of up to 39% using three junctions, the extremely high cost (up to \$40/cm²) of their complex structure has precluded their use in anything except space satellites and subsidized terrestrial projects.

Now, however, RSL Energy in Arizona, US — a joint venture between RoseStreet Labs and Sumitomo Chemical — is pioneering a different breed of solar cell. Based on oxygen-implanted ZnMnTe or ZnTe, these cells can achieve the same efficiency as a multi-junction

cell but at a significantly lower cost, claim their proponents. Rather than using stacked semiconductor junctions, these new "multi-band" cells generate three individual bandgaps by having abnormally large quantities of mismatched atoms implanted into a single material. This, according to RSL Energy CTO Wladek Walukiewicz, avoids the need for expensive lattice matching and convoluted fabrication techniques. "Multi-junction cells can be a nightmare. Multi-band cells are much simpler, because they have just one junction."

Next-generation technology

RSL Energy's multi-band cells build upon a concept first proposed in the 1980s. Normally when semiconductors are alloyed, their properties are changed continuously and in a controlled manner. But some alloys are particularly averse to being formed. This is the case if one wants to replace some of the tellurium in ZnTe with oxygen: tellurium atoms are much larger and less electronegative than oxygen atoms, so ardently resist all attempts to be replaced.

In the 1990s, however, scientists discovered that they could force the substitution by using non-equilibrium processes. Walukiewicz was one of those scientists. He discovered that by accelerating oxygen atoms to high energies and firing them at a p-type ZnTe substrate, large amounts could be crammed into the dogged structure. The trouble with this heavy-handed approach, however, is that the crystallinity of the material is damaged during the bombardment. The crystal can be repaired by annealing, but in normal circumstances this process leaves the oxygen ample time to force its way out again.

"We have to use a process called pulsed-laser melting," explains Walukiewicz. "Oxygen does everything it can to avoid being a substitute, so you have to do the annealing fast and at a high temperature. One single pulse melts the layer, which then grows again very rapidly."

Walukiewicz replaces up to 5% of the tellurium with oxygen, of which about 3% is "active", meaning that it contributes to the modification of the bandgaps. In small amounts, the oxygen atoms only form localized energy levels. But as more is added, these energy levels eventually overlap to form a continuous narrow band, shifting up ZnTe's original conduction band slightly in the process. The result is a "split" band structure and three available absorption energies for incident photons: 0.8, 1.8 and 2.6 eV (see figure p19).

"These [energies] are close to what you need for opti-

"Multi-junction cells can be a nightmare. Multi-band cells are much simpler, because they have just one junction."

Wladek Walukiewicz
RSL Energy

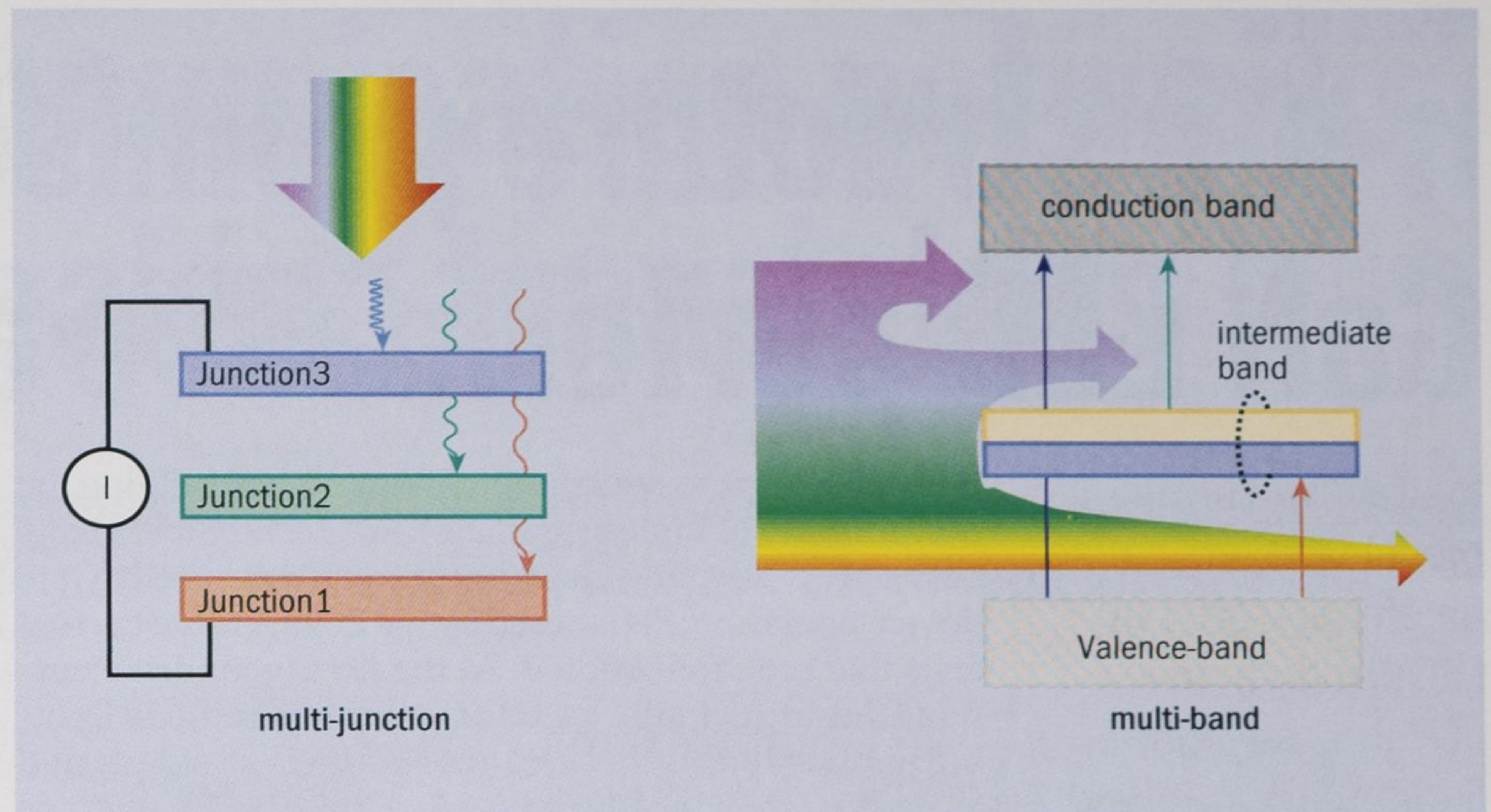
mal coverage of the solar spectrum,” says Walukiewicz. “The oxygen band provides a stepping-stone for near-IR photons to excite electrons from the valence band to the conduction band.” This, Walukiewicz adds, enables a theoretical efficiency of 56%, although in practice the devices are expected to demonstrate practical efficiencies closer to 48%. “A good rule of thumb is that if you get 80% of the theoretical maximum, you’re doing well.”

The potential for RSL Energy’s multi-band solar cells will probably lie where multi-junctions’ cost demands have proved broadly untenable – for domestic use on Earth. One possibility is that a multi-band layer could be added *ad hoc* to existing silicon solar cells to incrementally improve their efficiency, which could help to extend the lifetime of a rapidly maturing silicon industry.

However, on their own the high power conversion of multi-band photovoltaics would allow them, for example, to be used in residential applications where space comes at a premium. While companies such as Emcore and Spectrolab are targeting utility-scale power plants with their multi-junction technology, they acknowledge that residential or roof-top use is unlikely.

RSL Energy’s approach would also circumvent the need for “concentrator” optics that multi-junction cells require to generate power at high efficiencies. Currently, numerous concentrators are required to focus the Sun’s rays onto a relatively small area of III-V cells, but Walukiewicz claims that in the long run his multi-band cells could be made cheaply enough to make concentrators completely unnecessary.

All of which could be good news for tackling the world’s mounting carbon dioxide emissions. The US,



Conventional III-V cells (left) need multiple junctions to reach high efficiency, but ZnTe and ZnMnTe can form a multi-band, single-junction device (right) that is just as effective at converting solar energy.

one of the greatest consumers of electricity per capita, still obtains more than four-fifths of it from burning fossil fuels, such as oil. Solar cells account for less than a thousandth (US Department of Energy statistics). But RSL Energy isn’t solely aiming for the terrestrial market – it is now applying the ZnTe approach to phosphorus-implanted GaAsN for satellite power supplies, which have to withstand full-strength solar radiation. “II-VIs are not radiation-hard materials like III-Vs,” says Walukiewicz. “GaAsN could work in the same way and can even be grown by MBE very easily.”

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POWER LEDS

n-p-n structure promises efficient GaN LED performance at high currents

Ineffective current blocking layers cause an efficacy drop in LEDs at high drive currents, say Ioffe Institute researchers Igor Rozhansky and Dmitry Zakheim. They believe that this can be overcome by switching to an n-p-n structure, as **Richard Stevenson** reports.

It is imperative to read the small print when judging the performance of high-brightness GaN LED chips. That's because efficacy, the metric most frequently used to rate device operation, is flattered by the 20 mA drive current tests that are often quoted. At the far higher drive currents that are actually used for operating a chip in lighting applications, efficacies are significantly lower and at 1 A they are typically only half of the 20 mA value (see figure 1 for examples from two LED manufacturers).

This decrease in LED efficacy with increasing drive current is clearly an issue for chip manufacturers. Its origins are not well understood but, if uncovered, could provide a starting point for boosting the performance at operating conditions required for general illumination.

The misconception is that the quenching of efficacy at higher currents is caused by heating of the active region, say Igor Rozhansky and Dmitry Zakheim, researchers studying LED performance at the Ioffe Physico-Technical Institute of the Russian Academy of Sciences in St Petersburg. However, this has been ruled out by comparing the external quantum efficiency (EQE) of devices driven continuously with those operating in pulsed mode, which run cooler.

Rozhansky says that another popular theory for explaining reduced performance at higher currents is associated with the filling of localized states in the InGaN active region. This argument assumes that at low currents the electrons and holes are confined to areas where there are fluctuations in indium composition. This suppresses transport to non-radiative recombination centers. At higher currents these localized states are already full, which increases the probability that the additional electrons and holes reach, and are trapped by non-radiative recombination centers that prevent luminescence.

According to Rozhansky, this explanation predicts that InGaN LED efficacy is strongly influenced by the quality of the active region. However, measuring the efficacy of a range of LEDs with different active regions at high current densities has shown that this is not true.

Instead, Rozhansky and his colleague think that the explanation for the efficacy drop at higher currents is a decrease in the effectiveness of the electron-blocking barrier. This barrier, which features in many LEDs, boosts emission by preventing electrons from escaping into the p-type region. "In AlGaAs layers they are effective," he explains, "but in nitride-based LEDs it is a different situation – the piezoelectric field that is inherent in the AlGaN current blocking layer substantially reduces the barrier efficiency at high pumping."

Rozhansky and Zakheim have reached these conclusions by using a "drift-diffusion" model to calculate the charge transport in an AlGaInN LED (see I V Rozhansky *et al.* 2006 *Semiconductors* **40** 861). The modeling has led them to a new LED design with an n-

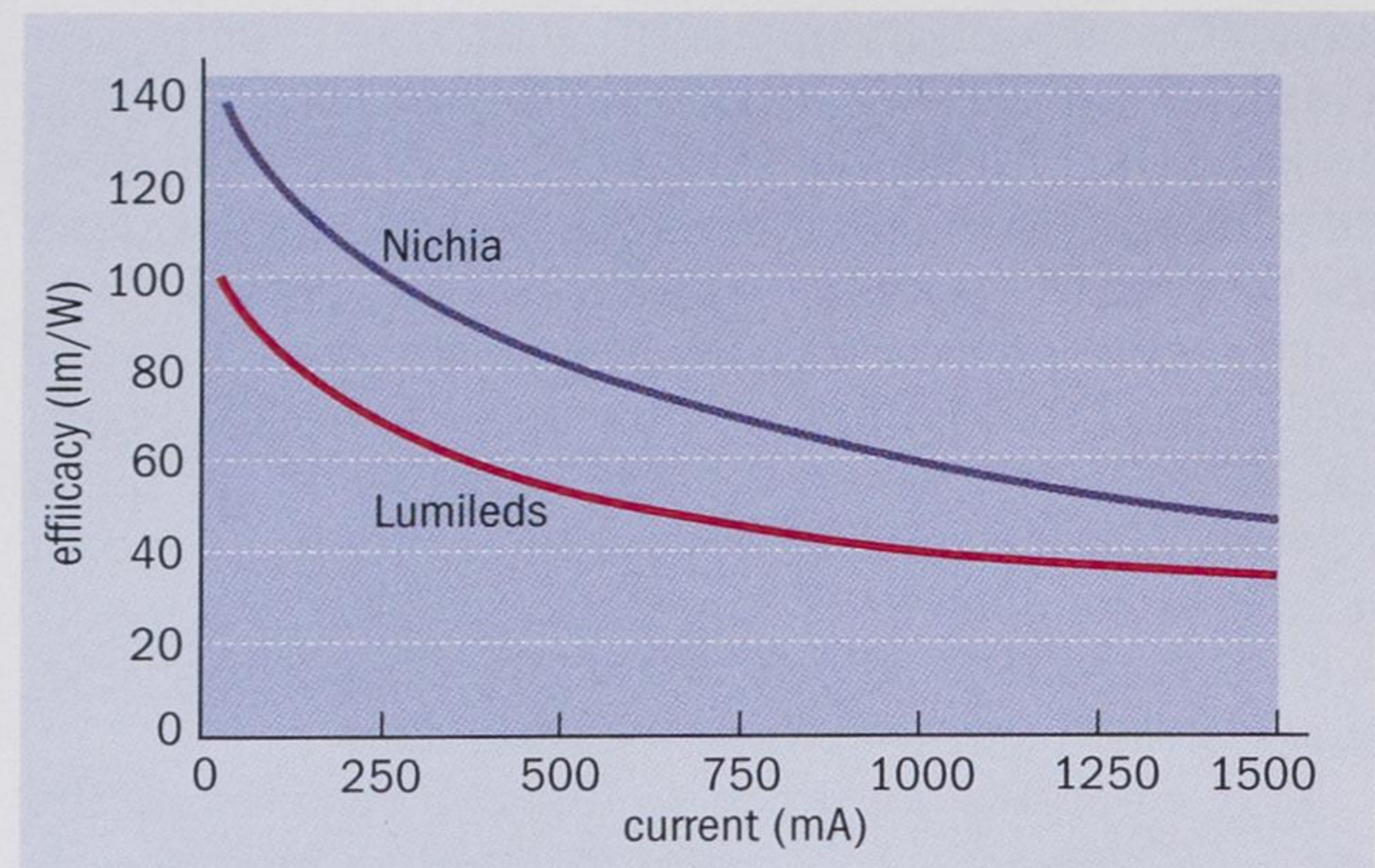


Fig. 1. The latest white LED chips manufactured by Lumileds and Nichia demonstrate the typical decline in efficacy with increasing drive current (data taken from *Appl. Phys. Lett.* **89** 071109 and *Jpn. J. Appl. Phys.* **45** L1084, respectively).

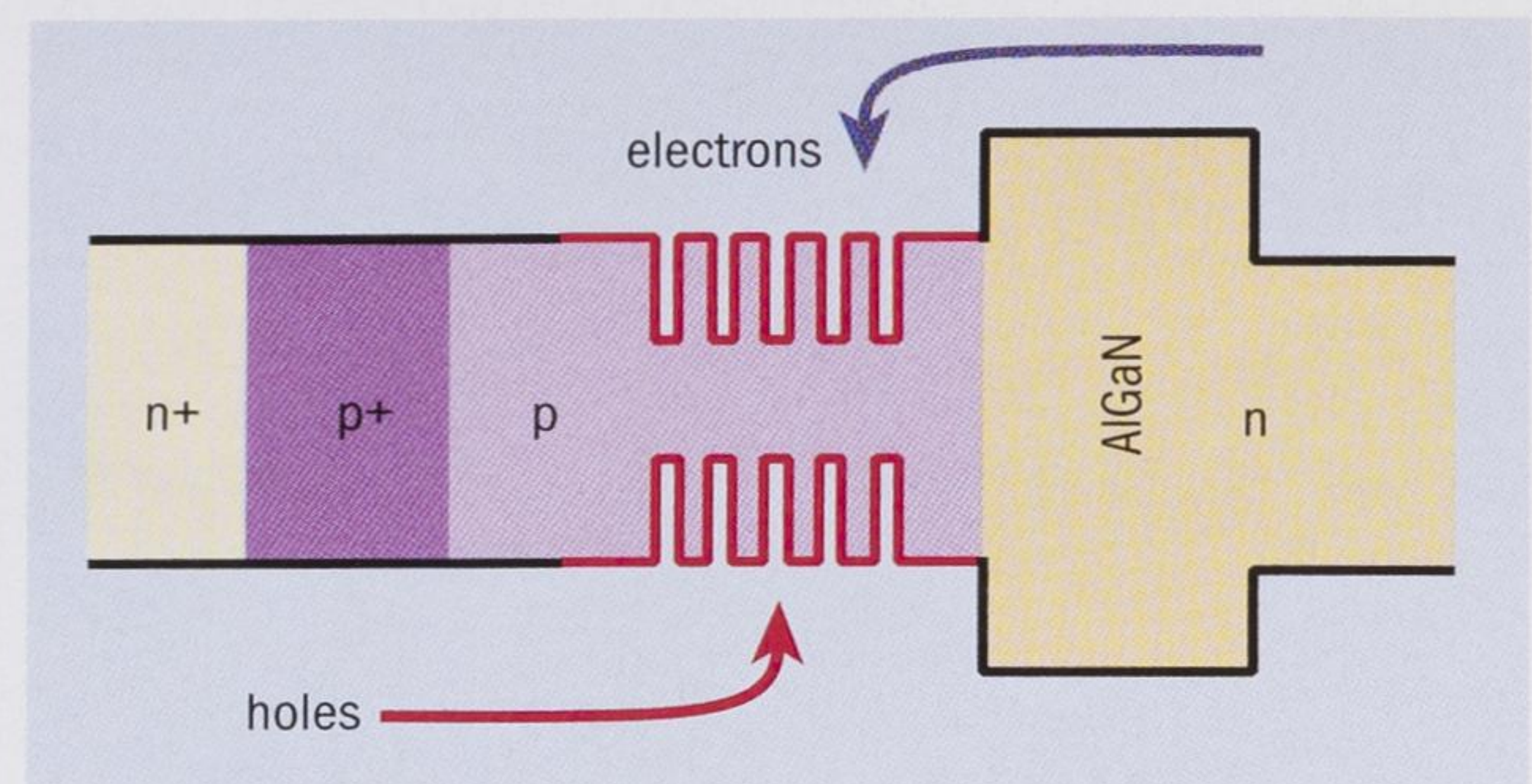


Fig. 2. GaN-based LEDs with an n-p-n structure feature an efficacy that does not decline with increasing drive currents.

p-n heterostructure that is expected to maintain its efficacy at high drive currents (see figure 2). In this design, the active region is shifted to the LED's p-side and emission is controlled by the injection of electrons instead of holes. LEDs made with this design have backed the theory, bucking the trend of a decreasing EQE at high current densities.

Unfortunately, the on-wafer EQE of the n-p-n structures is typically only 1%, but Rozhansky believes that there are no fundamental reasons why improvements can't be made. The low efficiency is partly caused by a diffusion of the magnesium dopant from the p-type region to the active layer, but this can be addressed by adjusting the doping profile near the active region. Poor quality material, due to growth on magnesium-doped GaN, could also be an issue but it can be dealt with by growing magnesium-doped GaN at higher temperatures, says Rozhansky: "In conventional structures the active region would be destroyed by higher temperatures, but in the n-p-n structures this problem does not exist, so one can obtain much better quality."

Japan eyes communication networks with record-breaking transistors

A government-sponsored Japanese program has built a range of high-power GaN transistors that are set to benefit mobile phone networks and automotive radar systems. **Richard Stevenson** investigates.

The Japanese and US governments have different reasons behind their funding of national GaN transistor development programs. While the US sees the technology as a key to its next generation of military hardware, Japan believes that GaN transistors can form the heart of tomorrow's civilian communication systems.

Japan hopes that the GaN HEMTs can replace the silicon and GaAs chips that are employed to amplify the signals of today's base stations used for wireless networks. The relatively low output power of the incumbent transistors means that several of them have to be used together in large and inefficient power-combining circuits. These drawbacks could be overcome, however, by using a single GaN transistor that is more powerful. The stronger signals could also improve automotive radar's detection range and boost the reliability of the associated modules, thanks to GaN's reliability at the high temperatures found within a car.

To create the devices for these applications, Japan launched a five year program in September 2002 that has funding of ¥3 billion (\$25 million) (see figure 1). The money is fed through Japan's New Energy and Industrial Technology Development Organization (NEDO) and involves four main organizations: Risumeikan University, the government's National Institute of Advanced Industrial Science and Technology (AIST), Toyoda Gosei and NEC. Each of these organizations is responsible for different aspects of the development, like material and wafer development or device design (see figure 2). According to Yasushi Nanishi, the program's leader and a professor at Risumeikan University, this horizontal approach is needed because of the difficulties of GaN development.

Ambitious targets

Nanishi says that the program is going well and has delivered steady improvements in device performance. He is clearly a master of understatement, for the program has produced the world's highest output transistor chips at 2, 5 and 26 GHz. These advancements makes the project on-track to hit its final targets that include outputs of 200 W at 5 GHz and 20 W at 26 GHz, a material mobility of $2000 \text{ cm}^2/\text{Vs}$, a sheet carrier concentration of $3 \times 10^{13} \text{ cm}^{-2}$, and thickness and uniformity specifications of $\pm 5\%$ on 4 inch substrates.

The high output power of NEDO's transistors results from a design that features a recessed gate FET and a

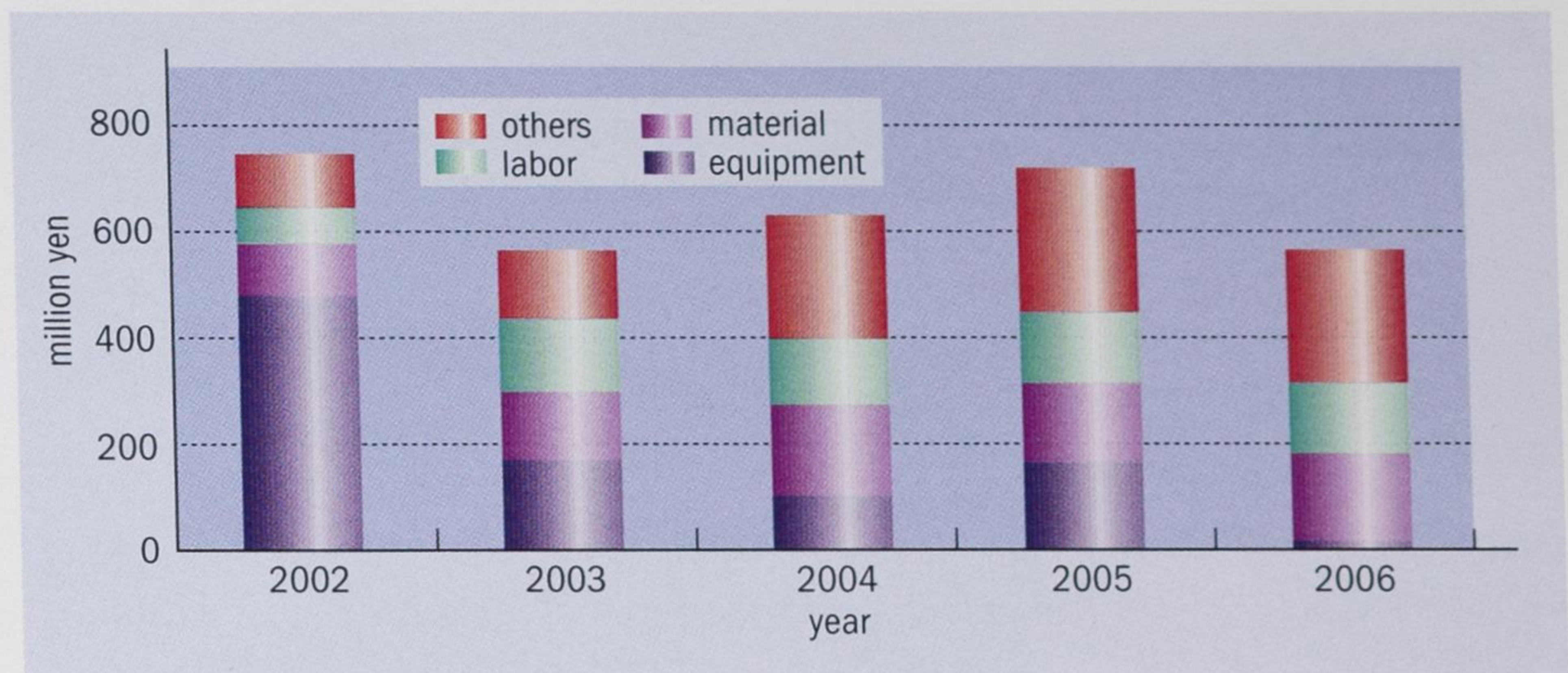


Fig. 1. ¥3 billion (\$25 million) is being invested to enhance the performance of GaN transistors at 2 GHz, 5 GHz and 26 GHz. The money is fed through Japan's NEDO and involves four main organizations.



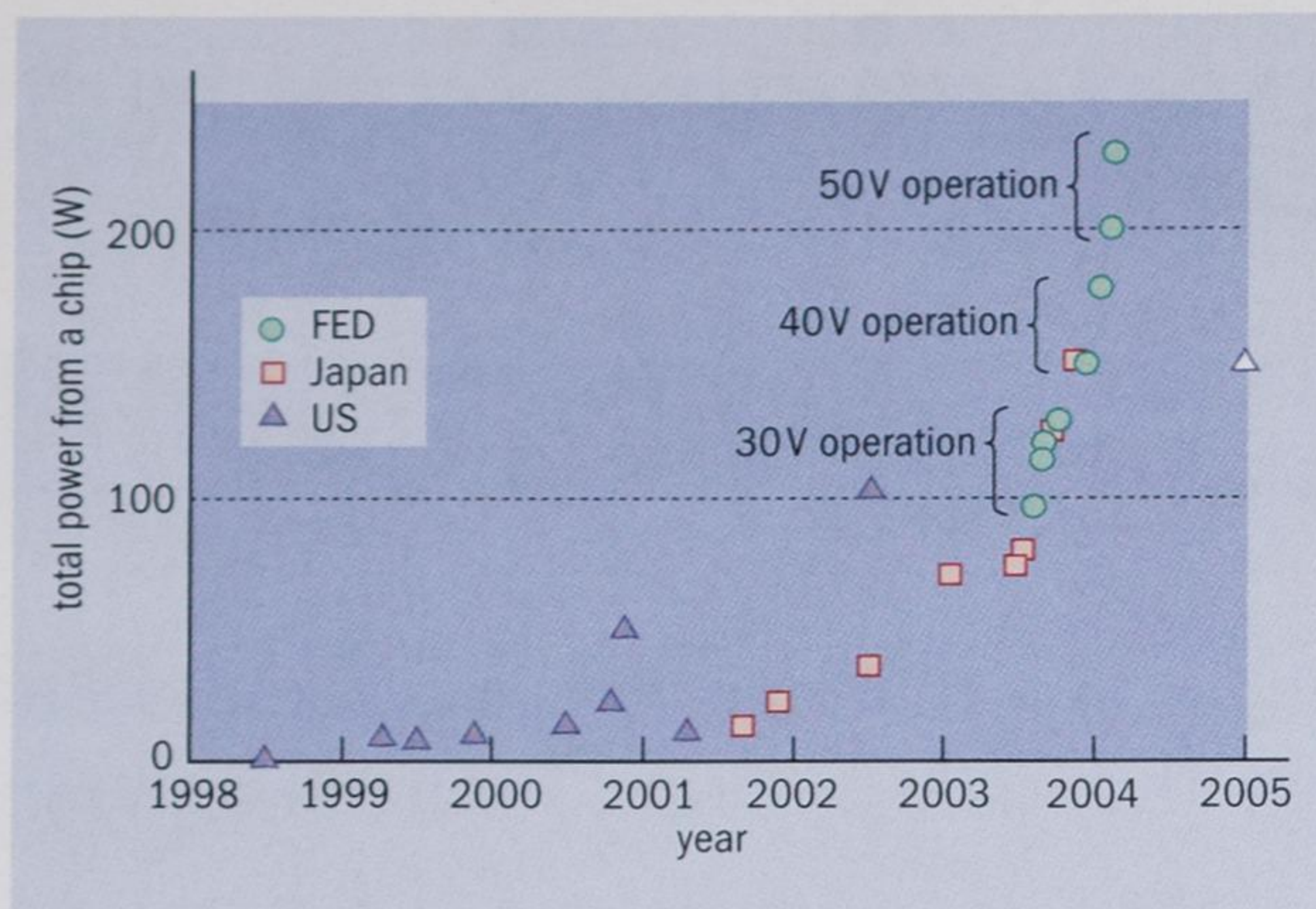
Fig. 2. The Japanese program for the development of high power GaN HEMTs involves contributions from four separate sites: Kusatsu, Aichi, Ohtsu and Tsukuba. At the Kusatsu site engineers from Risumeikan University, Furukawa Electric, Oki Electric, Mitsubishi Electric, Hitachi Cable and Matsushita Electric study material and device characterization. Toyoda Gosei at the Aichi site are investigating material and wafer properties, while NEC at the Ohtsu site are undertaking device design and fabrication. Materials characterization and device processing take place at the Tsukuba site by engineers from Advanced Industrial Science and Technology, Sumitomo Chemical, Hitachi Cable and ULVAC.

field modulating plate (FP). The planar FP significantly reduces current collapse, a degradation of the drain current under operational or stress conditions, while further gains are made with a recessed design. These changes also improve the breakdown voltage from 50 V to 160 V and then 200 V.

Implementing the design has driven a rapid performance improvement in the output power of the projects FETs that are grown on semi-insulating SiC substrates. For frequencies of around 1.5 GHz, the L-band used in mobile phone networks, output power has rocketed in recent years (see figure 3, p22).

There has been similar success at 2.14 GHz, a frequency used for CDMA cellular base stations.

Fig. 3. Adding field modulating plates to the transistors has produced a rapid improvement in the output powers of L-band transistors. The R&D Association for Future Electronics Devices, which is part of the NEDO project, is leading the way, followed by other Japan institutions independent from the program, which are labeled as 'Japan'.



Reports last year described a single-ended 280 W amplifier and a paralleled gate design delivering 371 W, and this year the bar has been raised to 416 W. “We have matched the needs for commercial deployment,” explains Nanishi, revealing that progress came from “small advancements” such as optimizing the circuit and the production process.

Amplifiers that operate at 2.14 GHz have also been fabricated with a second FP. “This shields the capacitance between the gate and drain, minimizes feedback capacitance and increases the gain,” explained Nanishi. This has produced an amplifier that delivers 160 W at 17.5 dB of linear gain under a 2.15 GHz W-CDMA modulation scheme.

Targeting tomorrow's networks

The team have also made efforts to improve the output power of 5 GHz amplifiers for 4G networks and satellite communication systems. In 2005 the team reported a single-chip amplifier with a 61 W output, and this year it has announced a 100 W version that can deliver 12.9 dB of linear gain and 31% power added efficiency at a drain bias of 56 V. In pulsed mode output is boosted to 155 W. Toshiba, which is working outside the NEDO program, has produced even higher powers of 174 W at 6 GHz but this features four separate chips. Both results are short of NEDO's 200 W goal, but Nanishi says that he is very confident that his team will hit the target before the project is wound up early next year.

At 26 GHz NEDO's best published results are for amplifiers based on 0.25 μm T-shaped gate devices that deliver 5.8 W and a linear gain of 9.2 dB. However, Nanishi says that more impressive results have been produced in the lab and he expects that reports of amplifiers with outputs exceeding the 20 W goal will emerge.

At the core of all of these performance improvements are a range of characterization methods like photoluminescence, Raman spectroscopy, Kelvin probe microscopy and device performance simulations.

Photoluminescence studies with an ultraviolet lamp have revealed that more intense yellow emission from the buffer layer is related to higher leakage currents (see figure 4). This emission has been used to optimize the growth process for the buffer.

After the team established the buffer's growth conditions they investigated the influence of this layer's

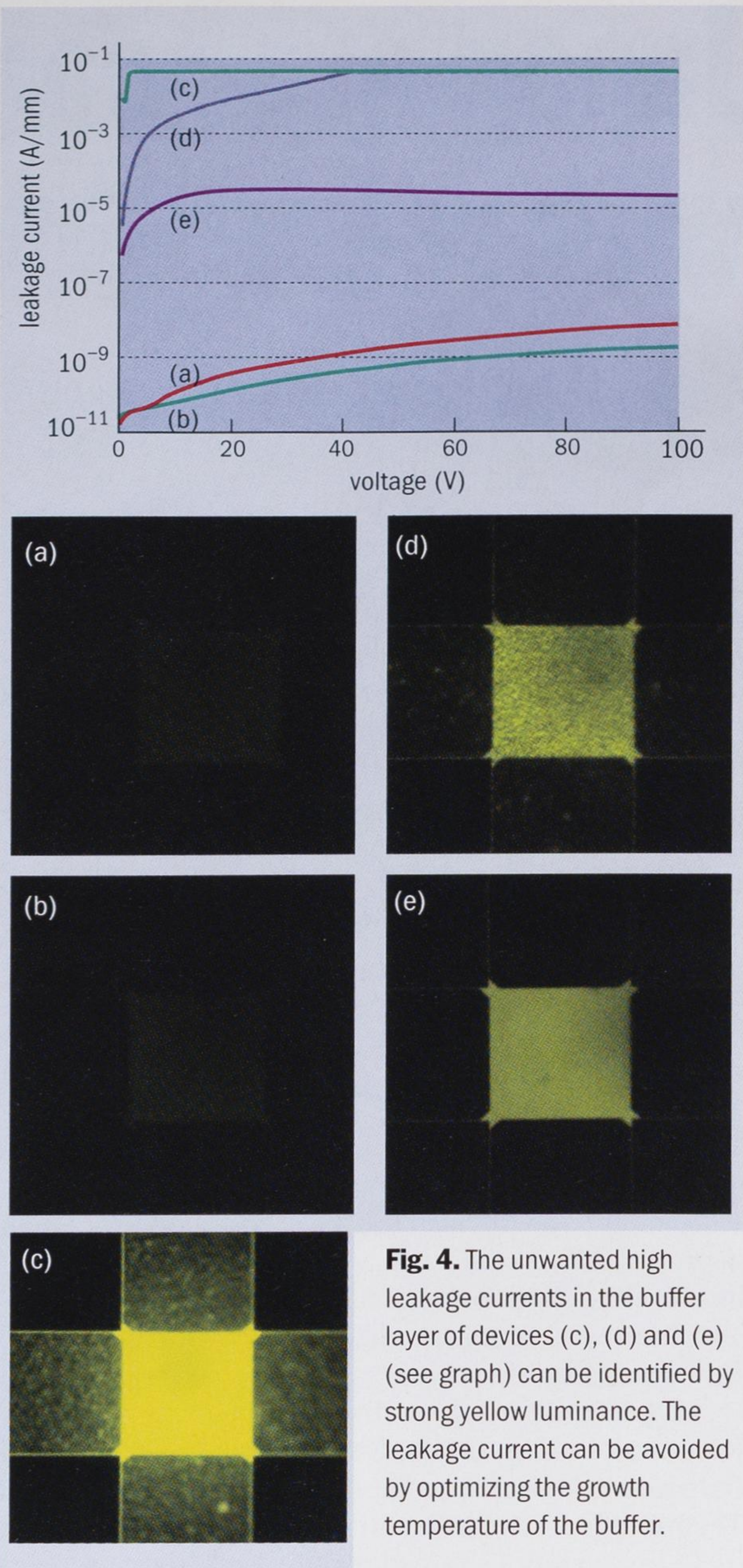


Fig. 4. The unwanted high leakage currents in the buffer layer of devices (c), (d) and (e) (see graph) can be identified by strong yellow luminance. The leakage current can be avoided by optimizing the growth temperature of the buffer.

thickness on leakage current. The results are contrary to what one would expect. “Usually, to obtain higher performance devices we should make the buffer layer thicker to obtain a higher-quality two-dimensional electron gas structure,” says Nanishi. “But what we have discovered is that reducing the buffer layer thickness reduces the leakage current.”

According to him even very thin buffer layers, which lead to increases in threading dislocation density, can produce good results because of the very high carrier concentration in the two-dimensional electron gas. Recent discussions revealed that other groups outside the NEDO program had also observed a similar relationship between the buffer layer thickness and leakage current.

Temperature profiles of the HEMTs can identify the chip's highest temperatures and lead to device improvements. “The dimensions of our structures are just a few microns, which means that Raman spectroscopy

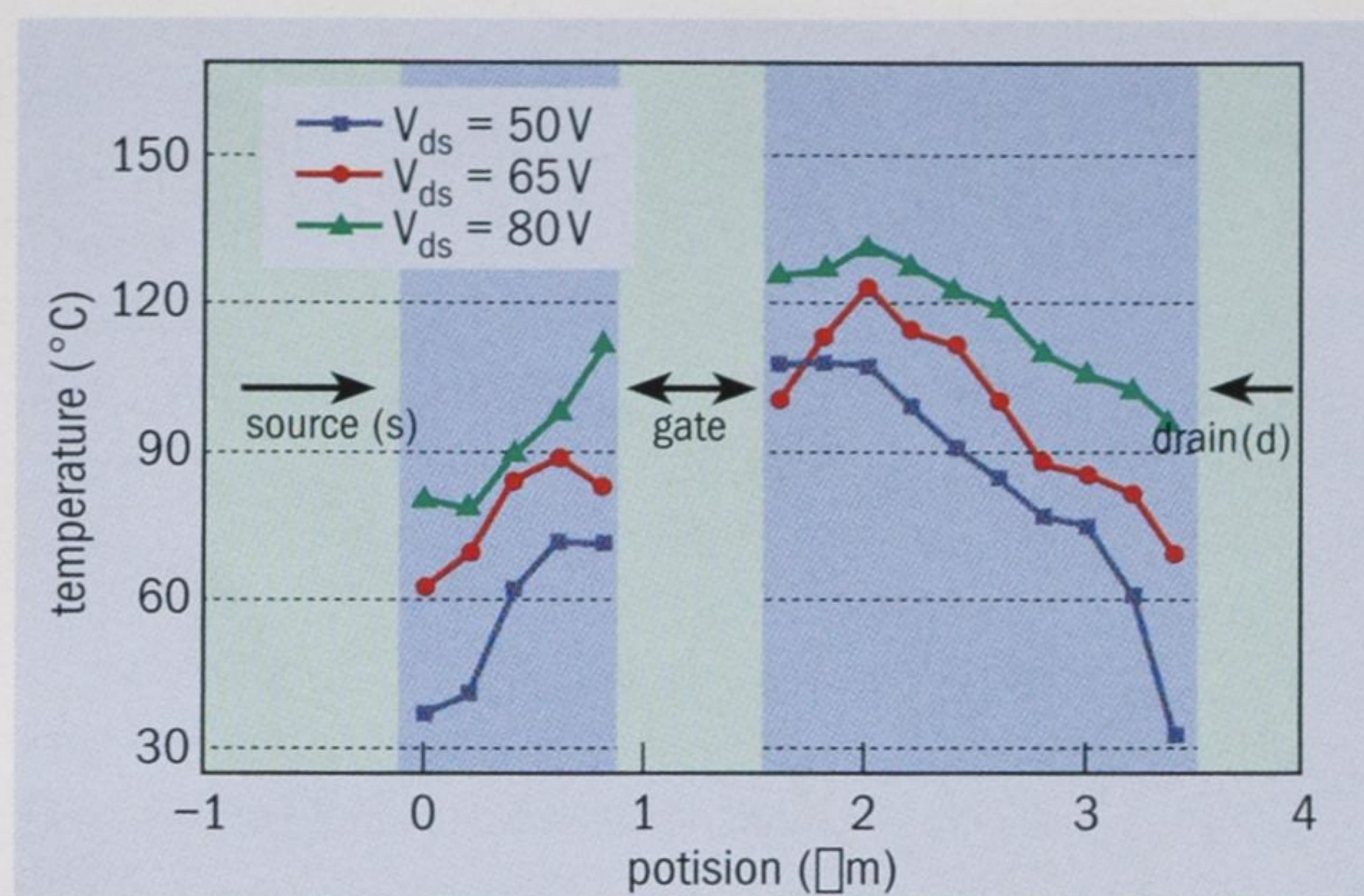


Fig. 5. Raman microscopy can reveal the shift in the location of the transistor's hottest area with operating voltage and could ultimately lead to HFET designs delivering improved thermal management.

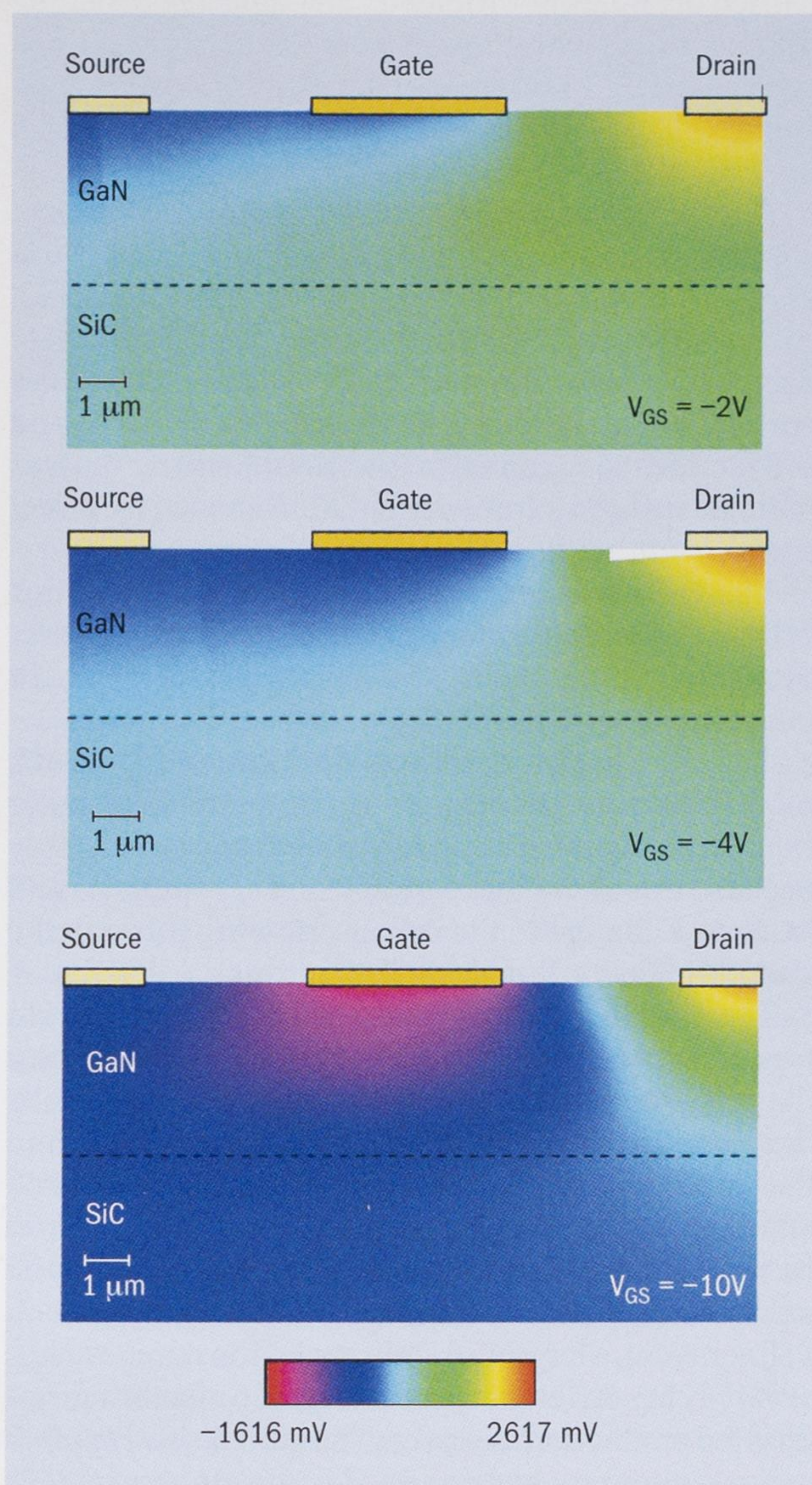


Fig. 6. Kelvin probe microscopy is able to measure the electric field distribution across a cleaved HFET and identify regions where high-voltage breakdown is most likely to take place.

is the only way to measure temperature,” explains Naishi. An unexpected shift in the position of hottest area with drain-source voltage was also observed using this method (see figure 5).

Europe's GaN development

Europe also has a GaN development program, which was launched in 2005 and is called “Key Organization for Research on Integrated Circuits in GaN Technology” (KORRIGAN). Like the US Defense Advanced Research Projects Agency, its efforts are directed at defense applications and its main objective is to develop a stand-alone European supply chain for GaN HEMT technology.

France's Thales Airborne Systems is leading the project and 28 institutions from Italy, the Netherlands, Germany, Spain, Sweden and the UK are also involved.

The collaboration is aiming to develop circuits, MMICs and ultimately module demonstrators by 2009 that include low noise amplifiers, switches and amplifiers operating in the S-band and X-band. To meet these targets the program has been split into four subprojects dedicated to materials, device and circuit processing technologies, reliability evaluation, and thermal management and packaging.

The materials project, which includes substrate technology and epitaxial growth, involves QinetiQ, a UK defense technology company that has been developing its own GaN capabilities since the late 1990s.

The firm will provide MOCVD-grown epiwafers and processed device wafers, has been involved with KORRIGAN from the start and hopes to benefit from the expertise of the collaboration. “We have the capability to be vertically integrated,” says Trevor Martin, a member of QinetiQ's GaN division, “but our strength is R&D and prototyping.”

QinetiQ's efforts will help to fulfill the wishes of Lord Drayson, the UK's procurement minister, who wants the country to establish a European supplier of GaN chips to the Ministry of Defence by the end of 2007.

QinetiQ is also working on a domestic Defence Technology Center electromagnetic remote sensing project that will cover nitride technologies and involves Filtronic, an established UK foundry.

The team has also determined the electric field distribution within its devices by scanning cross-sections of HFETs with a Kelvin probe force microscope. This approach, which is similar to atomic force microscopy, has identified the high electric field gradient between the gate and drain contacts, which probably limits the transistor's breakdown voltage (see figure 6).

In addition to all these measurement techniques, computer models are now being used to simulate device behavior and optimize gate design. This approach could ultimately drive improvements in reliability, which is not actually one of the goals of the project.

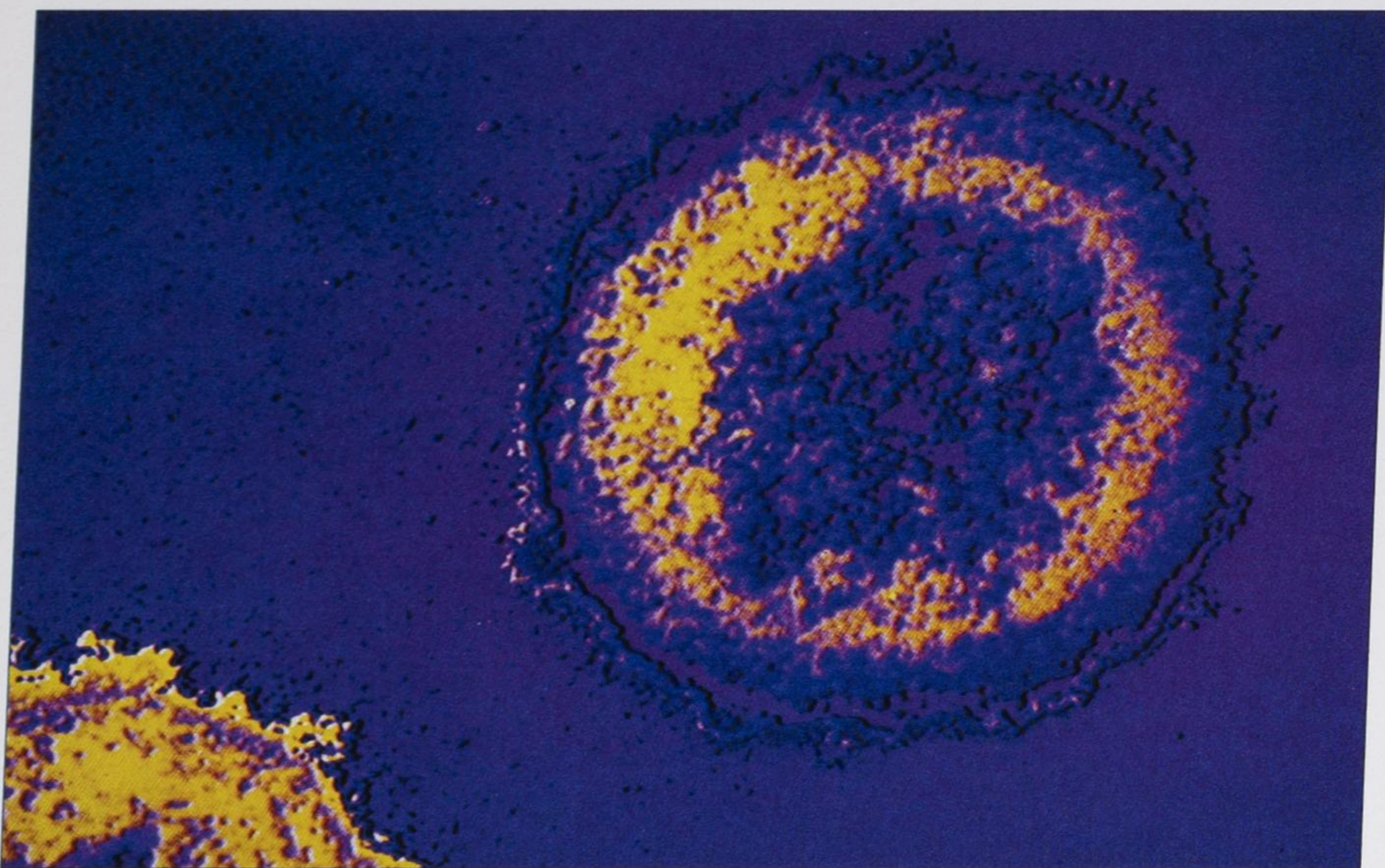
The absence of any reliability target is not an oversight, explains Nanishi, although the project is seeking technologies that are reliable and cost-effective. “The final developments for cost and reliability should be carried out in private companies, and will be the major works after this project finishes.” Shipments of reliable devices developed during the NEDO project are expected within two years, so it should not be long before we can all reap the benefits of this program. ●

“The final developments for cost and reliability should be carried out in private companies, and will be the major works after the project finishes.”

Yasusushi Nanishi
Project leader

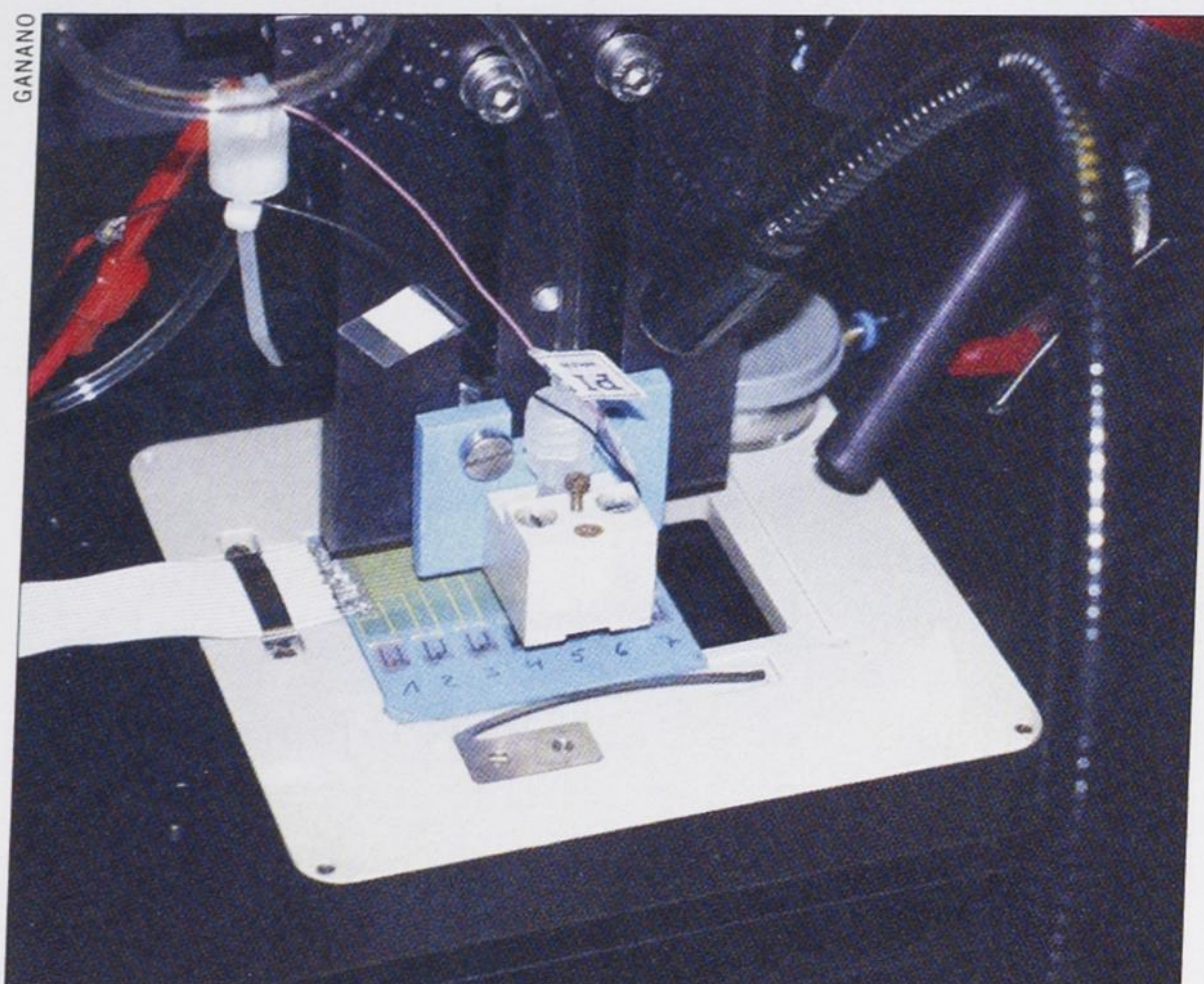
European consortium turns to GaN devices for medical sensor arrays

Oliver Ambacher and **Gabriel Kittler** from the Technical University of Ilmenau describe how a European consortium is building a medical analysis tool from GaN devices for use in hospitals and laboratories.



The Technical University of Ilmenau, Germany, is leading a European consortium that is building a GaN-based analytical tool for the detection of diseases such as cancer, AIDS and Creutzfeldt-Jakob Disease. The other partners in the three-year GaNano project, which started in 2004, are the Technical University Munich, Germany, the University of Crete, Greece, the Foundation for Research and Technology-Hellas, Greece, Madrid Polytechnic University, TopGaN, Unipress, Analytik Jena and the European Aeronautic Defense and Space Company. The project is supported by the European Union (EFRE program: B 678-03001, 6th framework program: GaNano NMP4-CT2003-505614).

“Our work with cations, anions and enzymes illustrates the potential of GaN-based sensors.”



At the heart of the GaNano instrument is an arrangement of seven labeled sensors on a translation stage that are able to analyze droplets with a volume of 50 pl to 1 nl.

Hospitals and medical laboratories have to analyze thousands of tiny samples every day. This is ideally carried out quickly, efficiently and with a high degree of sensitivity, enabling early detection of conditions such as AIDS, Creutzfeldt-Jakob Disease and cancer. Rapid diagnosis can save lives, improve a patient's quality of life and reduce medical treatment costs.

At the Technical University of Ilmenau, Germany, we are coordinating a three-year €3.7 million (\$4.6 million) project, involving eight other European partners to construct the first instrument based on GaN devices to address this need. GaN and its related alloys are well suited to this task because unlike the GaAs and InP families they can form the basic chemical sensors without suffering from degradation caused by direct contact with acidic and alkaline solutions.

The GaN sensors, which are the key part of our “GaNano” instrument, analyze the chemical properties of nanolitre and picolitre samples that are brought into contact with the device's surface. The devices – essentially transistors with an eliminated top gate or a modified active gate region – can detect dipoles, polar liquids, changes in ion concentration and cell activity because this alters the device's surface potential and leads to a change in the current flowing through the underlying two-dimensional electron gas (2DEG).

The sensors can be tailored to respond to a certain type of substance by applying specific membranes to the gate area that are made from either biological cells or artificial materials. For example, researchers from the University of Crete and the Foundation of Research and Technology Hellas have modified our detectors to be sensitive to potassium by covering the gate area with a polyvinyl chloride membrane, which is doped with valinomycin, a large molecule made from amino acids.

Applying different types of organic membrane has enabled production of sensors that are selective to other cations like ammonium and sodium, and also to anions like nitrate and chloride. In each case the sensor's signal results from the potential difference at the interface between the membrane and the aqueous solution. This is created by the reaction between the ion carrier and the analyte ion. At the Technical University of Munich experiments have also shown that immobilized enzymes like penicillinase can be applied to the sensor's surface, altering the device's selectivity and sensitivity.

Features of the chemical sensor

Our chemical sensor features an AlGaIn/GaN heterostructure, an 8–25 nm-thick AlGaIn barrier and a thin GaN capping layer that provides a chemically stable surface. Strong polarization along the c-axis that results from the wurzite crystal structure produces spontaneous polarization within the layers.

Acting in combination with the piezoelectric polarization of the AlGaIn barrier, this leads to a fixed polarization charge at the GaN/AlGaIn interface. This charge is screened by a 2DEG confined at the interface that has a typical sheet carrier concentration of $1 \times 10^{13} \text{ cm}^{-2}$.

Any change in surface potential caused by dipoles, polar liquids, different ion concentration or cell activity potentials leads to a change in carrier concentration of the 2DEG and current flows through this region of the device.

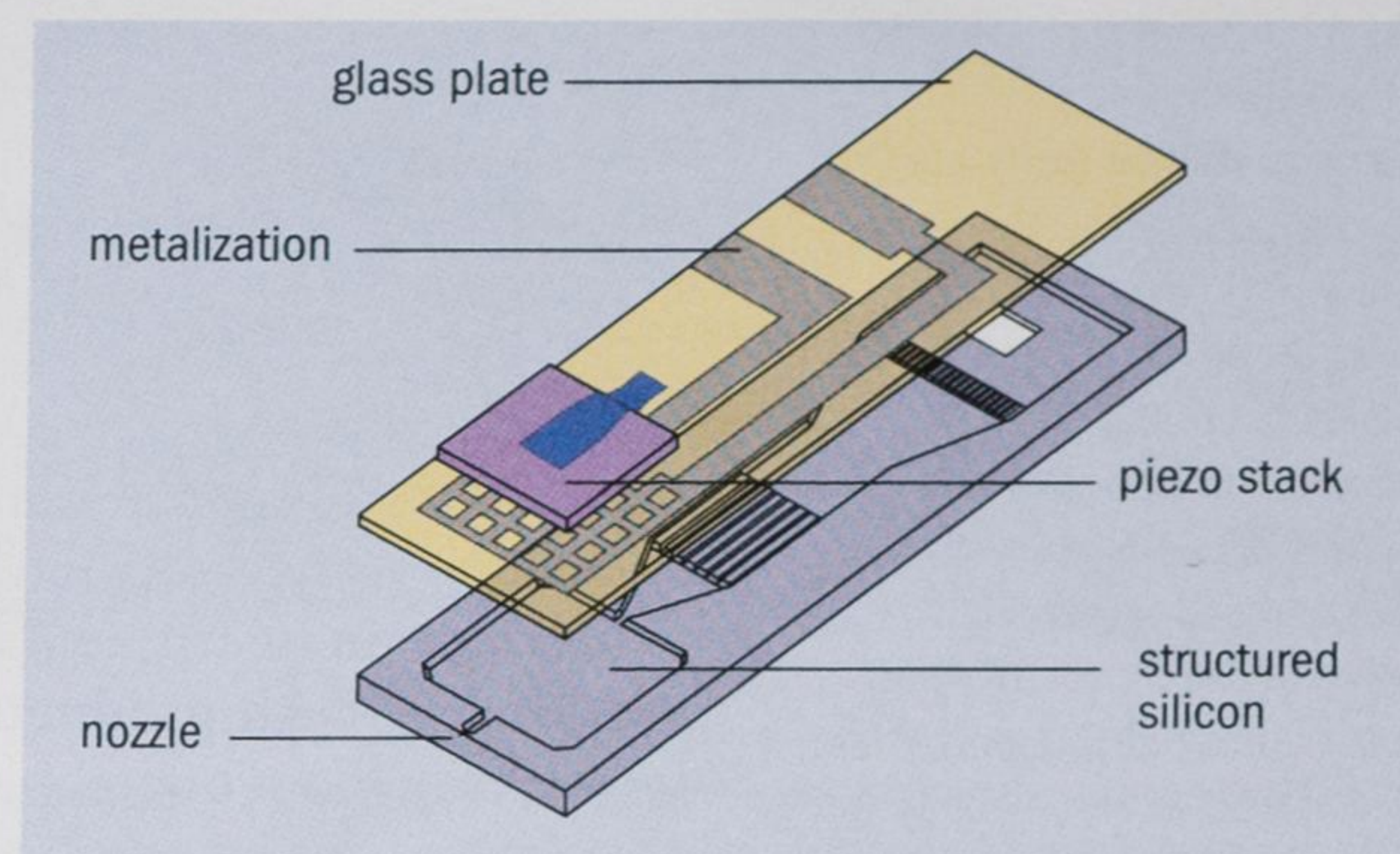
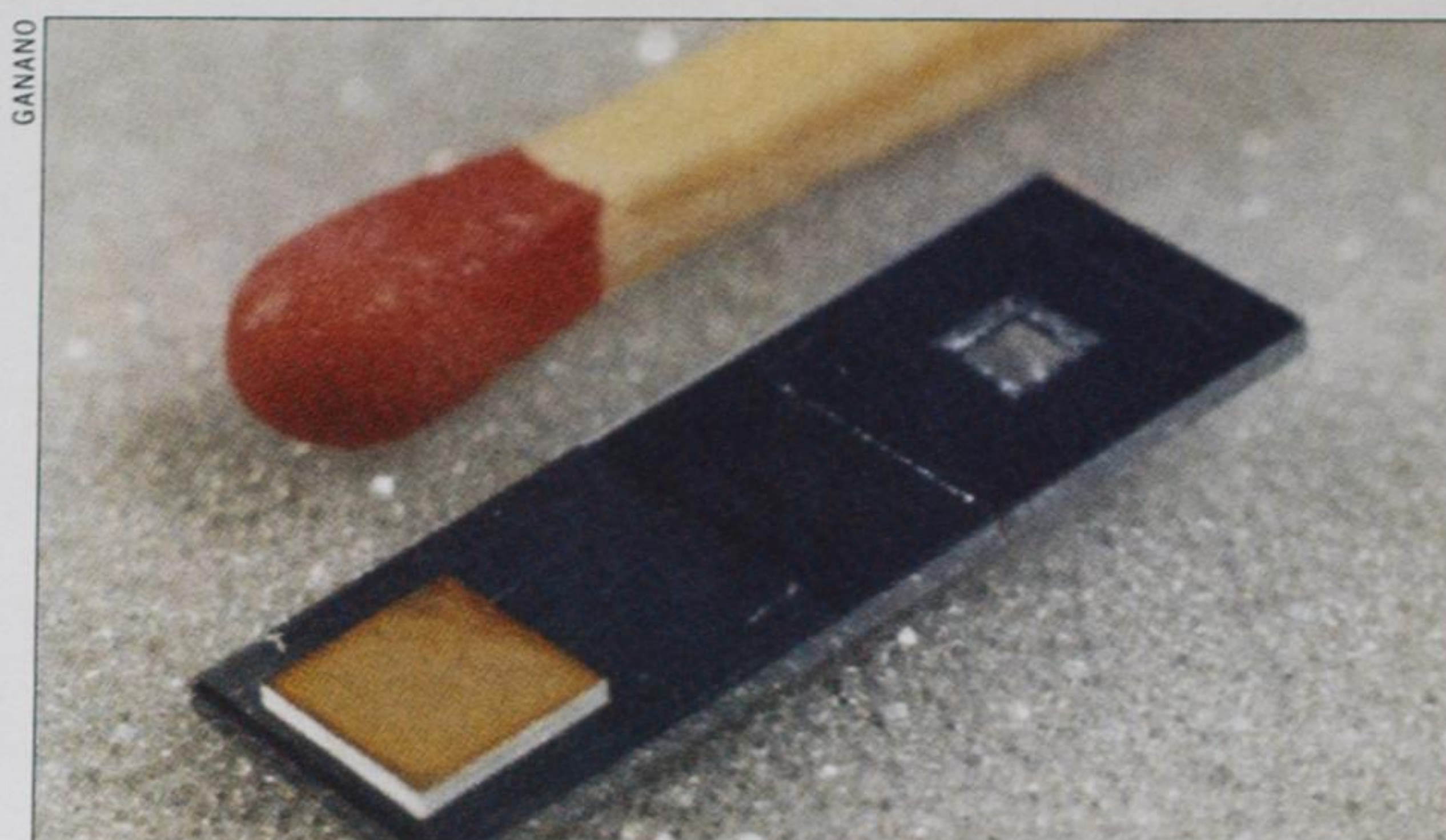
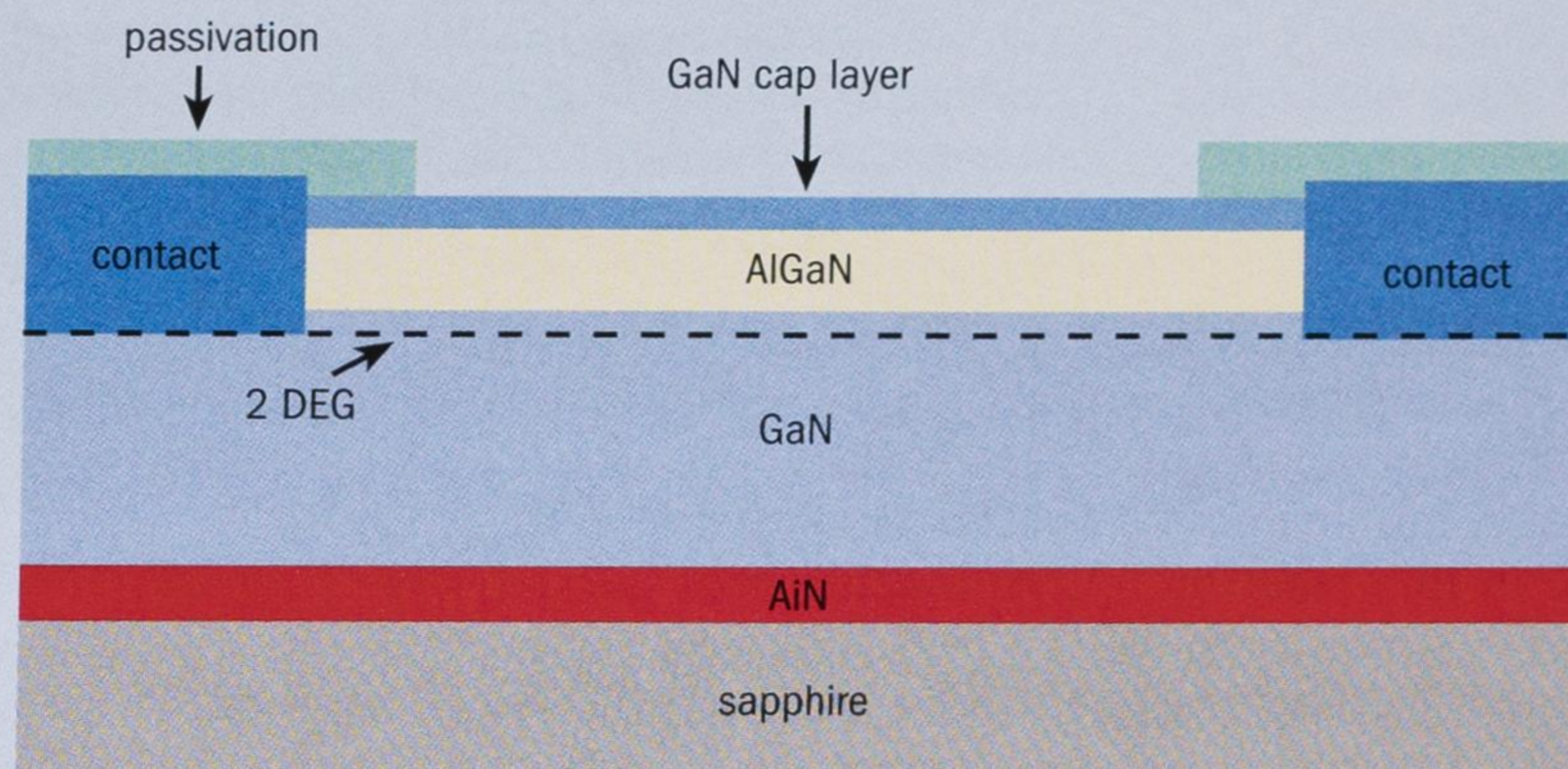


Fig. 1. Droplets are applied to the sensor with a silicon device that uses microchannels and pumps driven by piezoelectric actuators.

Our work with cations, anions and enzymes illustrates the potential of GaN-based sensors. Sensing with these devices can be extended to different biological systems by adapting the surface and the sensor, enabling a series of different detectors to be made that can form the basis for a multifunctional sensor array.

Manipulating the droplets

We apply our samples to the sensor's surface with a dispenser that resembles an inkjet printer head (see figure 1). Forcing a solution through a membrane and orifice creates a liquid jet that can be controlled to deliver samples at rates of up to 300 drops/s onto a moving sensor array. One or more droplets are applied to each sensor and by adjusting this system droplets can be delivered at 1–3 m/s and volumes of between 50 pl and 1 nl.

Our project also benefits from GaN's optical transparency at shorter wavelengths, where silicon, GaAs and InP are highly absorbing. This transparency enables biological samples to be identified by their fluorescence spectra, which often contain prominent features at ultraviolet wavelengths.

Members of the research team at Madrid Polytechnique University, TopGaN and Unipress have developed various GaN-based devices for this type of measurement, such as lasers and photodetectors. For determining the concentration of lipase – a key enzyme in the human body that is required for the absorption and digestion of nutrients in the intestines – we have built laser diodes emitting at 412 and 419 nm, and photodetectors with an InGaIn-based filter that restricts detection to the 400–415 nm band, while negating the need for an external dielectric filter. These devices

could be used to see if a patient is suffering from an inflamed pancreas by testing for a high concentration of pancreatic lipase.

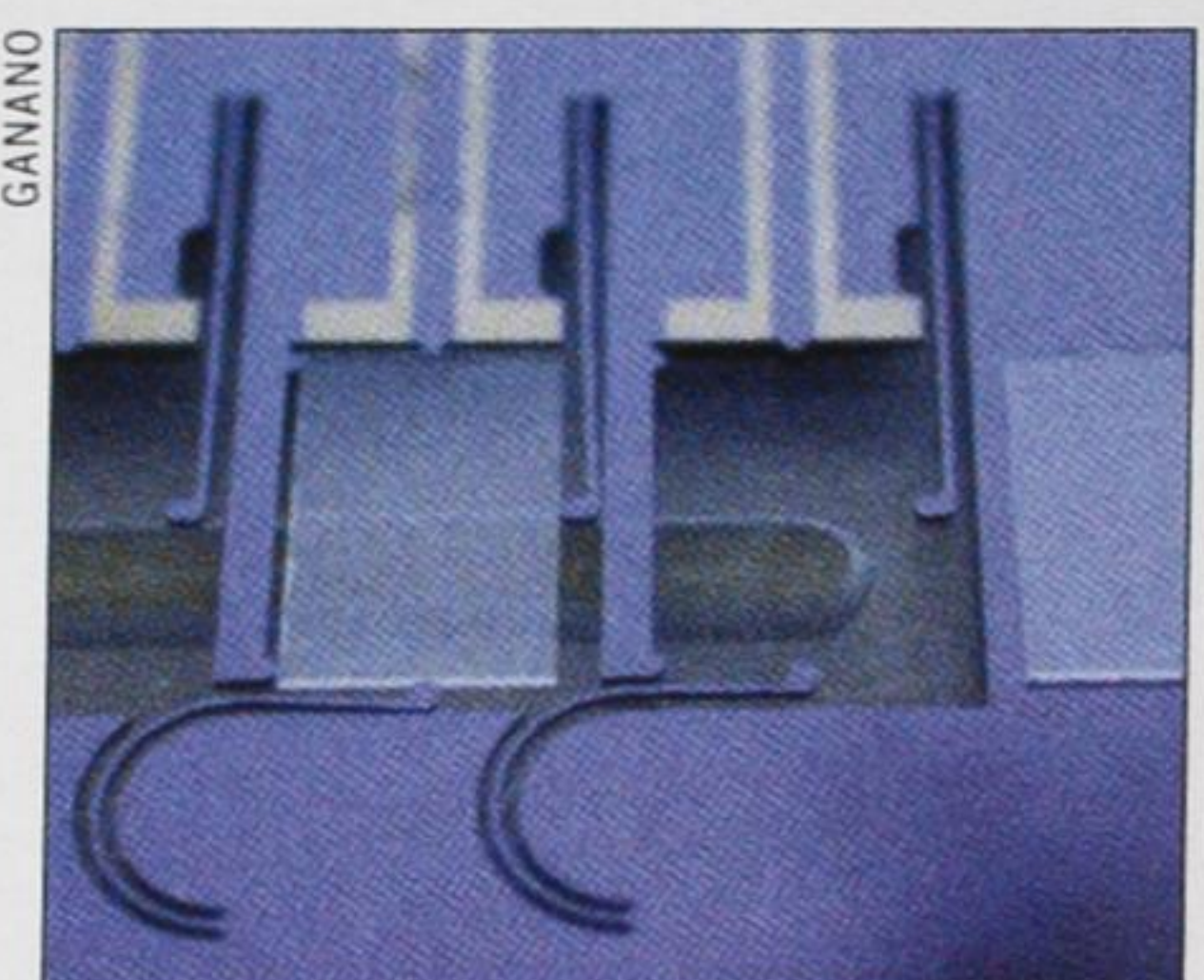
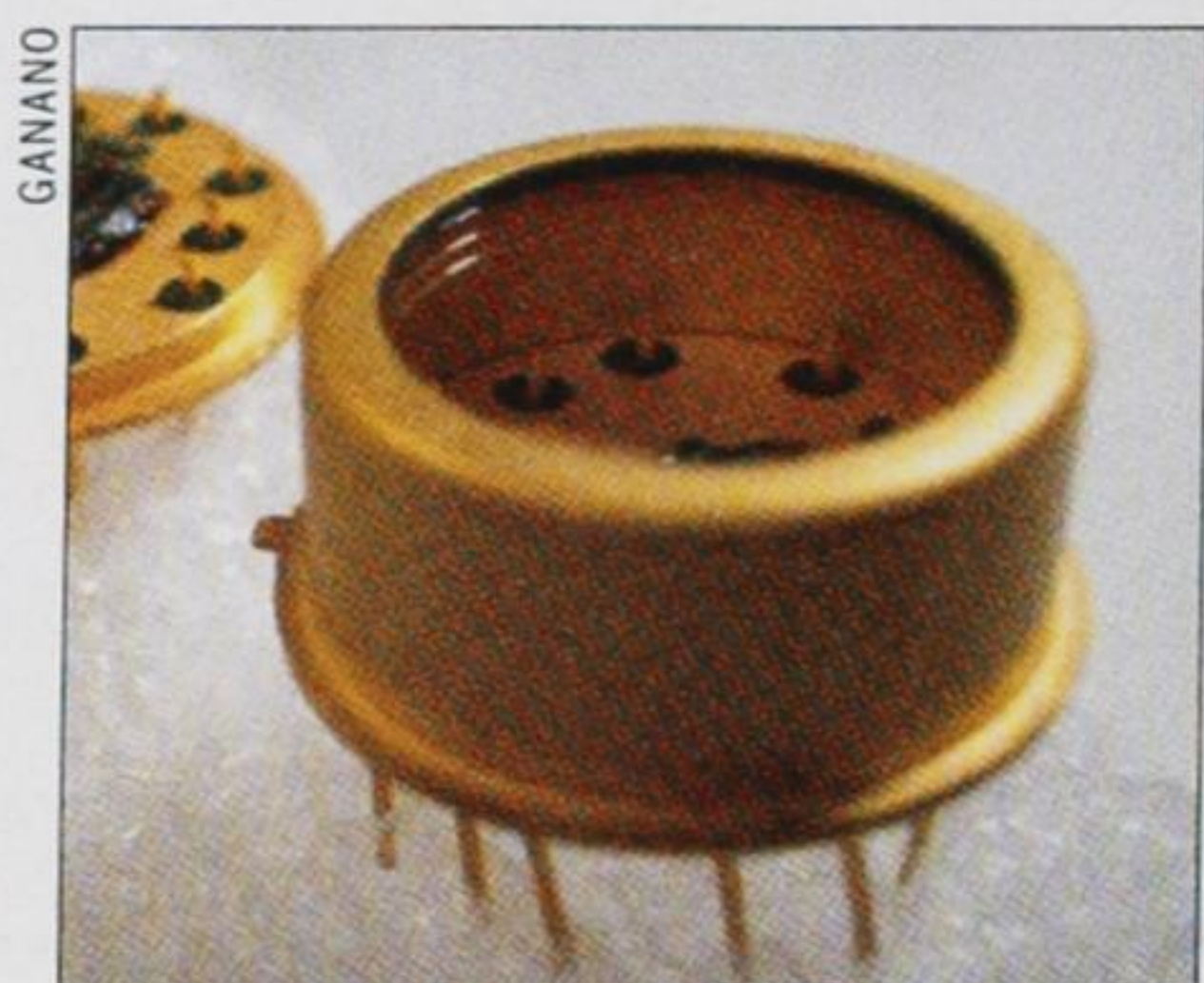
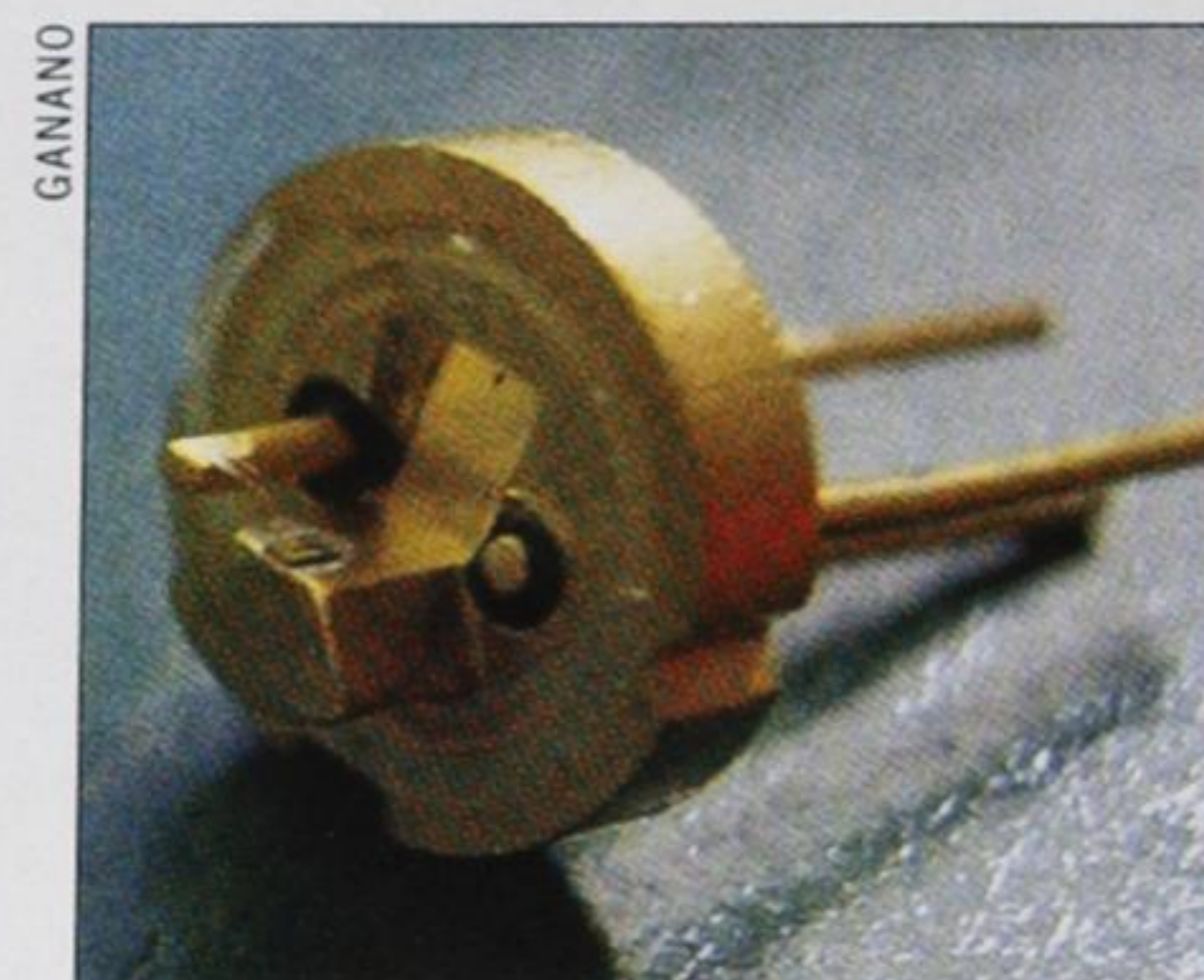
All of our GaN devices have been installed in a temperature-and-humidity-controlled glove-box that reduces the evaporation rate of our various samples. The fast evaporation rate is a consequence of our “open” design, which has the advantage of fast mixing between solutions. The more common “closed” systems that route liquids through micron-sized channels do not suffer from fast evaporation rates, but mixing between solutions is slow.

Initial measurements

The first continuous optical and electrical and measurements with the GaNano system were conducted on lipase at the Technical University of Ilmenau. This enzyme provides the catalyst for the decomposition of organic molecules (either 4-nitrophenylcaprylate or 4-nitrophenylacetate) into an acid and a dye (4-nitrophenol). Our electrical measurements, which employed AlGaIn/GaN sensors that did not require any modification to provide a selective response, monitored the change in pH of the products of this reaction.

After adding lipase the system's pH initially increases from 7.2 and then decreases, as expected, to 6.4 (see figure 2). The metabolic rate of the enzyme can be calculated from the pH value and a titration of the resulting acid. The optical measurements determined the concentration of the other product of the reaction, the dye, by measuring the transmission characteristics of the solution (see figure 3).

Our electrical and optical measurements enabled us to track the behaviour of both of the products of this reac-



The GaNano system features GaN-based lasers (top), detectors (middle) and pH sensors (bottom).



About the authors

Gabriel Kittler (left) is a PhD student at the Technical University of Ilmenau and is focusing his studies on the development of GaN-based pH sensors. E-mail gabriel.kittler@tu-ilmenau.de.

Oliver Ambacher (right) is the head of the Center of Micro- and Nanotechnologies at the Technical University of Ilmenau and the project coordinator of the three-year GaNano project. E-mail oliver.ambacher@tu-ilmenau.de.

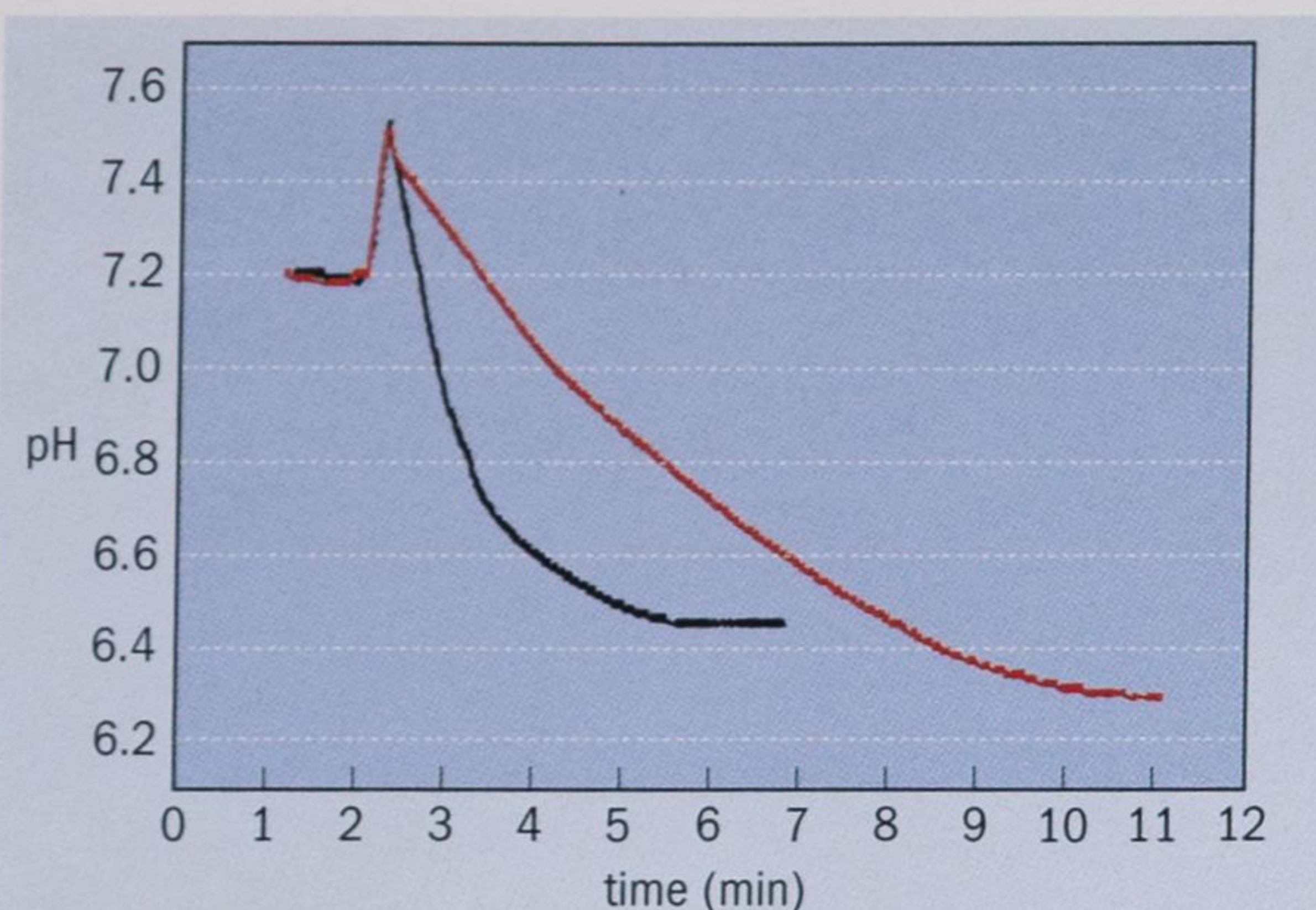


Fig. 2. The sensor monitors the jump in pH when the lipase is added, followed by the increase in acidity as 4-nitrophenylcaprilate decomposes into capryl acid and 4-nitrophenol (red line). Doubling the lipase concentration speeds the reaction (black line).

tion and observe the influence of lipase. With Analytik Jena and the European Aeronautic Defense and Space Company, our next step is to integrate these components to produce an instrument capable of simultaneously monitoring both products created in this reaction. Integrating these components demands a high degree of precision because droplets with volumes of just 50 pl have typical diameters of 60 μm . We are now tackling this challenge and when this is complete we will begin to make measurements on other biological materials.

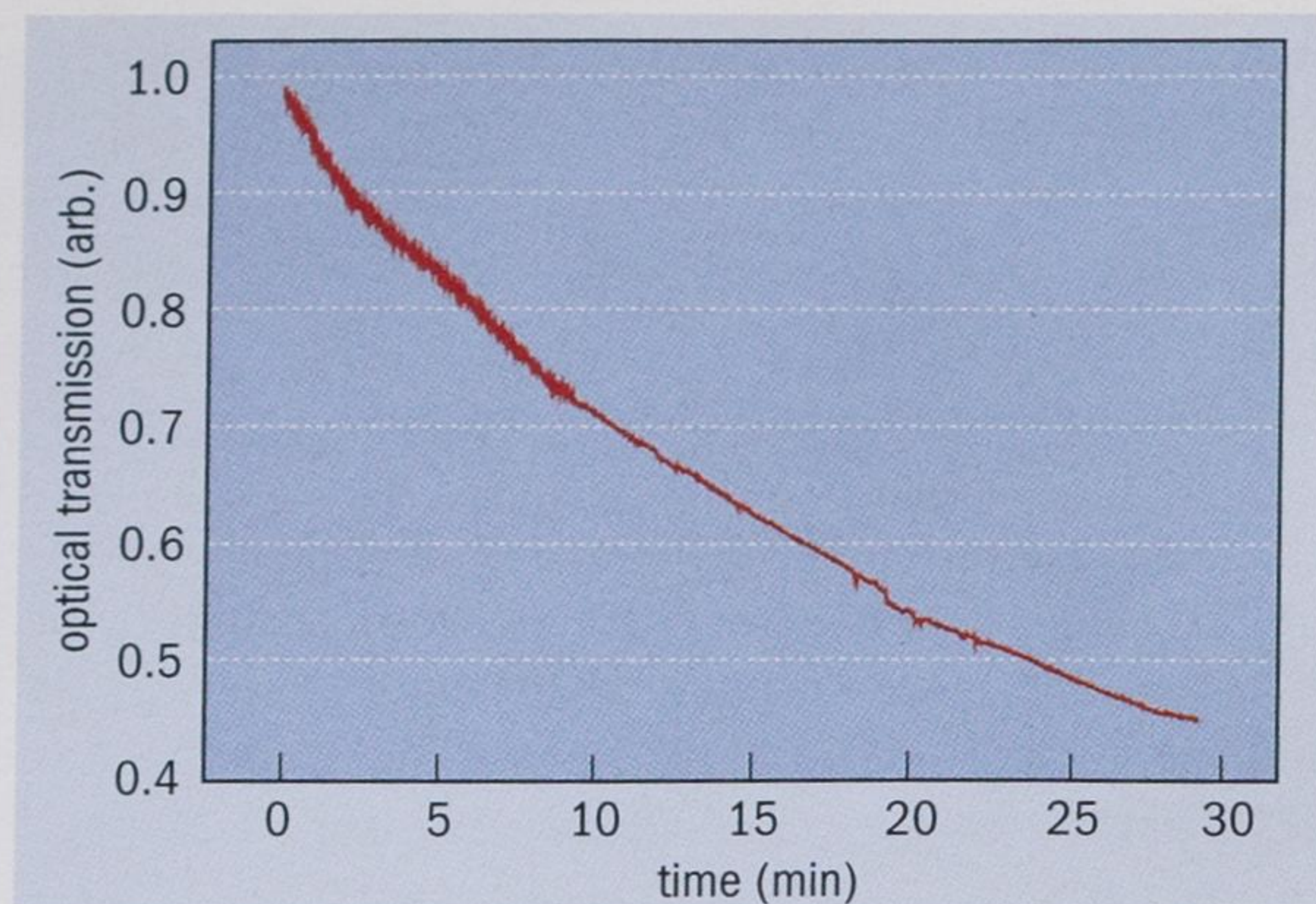


Fig. 3. GaNano's transparent sensor is compatible with absorption experiments that employ GaN lasers and detectors. The absorption data reveals the concentration of the dye 4-nitrophenol, which is a product of the decomposition of 4-nitrophenylcaprilate.

This will ultimately lead to the construction of a GaN tool for rapid identification of various diseases. ●

Further reading

O Ambacher *et al.* 2002 *J. Phys. Condensed Matter* **14** 3399.

Y Alifragis *et al.* 2006 EMRS Spring Meeting, Symposium Q, Nice, France, May 29–June 2.

B Baur *et al.* 2006 *Appl. Phys. Lett* (in press).
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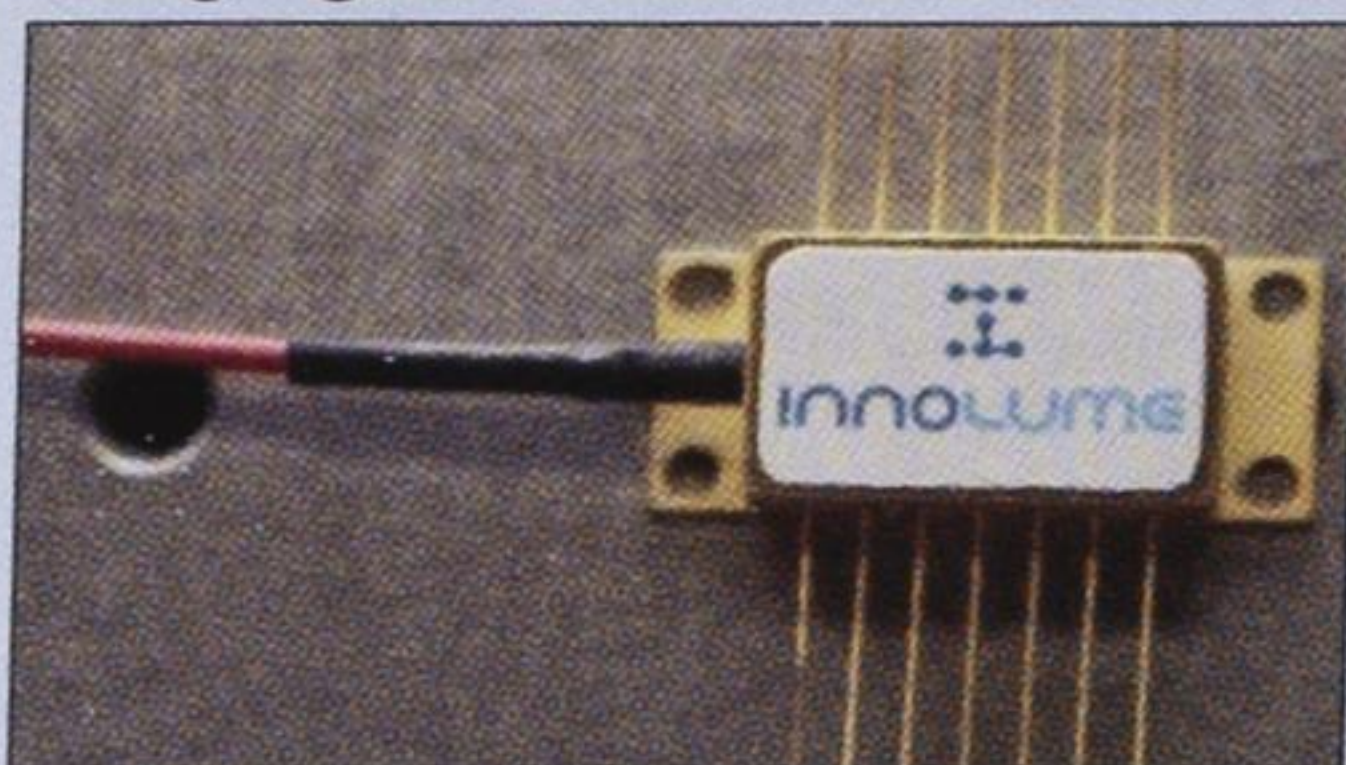
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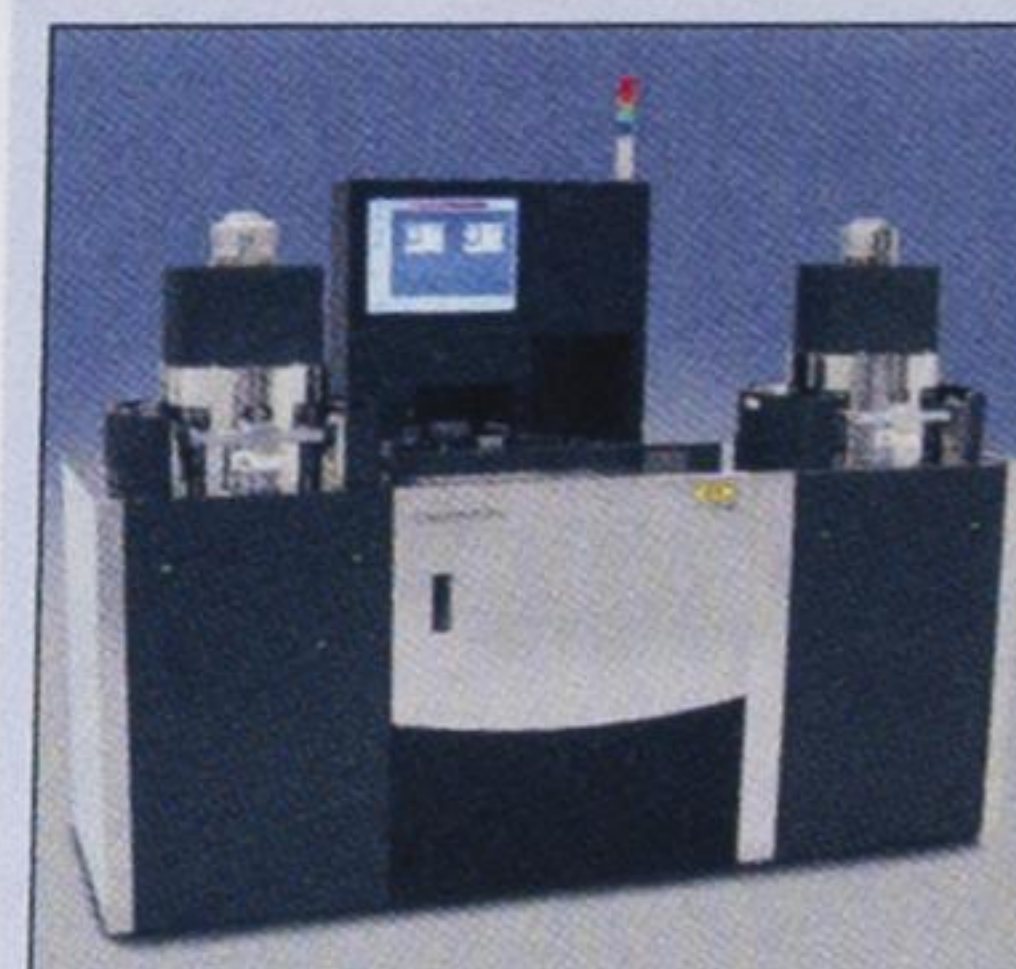
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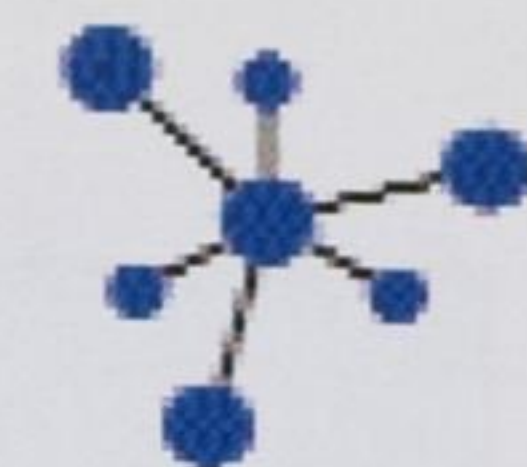
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SURFACE TECHNOLOGY SYSTEMS





CHIP DESIGN

Nichia's white LED chips hit 138 lm/W

Japanese LED manufacturer Nichia has produced a small white-emitting chip with an efficacy of 138 lm/W at 20 mA and a larger device that delivers 92 lm/W at 350 mA.

Nichia's small LED chip, which measures $240 \times 420 \mu\text{m}$, has a color temperature of 5450 K, a wall plug efficiency of 41.7% and a forward voltage of 3.11 V at 20 mA.

The $1 \times 1 \text{ mm}$ chip has a lower color temperature and efficacy, but can deliver 106 lm at 350 mA and 402 lm at 2 A, which is equivalent to the total flux from a 30 W incandescent lamp.

Both of the devices were made by MOCVD on c-face sapphire substrates and produce white light by exciting a yellow YAG phosphor with

450 nm emission from an InGaN/GaN LED.

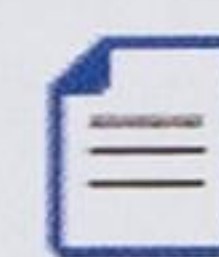
The high efficacy of the chips is thought to result from improvements in external quantum efficiency. The LEDs do not employ a conventional translucent Ni/Al p-contact, which has a transmittance of only 40%, but instead use an indium tin oxide electrode with a transmittance of 95%. Extraction is also boosted by growth on a sapphire substrate patterned with convex hexagons, which scatter more of the light emitted from the active layer.

Nichia's results compare favorably with those of Cree, which reported a white LED chip that delivers 131 lm/W at 20 mA earlier this year. This efficacy was claimed to be the

highest ever reported value at the time.

The Japanese team obtained their results by using pulsed operation (200 Hz repetition rate and a duty cycle of 1%). Cree did not provide details of its mode of operation.

Nichia believes that further improvements can be made to the chip. At low currents the smaller LED delivered 174 lm/W, which suggests that gains in luminous efficiency at higher currents can be made by increasing the crystal quality and optimizing the active region.



Journal reference

Y Nurukawa et al. 2006. *Jap. Appl. Phys.* **45** L1084.

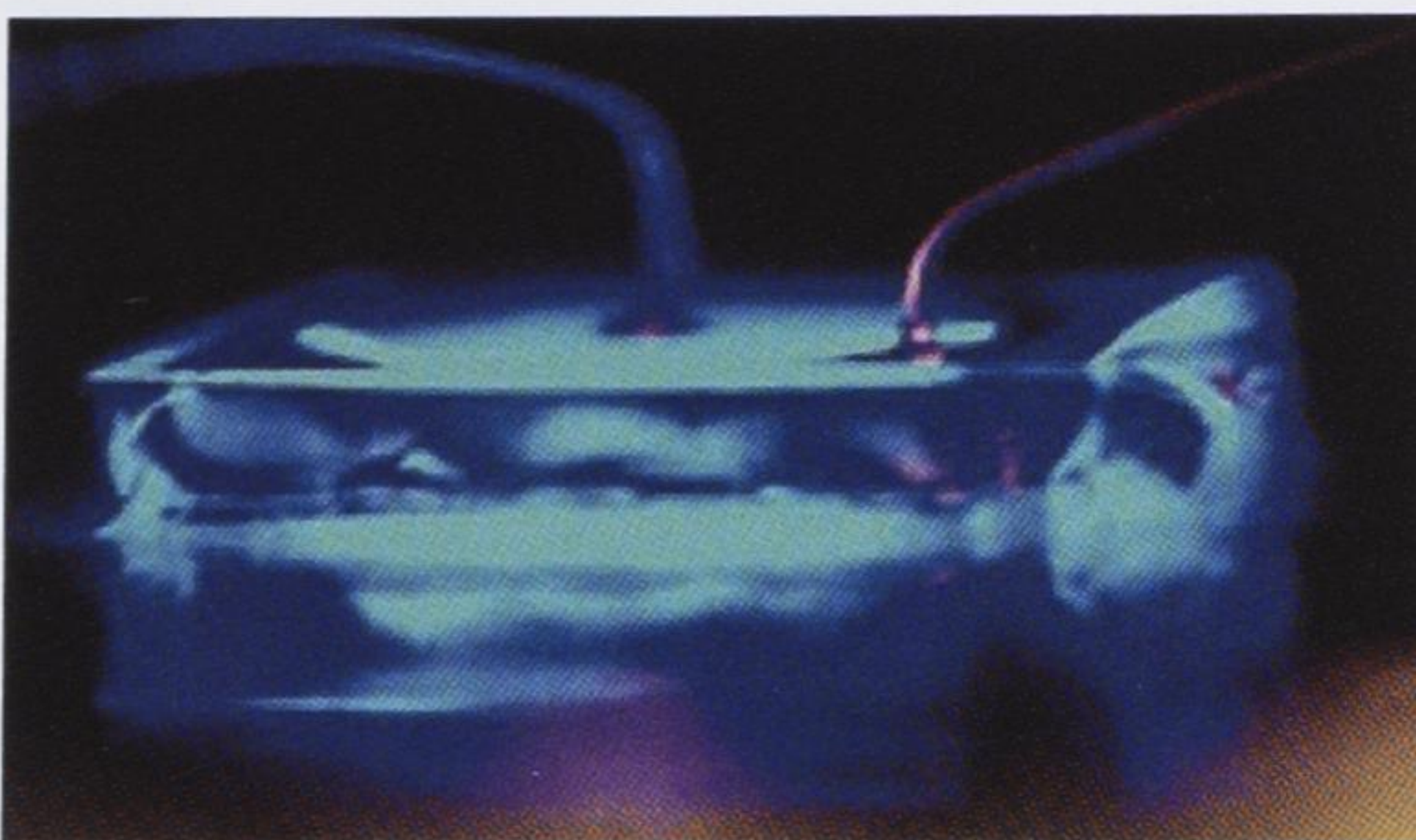
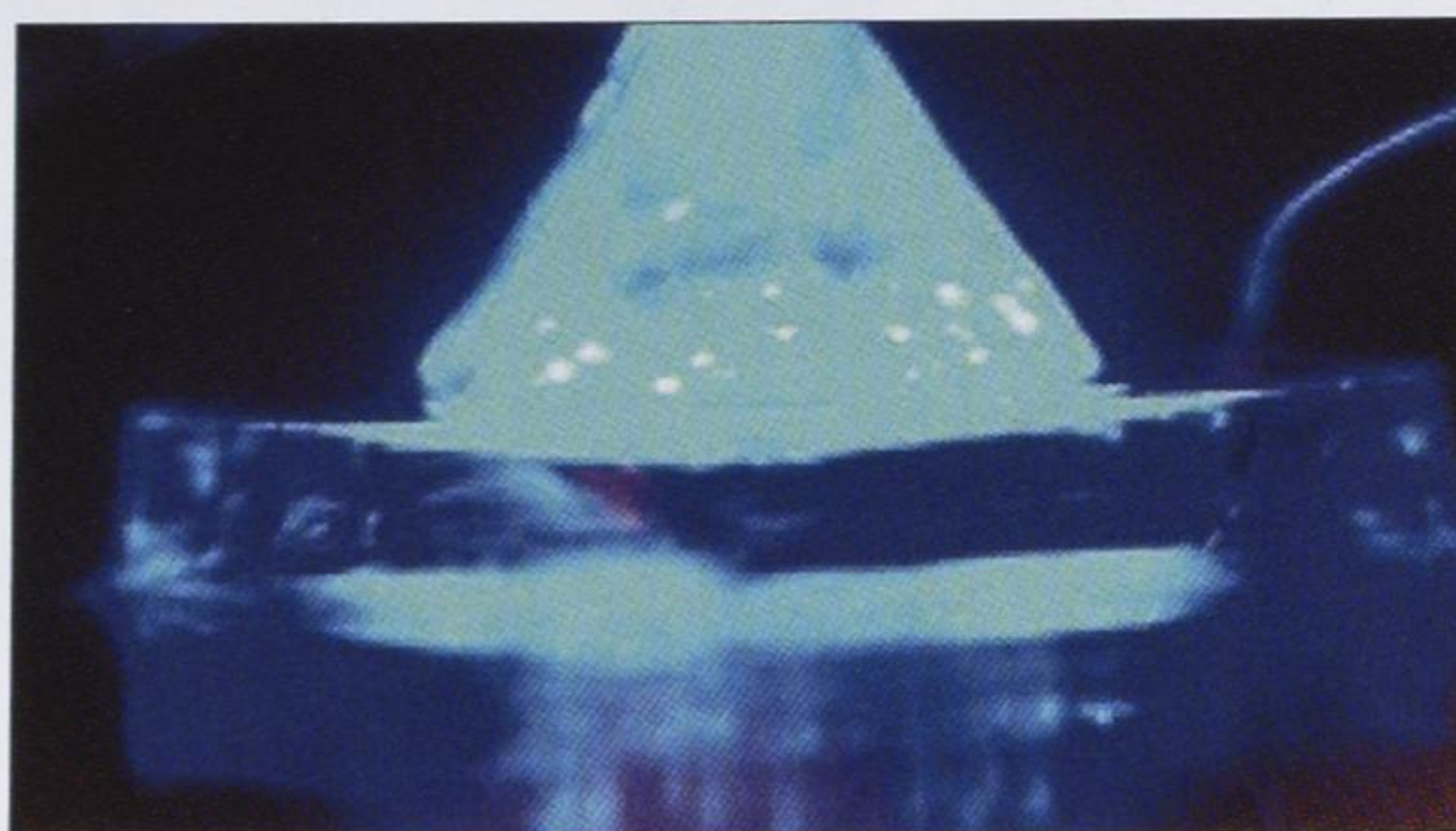
BLUE LEDs

Electrode with pyramid shape boosts emission

Blue-emitting GaN LEDs with a truncated pyramid-shaped p-type electrode can extract more than twice the light of conventional flat LEDs, claim researchers from the University of California, Santa Barbara.

The pyramid, which is made from a 500 μm -thick highly transparent ZnO substrate, cuts back on internal reflection and absorption at the p-type electrode, thereby boosting the extraction efficiency from the chips.

The team made their devices from a commercial hydrothermally grown ZnO substrate and a III-nitride LED wafer grown by MOCVD. They joined the GaN surface of the LED to the ZnO wafer by applying a 2 MPa pressure in a graphite fixture and then bonded them in a 600 °C nitrogen-filled furnace. Selective etching of the oxygen face of the ZnO wafer pro-



The pyramid-shaped LED (top) made by the University of California, Santa Barbara produces more than twice the light of conventional flat LEDs (bottom).

duced the hexagonally shaped pyramid.

The hybrid LED was compared with a conventional device that was made from the same wafer and featured a Ni/Au p-type electrode. Both 460 nm emitters had the same 0.46 mm^2 junction area. At a 5 mA forward current, the output power from the pyramid LED improved by 230%. At 20 mA, the improvement was 120%.

Measurements of the pyramid chip's efficiency showed that the device had a sweet spot with an external quantum efficiency of more than 20% at 0.5–10 mA. At a drive current of 50 mA the efficiency was around 12%.

The researchers believe that this decline in efficiency with increasing current could be caused by imperfections at the ZnO/GaN interface that lead to heat generation and an inhomogeneous current density. Nevertheless, the team thinks that the problem could be cured by improving wafer-bonding techniques.



Journal reference

Akihiko Murai et al. 2006. *App. Phys. Lett.* **89** 171116.

Research in brief...

...Trapped surface charges degrade HFETs

Surface charge trapping is responsible for the current collapse mechanism that limits the performance of GaN HFETs, claim Mohammed Sabuktagin and Pramod Karulkar from the University of Alaska Fairbanks, and Hadis Morkoç from Virginia Commonwealth University.

The origin of current collapse, a degradation of the drain current, was revealed by Kelvin probe measurements. The approach monitored the evolution of band-bending when different voltages were applied to and then removed from the HFET.

This technique also enabled the source of the trapped charge to be identified as tunneling of

charge from the gate electrode.

The team told *Compound Semiconductor* that they will now conduct simulations to establish the exact role of the trapped surface charge on the decrease in drain current.

...Dual-beam VCSEL eyes interferometry

Researchers from the Tyndall National Institute in Ireland have produced 850 nm dual-beam VCSELs with integrated linear gratings that can be used to efficiently split the output light into two coherent pulses.

These dual-beam VCSELs, which can diffract more than 90% of the light emission into first-

order beams at $\pm 20^\circ$, may be used as compact light sources for interferometry and avoid the need for the beam splitters used in existing set-ups.

The team made the diffraction gratings, which consisted of $1 \mu\text{m}$ lines separated by spaces of $1 \mu\text{m}$, using photolithography on the output facets of oxide-confined VCSELs. In light-current measurements, the diffraction efficiency into first-order emission was consistently more than 80% for singlemode and multimode devices, peaking at 30 mA with more than 90% conversion.



Journal reference

J P Justice et al. 2006 *Electron. Lett.* **42** 1226.

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