

# COMPOUND SEMICONDUCTOR

June 2006 Volume 12 Number 5

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY



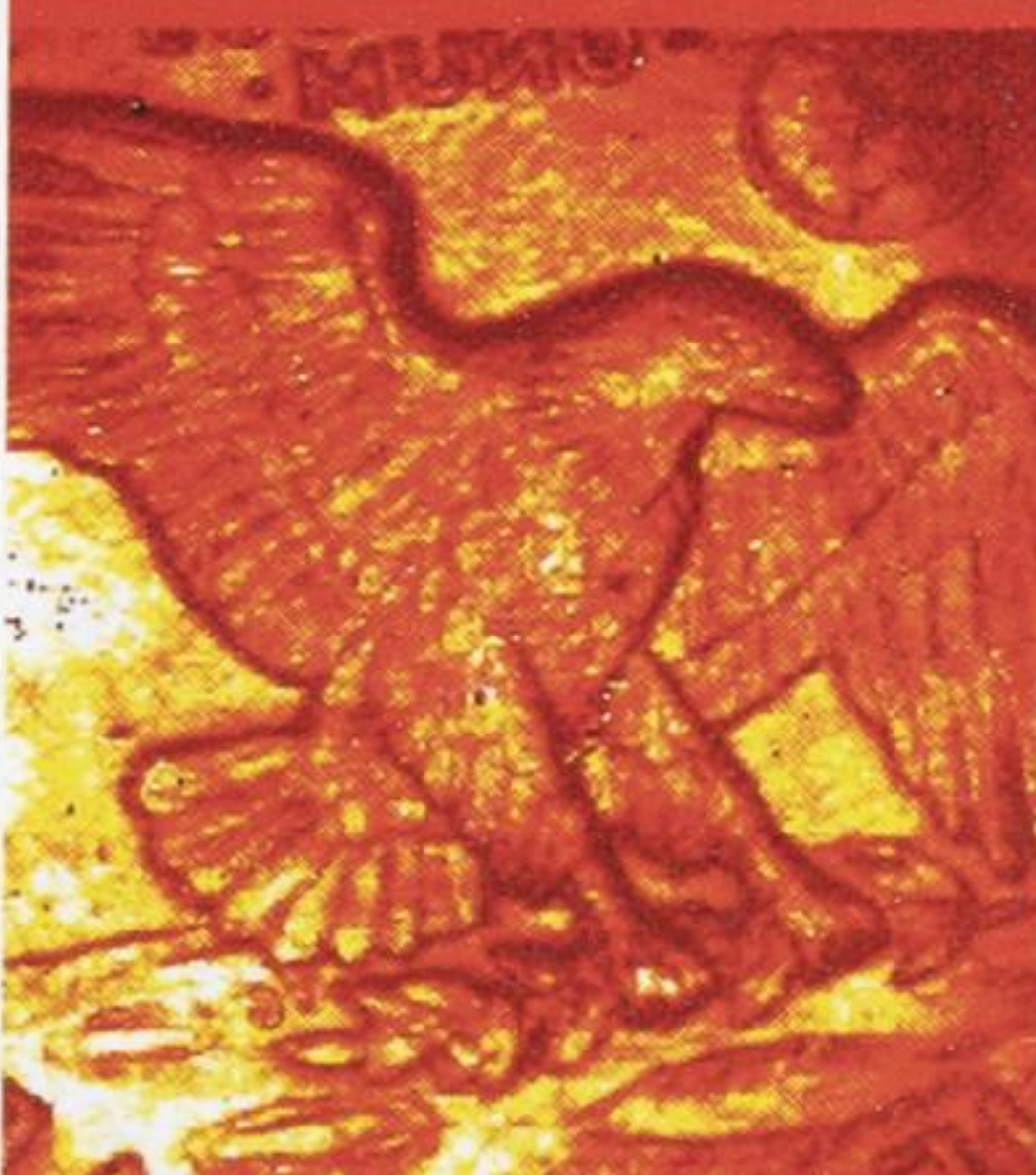
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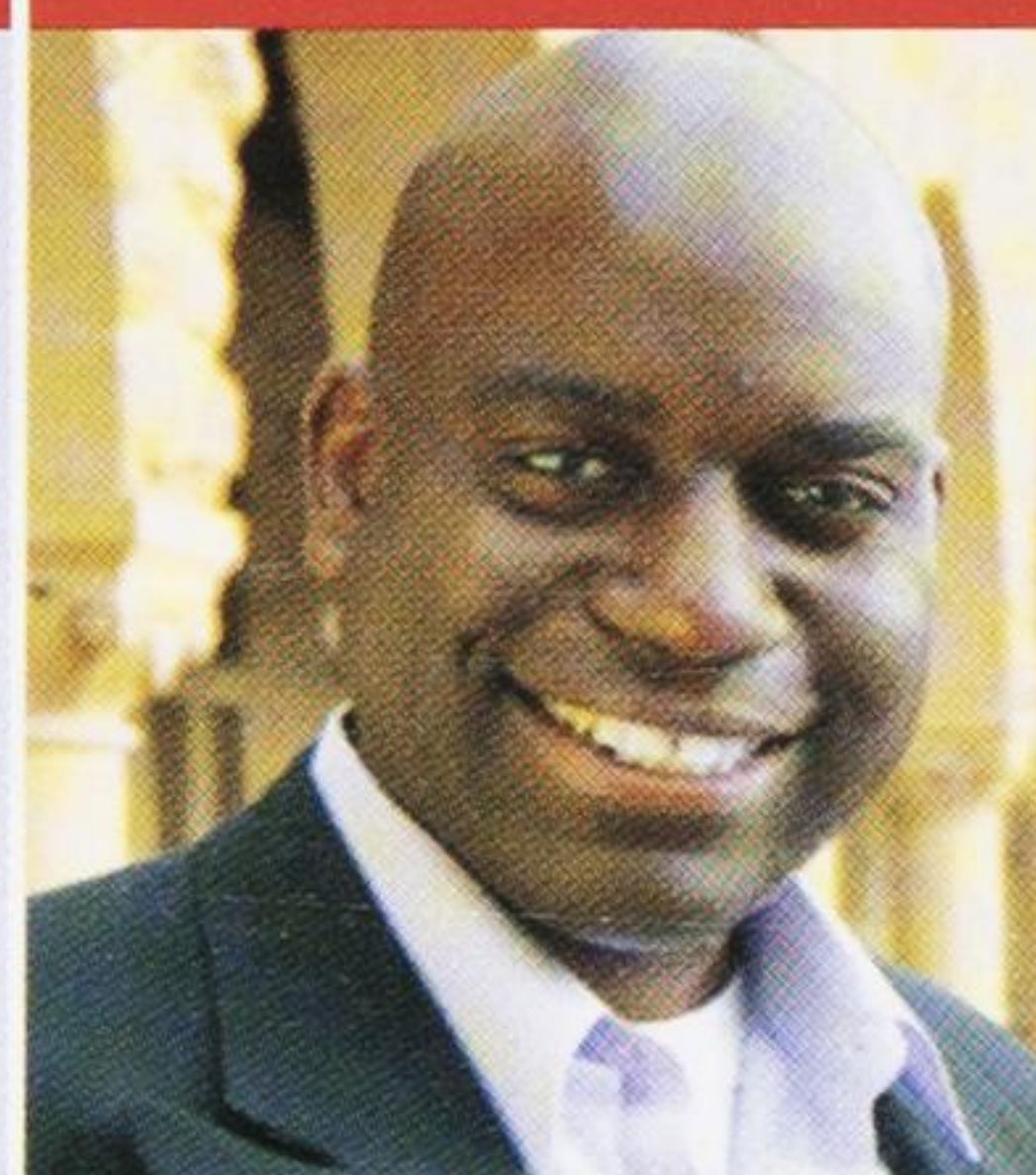
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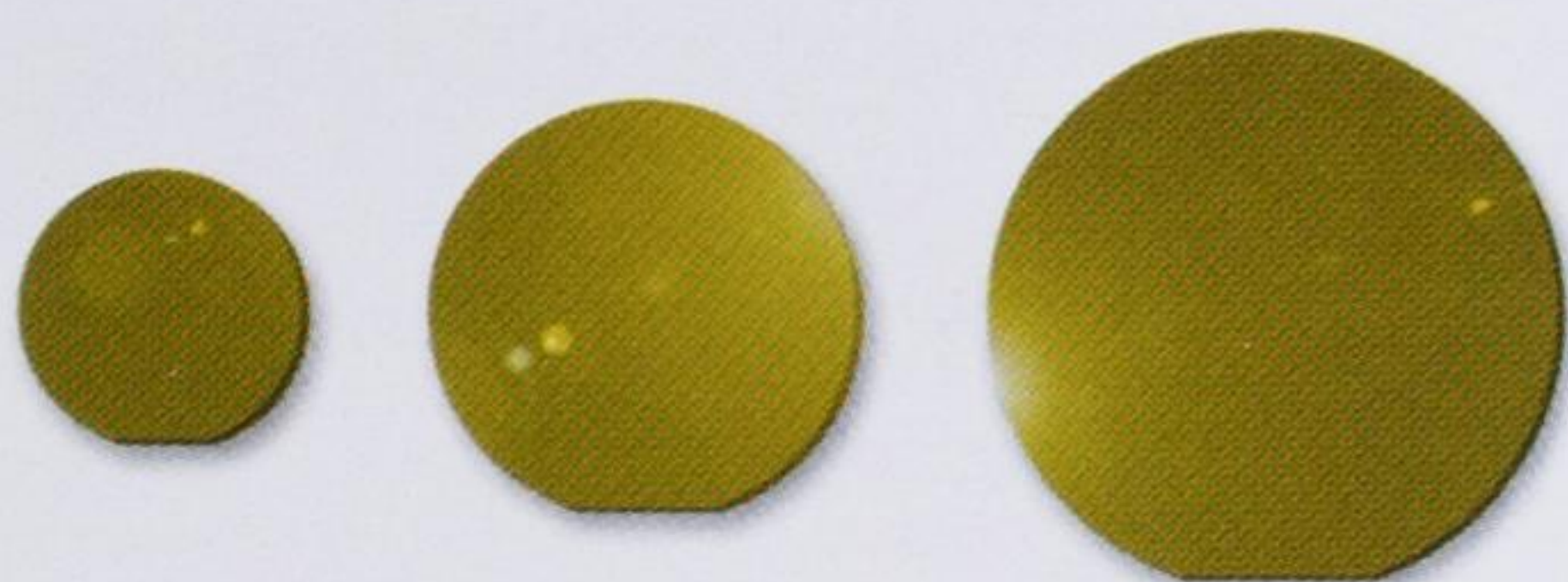
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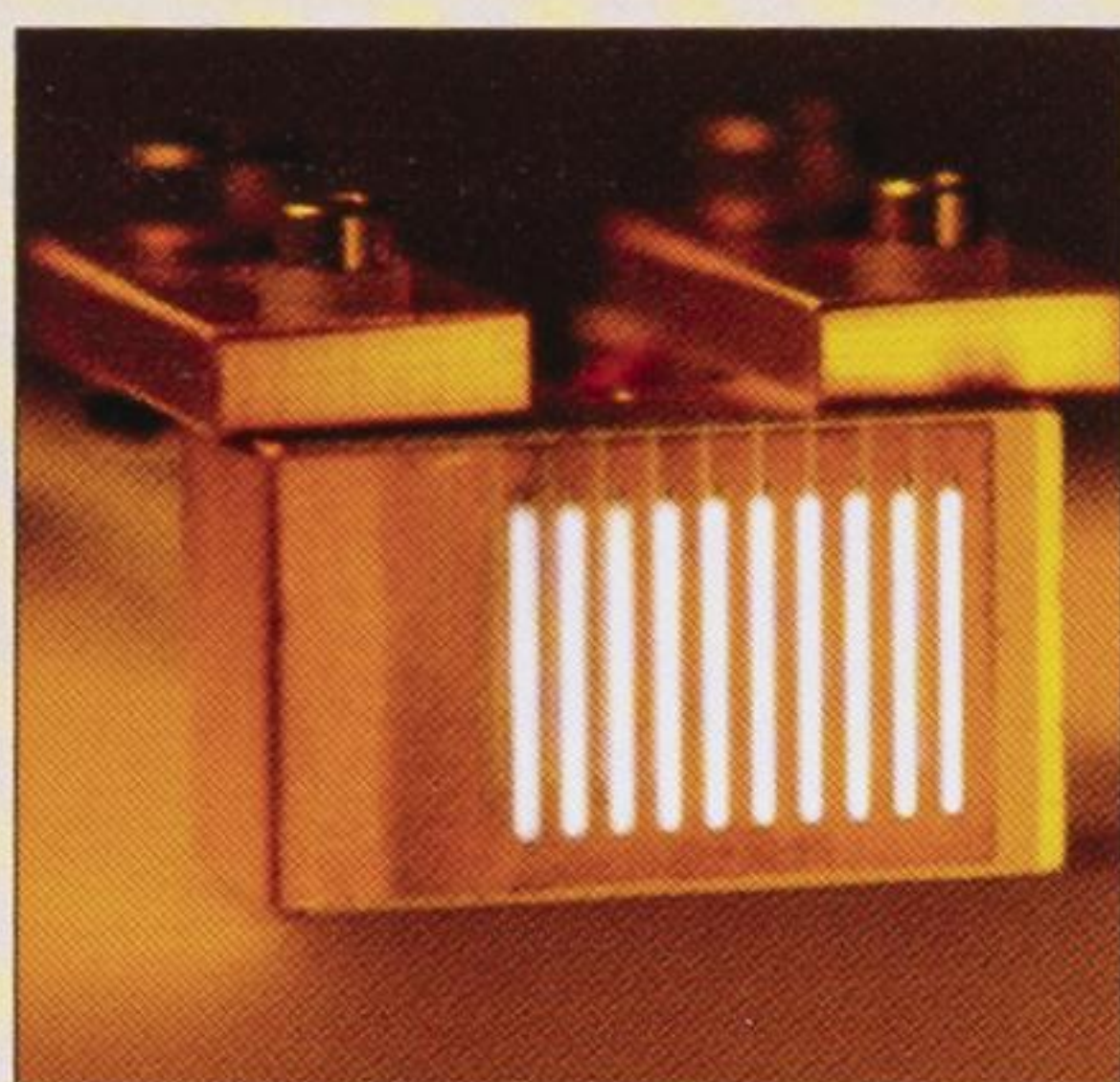
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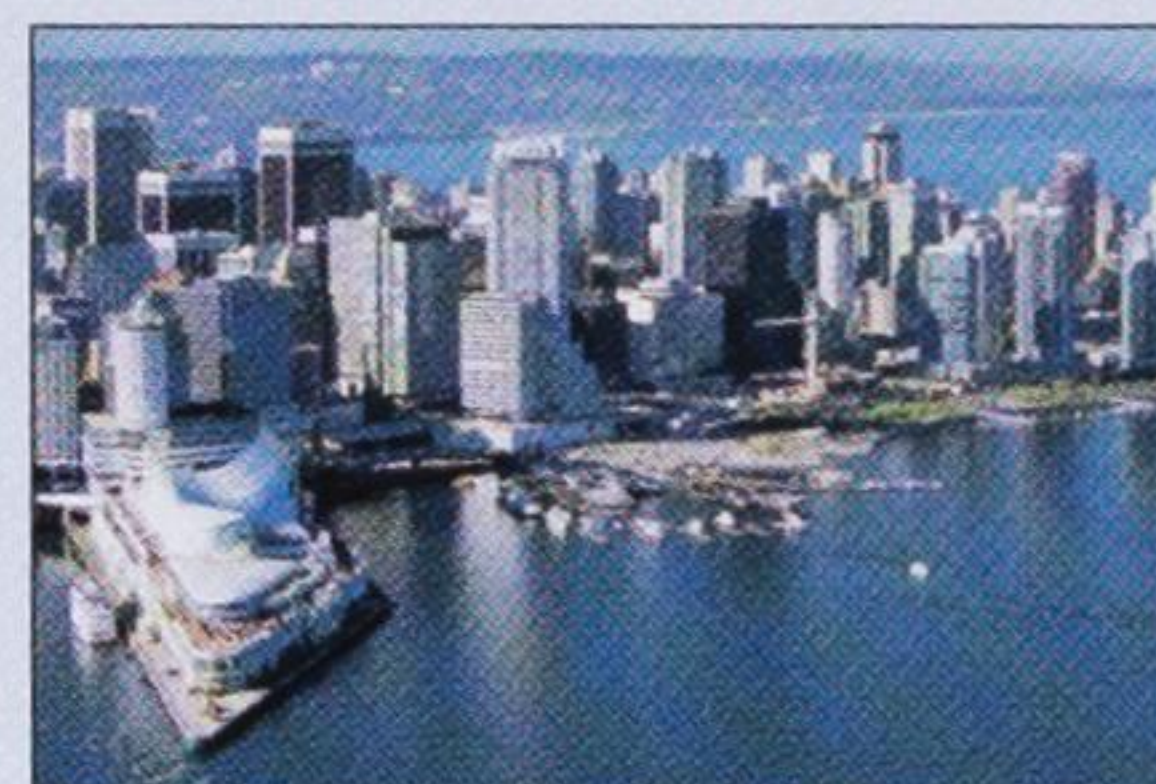
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### Good vibes

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**Main cover image:** The cleanroom area of Skyworks' back-end facility in Mexico. The company is considering its options for a huge increase in production.



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# Size matters



For makers of GaAs-based components for RF applications, 2006 is turning out to be a bit like a repeat of 1999. With demand from Nokia, Motorola and the gang skyrocketing as advanced handsets with tougher requirements on linearity and multiple frequency bands sell like hot cakes, the main challenges facing GaAs manufacturers now relate to getting sufficient wafer volumes through their fabs.

And for different manufacturers, some problems have already cropped up at different points in the process. According to TriQuint Semiconductor's CFO Steph Welty, her company has been somewhat hampered by bottlenecks at the front-end wafer-processing stage in its 6 inch Orgeon GaAs fab. TriQuint has invested in equipment to alleviate the capacity strain, despite its overall fab utilization running at around 74%.

RF Micro Devices' bottleneck has been at the test and measurement end rather than at its wafer fabs in Greensboro. Its \$80 million fab expansion won't be ready for volume requirements until late this year at the earliest, but it sounds like the company is going to need that new capacity pretty fast. At a recent investor conference, RFMD's CEO Bob Bruggeworth was confident that late 2006 would see a big increase in demand for the latest "n" version of the IEEE's 802.11 wireless communications protocol. This application will require as many as four different power amplifiers and, as a result, yet more switches. Bruggeworth has even sounded notice of an increase in prices for some RFMD products later in the year.

As the last of the major US-based GaAs manufacturers still working exclusively with 4 inch wafer technology, you might think that Skyworks would be suffering more than its rivals as demand ramps. Not so, claims the Woburn, MA, firm. By making the most of a flexible foundry relationship, Skyworks has been able to keep pace with demand. And while rumors of a switch to 6 inch production have surfaced, Skyworks is yet to confirm such a move.

Or, as Skyworks might put it: it's not how big your wafers are, but what you do with them that counts.

**Michael Hatcher** *Editor*

**"It's not how big your wafers are, but what you do with them that counts."**

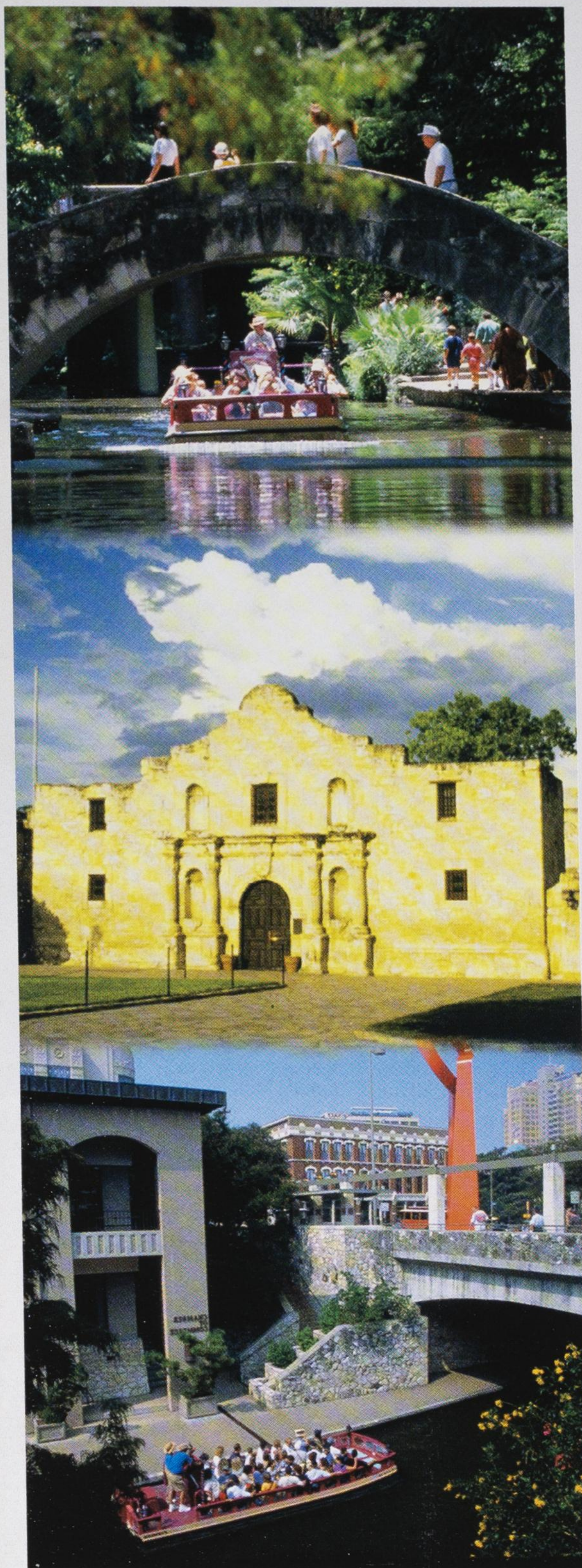
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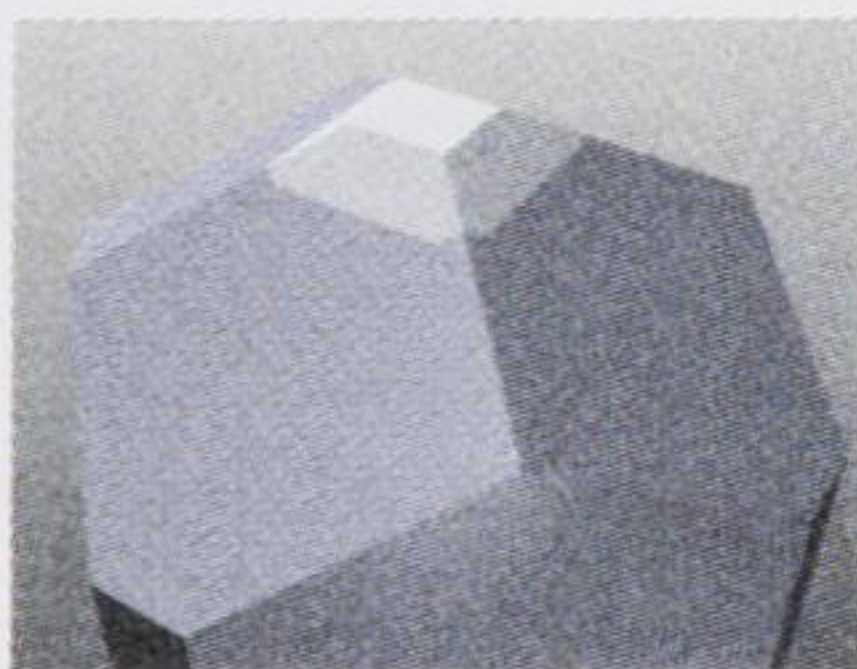
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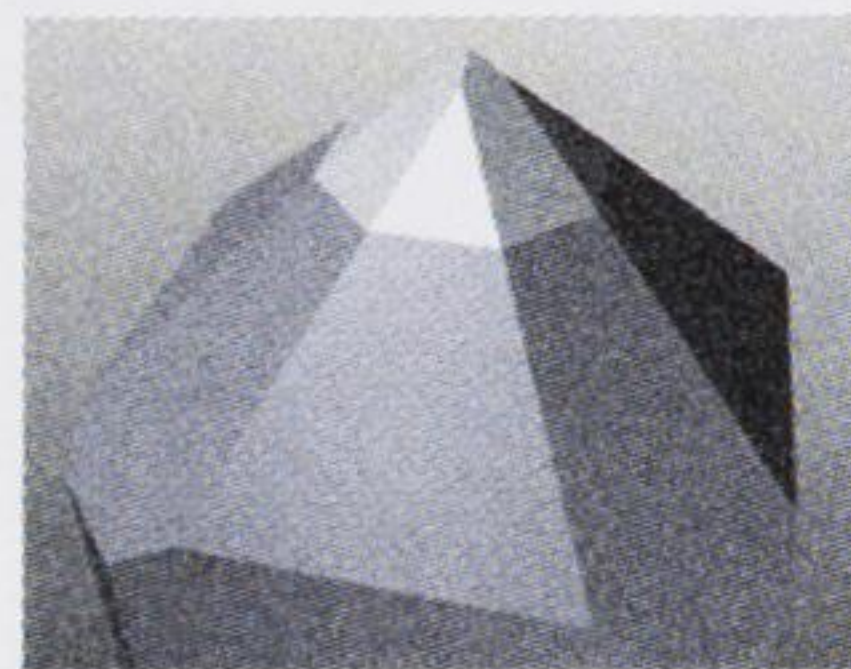
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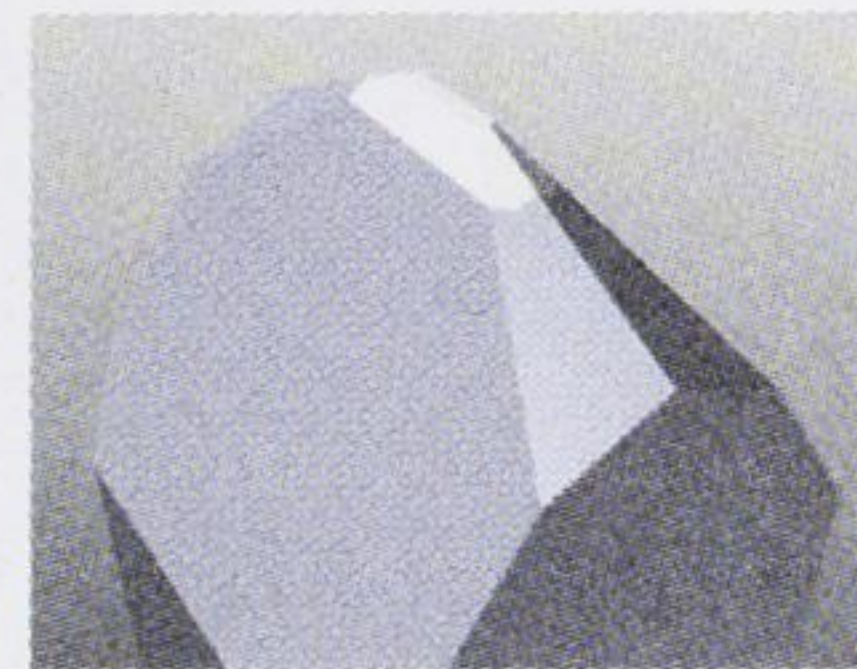
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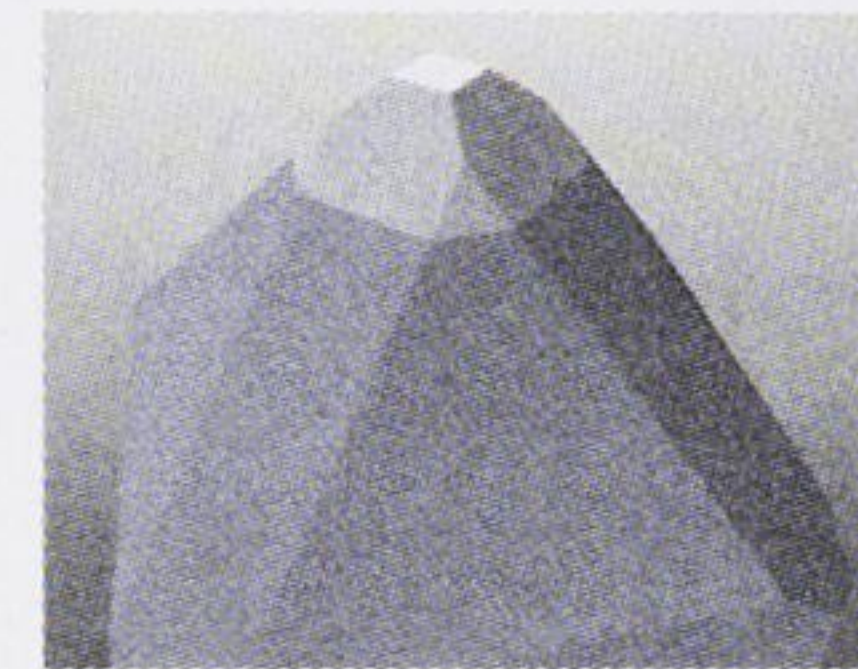
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## MANUFACTURING

# Capacity limits fuel foundry comeback

Demand for a variety of compound semiconductor components is driving a renewed boom in the wafer-foundry business.

While the growing need for GaAs-based RF components is largely responsible for the resurgence, epiwafer foundry IQE reports strong demand across all of its product lines.

The Cardiff, UK, company, which has manufacturing facilities on both sides of the Atlantic Ocean, says that its sales in the opening quarter of 2006 were more than 50% higher than the same period in 2005. "[Our] major outsourcing contracts are all performing ahead of expectations," said IQE.

Providing a trading update prior to the company's annual general meeting in late May, CEO Drew Nelson said that business had been very strong since the beginning of the year.

IQE, which focuses on MOCVD at its Cardiff headquarters and has MBE operations in Bethlehem, PA, had already enjoyed a strong upturn prior to the update, with sales of £9.7 million in the first half of 2005 and £11.3 million in the June–December period.

Although all areas of the business are said to be enjoying strong growth, this is particularly true for the market for GaAs-based wireless devices, with IQE's Bethlehem operations providing much of the sales increase. Revenue



**The boom in demand** for GaAs-based devices and material was a hot topic at the recent Mantech show in Vancouver. See page 25 for our report from the event.

from IQE's US operations near-doubled to \$10.8 million in its 2005 results.

But with datacom and other optoelectronic applications also buoyant, the company believes that it is seeing something of a shift in III-V manufacturing strategies. "We are now

moving into a situation in the market where outsourcing is featuring more prominently in many companies' strategic considerations because the semiconductor industry is becoming capacity-limited in several areas," said IQE.

To help fund the additional working capital required by this upturn in business, IQE has taken out a £3 million loan and arranged a £2 million overdraft facility.

Meanwhile, over on the west coast of the US, Global Communication Semiconductors has recently launched an HFET process for wireless infrastructure applications.

With demand for wireless LAN and even WiMAX components also now beginning to eat away at existing fabrication capacity in the industry, Simon Yu at GCS believes that there may be a GaAs capacity shortage by next year.

Stephanie Welty, CFO at TriQuint Semiconductor, admitted in a recent investor presentation that although overall capacity utilization at the company was not a problem, it had been affected by bottlenecks at various points in the chip-manufacturing process. It has been purchasing new equipment for both front-end and back-end fabrication as a result, particularly at its 6 inch facility in Oregon where TriQuint makes high-volume products for cell-phone handsets.

## CONVERGENCE

## Riber machine to prolong march of Moore's Law

The world's leading manufacturers of silicon chips are getting their hands on a cluster MBE tool from Riber to research the long-term continuation of Moore's Law through the use of III-V materials.

Leading semiconductor research center IMEC, which is based in Belgium, is to install a "unique" MBE machine from the French equipment vendor. The cluster tool, which is compatible with 200 mm (8 inch) wafers, will be used in a research program whose aim is to demonstrate the feasibility of using germanium and compound semiconductors in future CMOS processing.

IMEC is working with a host of leading semiconductor manufacturing companies on a sub-45 nm node CMOS research program. Industrial partners in this effort include Intel, Infineon, Matsushita, Philips, Samsung, ST Microelectronics, Texas Instruments and the world's biggest foundry – the Taiwan Semiconductor Manufacturing Company.

The MBE kit will be used in the "germanium and III-V devices" element of that research effort, enabling deposition of compound materials on germanium or germanium-based wafers. It will also be used to deposit high-k dielectric compounds to form the insulating

layers of devices and metal contact layers, and IMEC says that these processes will be based on silicon wafers, ensuring compatibility with a standard silicon-manufacturing line.

IMEC has already demonstrated the feasibility of sub-micrometer PMOS devices on a germanium wafer, but it says that other materials approaches and steps must now be developed to make very advanced CMOS devices.

The research center now aims to show that germanium and III-V compounds could be used in devices beyond the 22 nm "node", which is expected to reach volume production in about 2016.

## DEEP-UV LED

## AlN layers produce LED operating at 210 nm

NTT researchers have made an aluminum nitride (AlN) LED operating at 210 nm – the shortest wavelength at which such a semicon-

ductor device has been shown to emit light.

Although extremely inefficient and with a hefty operating voltage of 25 V, the LED made by Yoshitaka Taniyasu and co-workers at NTT's Basic Research Laboratories is a crucial first step towards the development of very low wavelength emitters that could be used to detect or destroy harmful biological species.

Reporting the work in the leading journal

*Nature*, the NTT group describes how it used a refined doping strategy to make the PIN LED and grew the device epilayers using MOCVD. Until now, researchers had been unable to control the doping of the n-type and p-type layers of AlN precisely enough to demonstrate an LED with the material, which has the widest direct bandgap among semiconductors.

● See page 31 for more on the AlN LED.



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## MANUFACTURING

# Skyworks weighs up GaAs options to meet orders

GaAs chip and RF device maker Skyworks Solutions is considering a variety of options with a view to increasing its manufacturing capacity, including a conversion to 6 inch wafer production.

Like the rest of the industry, the Woburn, MA, company is striving to meet very high demand for its GaAs-based products because of the strength of the cell-phone handset market, where more GaAs content is being utilized in high-end phones.

Unlike rivals RF Micro Devices, Anadigics and TriQuint, Skyworks has stuck resolutely to a 4 inch GaAs manufacturing policy at its two fabs. It has met the strong recent increase in demand through foundry partners and "linear" increases in its own fabs through equipment purchases.

However, a step change in capacity may be

required if the demand for GaAs-based components continues to grow at the current rate. According to Skyworks' senior VP of mobile platforms, Kevin Barber, a move to 6 inch fabrication is something that the company has considered, although he says that the huge depreciation costs and potential disruption that would be caused by such a switch mean that 4 inch processing is still regarded as the best option for the moment.

In a presentation at the AeA Micro Cap financial conference in early May, AXT president and CEO Phil Yin suggested that Skyworks was looking more seriously at a 6 inch conversion, saying that bids for the larger wafer material had been initiated by the chip manufacturer.

• See our interview with Kevin Barber on p13 for more about Skyworks.

## MERGERS AND ACQUISITIONS

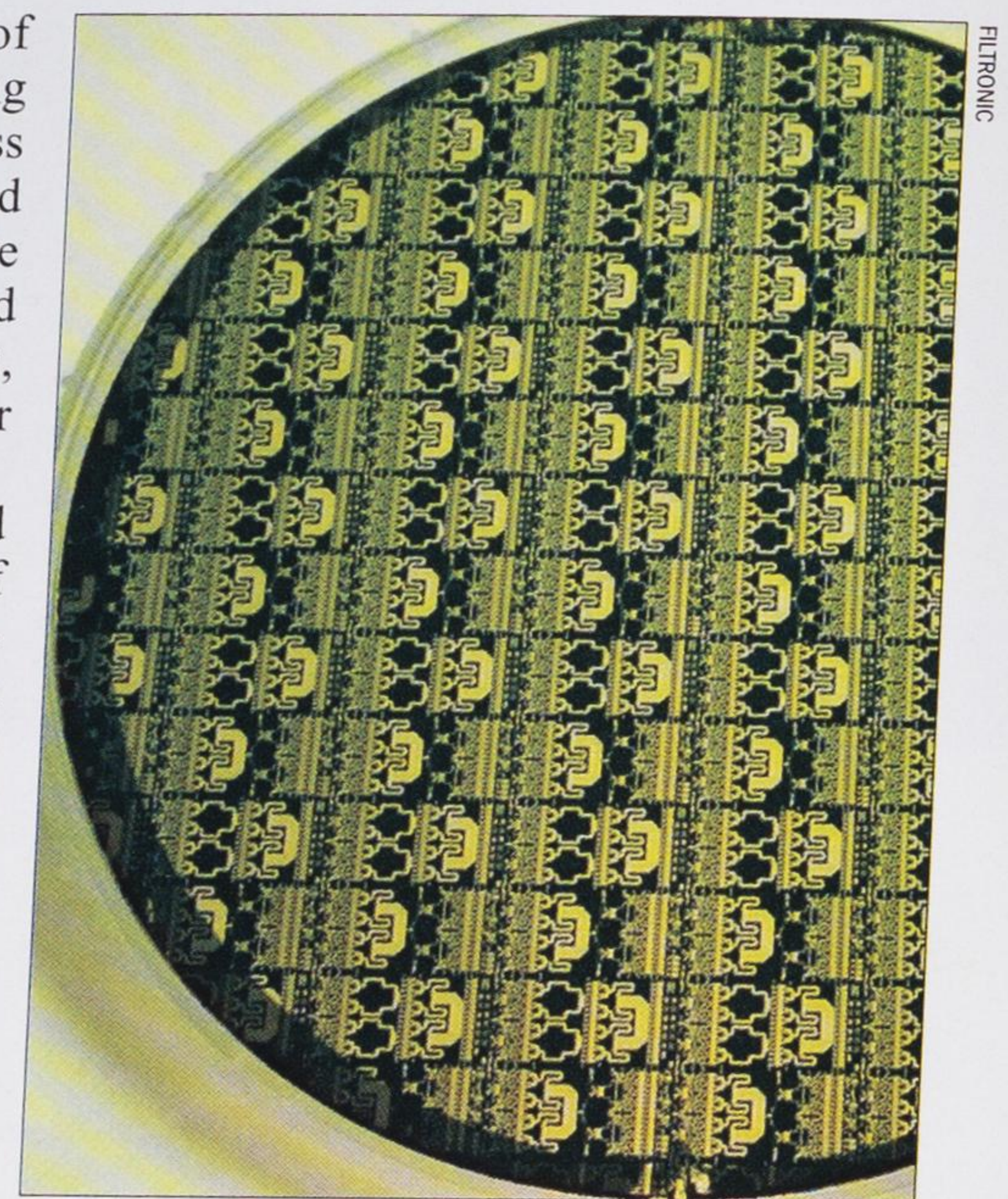
# Powerwave sizes up Filtronic unit

Filtronic, the UK-based manufacturer of GaAs-based chips and MMICs, is discussing the sale of its wireless infrastructure business to Powerwave Technologies. California-based Powerwave, whose European headquarters are in Sweden, describes itself as an end-to-end supplier of solutions for wireless networks, and its product portfolio includes RF power amplifiers (PAs) for cellular base stations.

"The two companies have entered a period of exclusive negotiations for the disposal of Filtronic's filter-based transmit-receive module and power amplifier businesses," read a statement issued by the pair. It added: "There can be no certainty that these negotiations will result in any transaction being completed."

Back in 2002, Filtronic and Powerwave formed a strategic alliance to jointly develop PAs and conditioning subsystems for 3G base stations. The alliance allowed Filtronic to increase the utilization of its 6 inch fab in Newton Aycliffe, UK. However, the GaAs fab remained underutilized as the 3G build-out became delayed.

More recently, Filtronic has rapidly ramped up its GaAs PHEMT activity to meet demand from RF Micro Devices for switches in cell-phone handset transmit modules. The UK company will be keen to continue this production ramp-up, despite RFMD's plan to



Filtronic is currently developing GaAs-based MMICs for wireless infrastructure applications.

move GaAs PHEMT manufacturing in house.

If the Powerwave acquisition goes ahead, Filtronic will be left with only two business units: its compound semiconductor and its defense electronics divisions.



## MANUFACTURING

## RFMD to ride out back-end capacity shortfall

RF Micro Devices (RFMD) is set to ride out concerns over capacity constraints and maintain its leading position among suppliers of RF semiconductors. That's according to John Lau, an analyst who covers the company for US-based broker-dealer Jefferies and Company.

Lau says that business is extremely brisk at the Greensboro-based firm. "[RFMD is] capacity constrained for the current quarter to the upper end of its revenue guidance of \$230-245 million," he wrote in his latest report on the company's financial performance.

Lau reckons that RFMD is now being very selective in making sure that it can support key accounts with leading handset makers, including Nokia and Motorola, both of which are said to be accelerating orders.

Although the major capacity constraint is at RFMD's test facility in Beijing, China, the firm's GaAs wafer facilities are also thought to very full because of red-hot demand for products containing HBT die.

Responding to rumors that RFMD had lost out on a Taiwanese contract recently, Lau said that such talk was inevitable but added that RFMD was responding in the right way by declining such low-margin business. "We believe that RFMD is making prudent business decisions to build longer-term relationships with its customers. Since it is capacity constrained, it is making the right choices about which orders it can support," explained

the analyst. RFMD has already taken steps to expand its GaAs wafer fabrication capacity by 40% as it seeks to alleviate capacity constraints and bring PHEMT manufacturing in house.

With increasing dollar content in Nokia, LG and Motorola handsets, RFMD is also well placed to head off any emerging threat from a raft of second-tier suppliers that are gaining market share in RF semiconductors.

Consulting firm Strategy Analytics reckons that smaller suppliers, including Anadigics, Avago, Mitsubishi and TriQuint Semiconductor, have doubled their share of the cell-phone power amplifier (PA) market by concentrating on innovative technologies, and they are now benefiting from fast-rising sales of wideband-CDMA phones.

Growth across the handset sector is now rapid, and the market for cell-phone PAs looks certain to rise strongly from the 2005 Strategy Analytics estimate of \$1.5 billion as handset sales move towards 1 billion. The value of the PA component averages out at just under \$2 per phone, estimates the market research company.

However, despite this recent good showing by the smaller firms, Chris Taylor at Strategy Analytics believes that larger companies like RFMD still hold the advantage in the longer term. This is because they have greater resources with which to develop front-end modules with greater functionality and frequency-band coverage.



## From our Web pages...

visit [compoundsemiconductor.net](http://compoundsemiconductor.net) for daily news updates

## ...Sirenza targets WiMAX

Sirenza Microdevices has moved a new family of high-performance linear power amplifiers for WiMAX (802.16 d/e) and Wi-Fi (802.11 a/b/g) applications into volume production. The SZP products, based on InGaP HBT technology, are single-stage, high-linearity power amplifier ICs.

## ...STS happy with orders

Nigel Randall, chairman of plasma processing equipment vendor Surface Technology Systems, told the company's annual general meeting on May 23 that shipments and orders for 2006 are well up on the previous year. At the end of April, shipments and orders for delivery totalled more than £15 million (\$28.2 million), says Randall. Last year the figure was just £8 million.

## ...Kopin stays confident

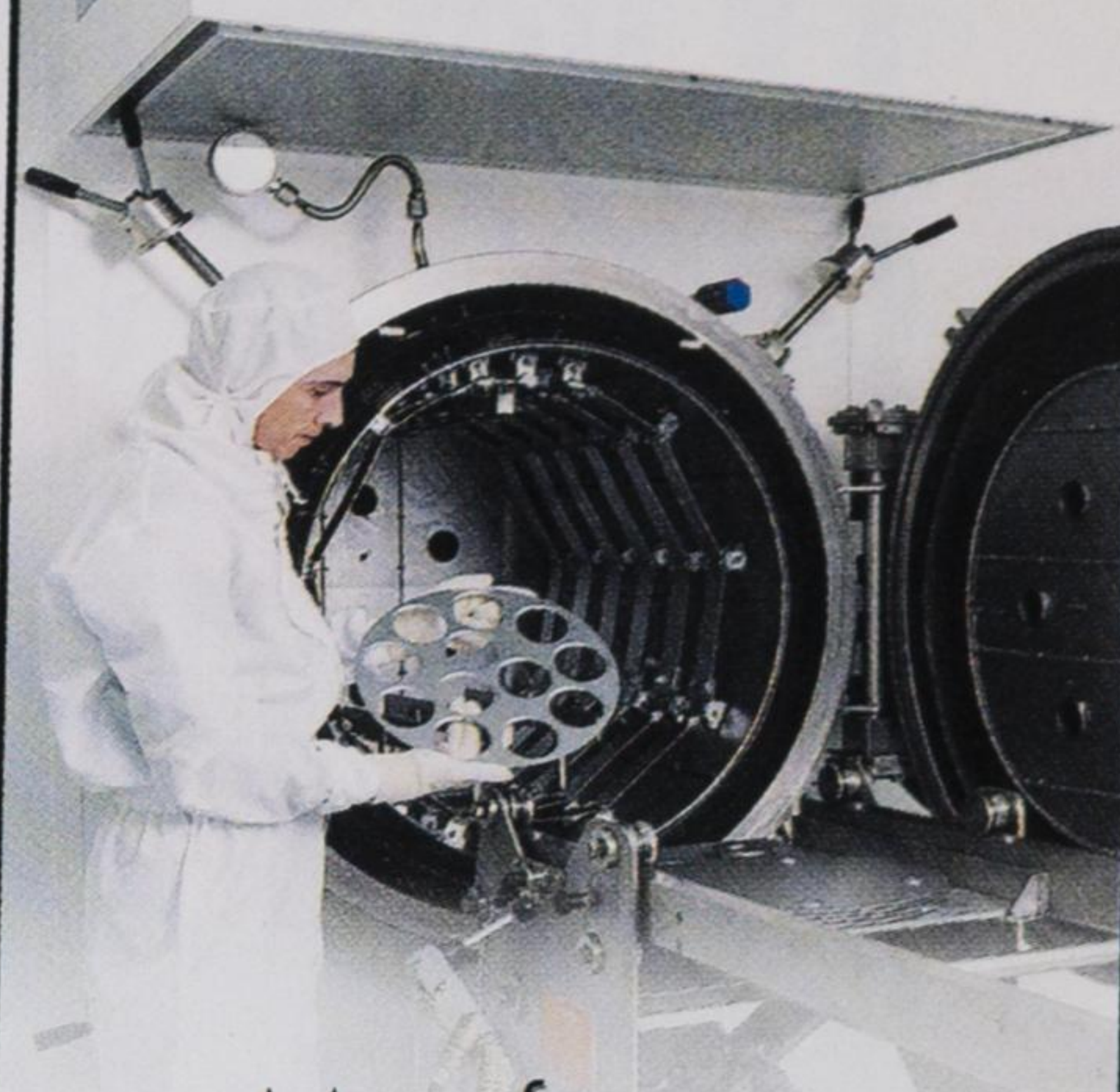
Sales at Kopin's III-V epiwafer division grew 37% year on year to reach \$12.8 million in the

quarter that ended on April 1. Although that represented a slight decline sequentially, company CEO John Fan is very confident about the current market activity and Kopin's prospects. As well as increasing MOCVD manufacturing capacity by 50% over the next two years to meet the anticipated ramp, Kopin is qualifying KTC, its licensed manufacturing partner in Taiwan.

## ...Yokogawa eyes HBTs

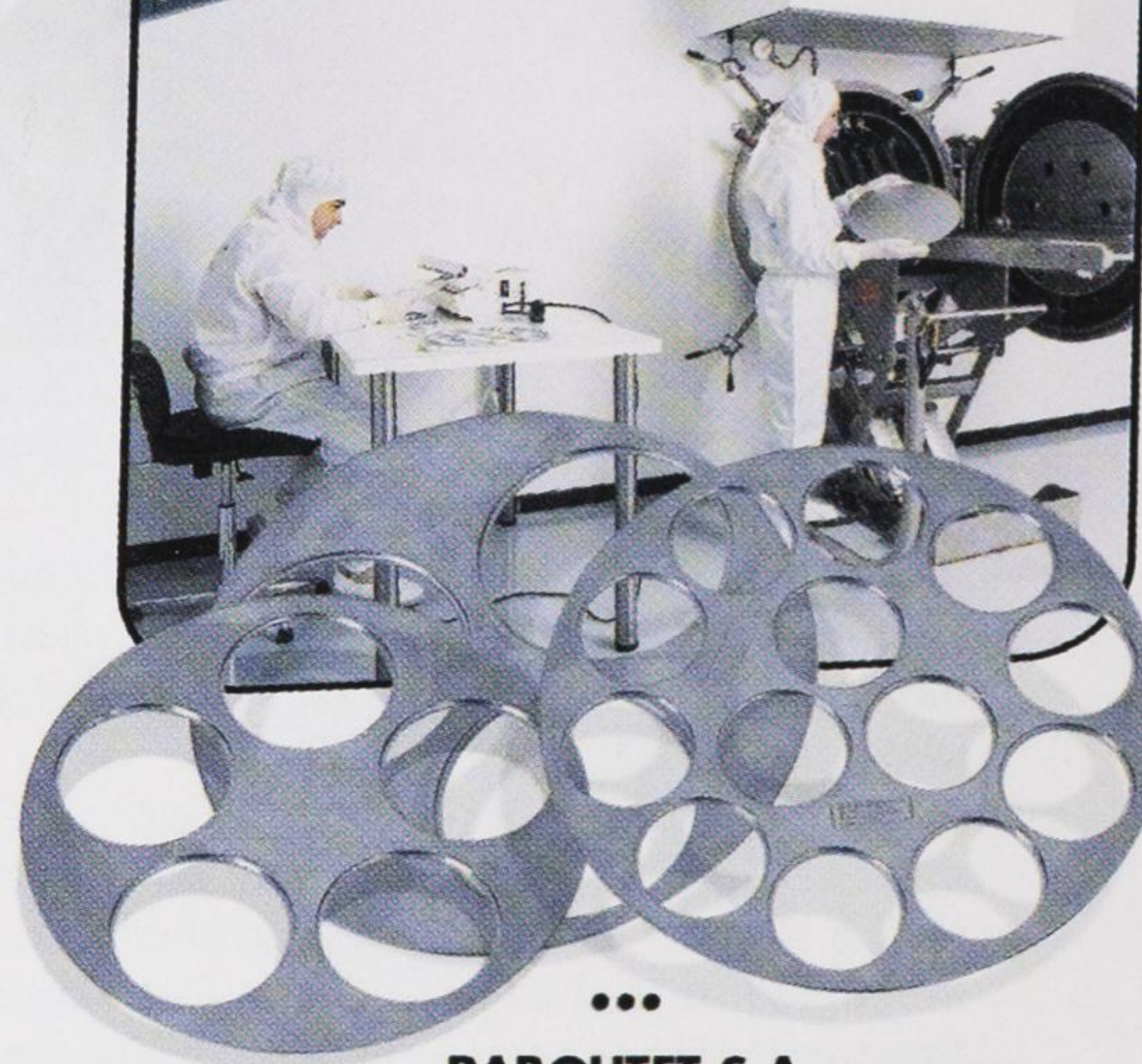
Japanese industrial giant Yokogawa has bought a production MBE machine from France-based Riber. The MBE49 kit, which supports manufacturing on multiple 4 inch wafers, will be used to make HBTs for next-generation communication networks, says Yokogawa. The company, best known for its industrial control and automation products, is building a huge compound semiconductor fabrication facility near Tokyo at a cost of around \$230 million.

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VENTURE FUNDING

# TV backlight firm bags a cool \$38 million in funding



**Samsung's award-winning** rear-projection television features an LED-based backlight from Luminus Devices. The company, which is only four years old, already has a chip-processing facility in Massachusetts, although it outsources epitaxial growth.

Luminus Devices, the Massachusetts Institute of Technology (MIT) spin-out that made a splash earlier this year with its LED-based television backlights, has scooped \$38 million in new venture financing. The Woburn, MA, firm says that it plans to use the cash to expand its chipset production capacity and its initial product line, which it calls PhlatLight.

PhlatLight is shorthand for the photonic lattice structures developed by Luminus founder and CTO Alexei Erchak. The lattices are complex arrays of microstructures in a solid dielectric material that are said to drive photons out of the semiconductor medium more efficiently than in conventional LED structures. "Not only is more light produced, but the light can be extracted in a narrower, collimated beam that is more readily collected and delivered to its target," claimed the company.

Luminus has a full wafer fab at its headquarters. It buys epitaxial material from various suppliers and performs chip processing, assembly and packaging in Woburn.

Television makers have been the first to pick up on this technology and Luminus boasted 10 of the biggest consumer electronics firms among its initial clients at the Consumer Electronics Show held in Las Vegas in January. These included Samsung, whose PhlatLight-powered 56 inch rear-projection television

won an award at the event.

Luminus says that its PhlatLight chipsets are now in mass-production and commercial television models featuring the technology will be available later this year.

"We are tremendously encouraged by the level of interest in our PhlatLight technology and the opportunity this [venture] investment has afforded to meet our customers' demand," said Luminus CEO Udi Meirav, who, like Erchak, is a graduate of MIT.

Participating in the latest venture round were Battery Venture Partners, Argonaut Private Equity and Stata Venture Partners, as well as a number of other existing and new venture capital firms. "We have watched Luminus perfect its technology, establish a high-volume manufacturing process and line up an impressive list of customers," said Jason Martin, managing director at Argonaut. He added that the latest funding round would support an expansion into other application areas beyond high-specification televisions.

Although little has been revealed about the photonic lattice technology that Erchak and colleagues developed at MIT, the approach appears to be similar to the photonic crystal structures under investigation at leading LED research institutions, such as the University of California, Santa Barbara. In US patent 6,831,302, Erchak and colleagues describe a chip structure including a layer of n-doped material whose surface has a dielectric function that varies spatially according to a pattern. A separate layer is designed to reflect at least 50% of the light generated by the semiconductor source via the n-doped surface layer.

Backlights for high-end televisions are expected by many to be the next big revenue driver for the HB-LED industry, which is currently reliant on the cell-phone handset industry for sales. However, Luminus is up against major HB-LED players Cree and Philips Lumileds as it fights for a share of the TV backlight market. Both have products aimed at the emerging sector. Revenue for chip-makers from this application market is now flattening out as the annual drop in average selling prices becomes greater than the annual growth in unit sales.

Market research firm Strategy Analytics has predicted that LED-based backlights will account for as much as 25% of the total market for LCD televisions by 2010.

APPLICATIONS

## Performance of Luxeon flash beats xenon lamp

Power LED manufacturer Philips Lumileds says that its Luxeon emitters now deliver superior performance over xenon lamps for cell-phone camera flash applications. In tests performed by the San Jose, CA, company, the LED-based flash produced 1 lux sec at a distance of 3 m, compared with a xenon lamp that delivered 0.67 lux sec. Philips Lumileds claims that this proves that LED-based flashes can be used in cameras for high-quality imaging.

According to the company, the Luxeon flash enables illumination of 30 lux or more at a distance of 2 m. Crucially the LEDs are more efficient and operate at a lower voltage than xenon lamps, so they don't drain the phone's battery power as quickly. The camera flash is now seen as the key application in cell-phone handsets to drive future revenue growth for LED chip makers.

The keypad and display backlights still represent a huge annual market in excess of \$1.7 billion, but the relative maturity of backlighting technology means that this market value will likely drop in future years.

Last year a report from Strategy Analytics predicted that, by 2009, revenues from the camera flash function would represent 36% of the total LED market in handsets.

DEVELOPMENT

## New warm-white light breaks efficiency mark

Solid-state lighting developer LED Lighting Fixtures has demonstrated a warm-white lamp with an efficacy rated at a record 80 lm/W.

The Research Triangle Park, NC, company, which is managed by a number of ex-Cree employees and executives, and uses Cree die in its lamps, is planning to launch the fixtures commercially by the end of the year. It says that they will be both "substantially cheaper" and much brighter than any LED-based products currently on the market.

Independently tested by CSA International's Atlanta Lighting Laboratory, the recessed downlight was measured to deliver 600 lm from a residential AC voltage power source operating at 7.5 W. Crucially, the colour temperature of the emitted light was 3100 K, known as "warm white".

This is the most conventional hue of white light used in residential applications, so achieving high efficacies at this color temperature is important if solid-state sources are to penetrate the residential market.



## INTELLECTUAL PROPERTY

# Key players resume battles over patents

Osram Opto Semiconductors and Nichia have begun more legal battles in the GaN-based LED space with two filings over patent infringement, although the latest lawsuits are not between the two heavyweights.

Osram has filed against Taiwan's Kingbright and its German subsidiary, saying that they have infringed patents for white and surface-mount LEDs. It hopes to obtain a restraining order and compensation from Kingbright, and it intends to prevent imports to Germany of Kingbright products containing the LEDs. The technologies covered by the patents include phosphors used to convert blue emission from an InGaN chip into white light, plus electrical connections and housing designs.

Osram launched a claim against Malaysia's Dominant Semiconductor but was only partly successful in that case, with no infringement found in five of the eight patents contested. Meanwhile, Nichia has filed against Germany-based Moeller Electric in the Osaka District Court. The lawsuit focuses on blue LEDs, with Nichia seeking damages and an injunction.

## COMMERCE

## Seoul boost for Cree as Sumitomo order shrinks

Chipmaker Cree and LED-based product vendor Seoul Semiconductor have signed a long-term agreement over the supply of LED chips. The Korean company will buy at least \$40 million worth of LED products from Cree during the first five quarters of the deal, while the overall agreement extends for five years.

Purchase commitments will be negotiated annually, but the deal confirms Seoul Semiconductor as one of Cree's top LED chip accounts, along with Japan's Sumitomo and Osram Opto Semiconductors in Germany.

Sumitomo is Cree's leading customer. It recently signed a \$180 million purchase agreement with Cree for fiscal 2007 – a 10% drop on the \$200 million order agreed a year ago. However, Sumitomo has only fulfilled around \$165 million of its 2006 order.

Cree and Seoul Semiconductor have also agreed to cross-license some patents detailing white LEDs, including Cree's much-quoted US patent 6,600,175, which details the production of a white light source using a blue- or UV-emitting LED. Late last year, Cree licensed the same patent to the Taiwanese firm Kingbright Electronic.



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#### ...Crystal IS nears \$7 million closure

Single-crystal AlN substrate developer Crystal IS is about to close a second-round venture finance package worth around \$7 million, according to the company's new CEO, Ding Day. The Green Island, NY, company has also just released the world's first single-crystal 2 inch AlN substrates, and it is targeting both optoelectronic and microelectronic applications. The material should allow growers to produce structures featuring a high aluminum content with fewer dislocations and therefore better performance. Short-wavelength LEDs operating in the ultraviolet region for applications like water and air purification should be one of the key beneficiaries.

#### ...Samsung orders Aixtron reactors

Aixtron has received an order for two more GaN MOCVD mass-production systems from Samsung Electro-Mechanics Co (SEMCO) in the first quarter of 2006. Shipment is expected during the first half of 2006. The order comprises two AIX 2600G3HT 24 x 2 inch

configuration reactors, which will be delivered to SEMCO's facilities in Kyungki-Do, South Korea. These will be for the volume production of high-brightness blue and white GaN-based LEDs.

#### ...Uni Light expands production base

Taiwan-based Uni Light Technology has ordered another Thomas Swan MOCVD reactor, which Aixtron is expecting to ship during the second quarter of 2006. The system, a Thomas Swan CCS 19 x 2 inch multiwafer machine, is to be employed for the development and manufacture of GaN-based epitaxial wafer materials for LED devices.

#### ...GaNzilla II on target in Taiwan

Veeco Instruments says that it has received several multi-unit orders for its GaNzilla II MOCVD system from a number of key Taiwanese manufacturers of high-brightness LEDs. Customers who have placed multi-unit orders during the first quarter of 2006 include Huga Optotech Inc, Highlink Technology Corp and Epitech Technology Corp.

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POWER LASERS

# QPC eyes expansion as public company

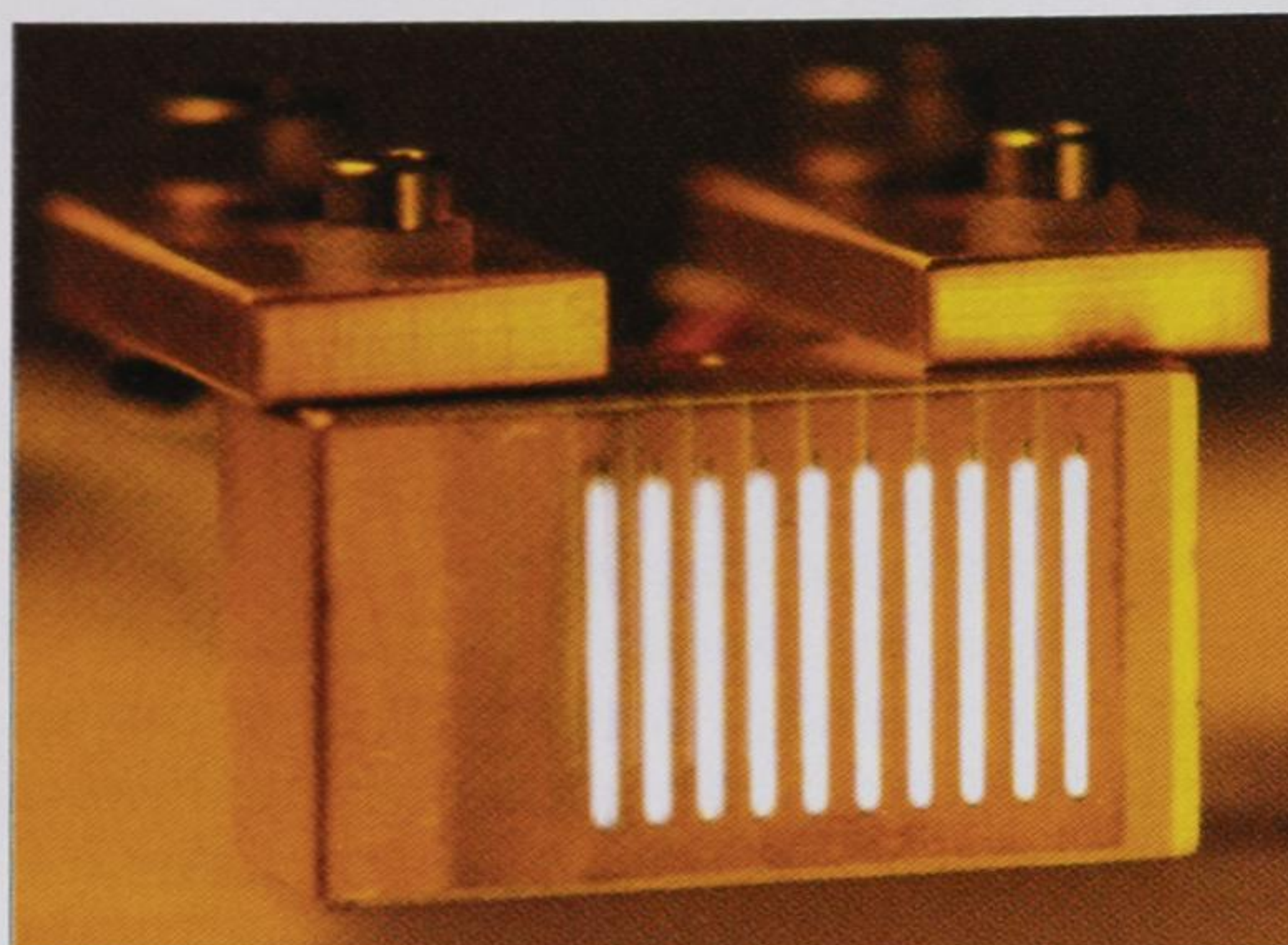
High-power laser manufacturer Quintessence Photonics Corporation has become a publicly traded company via a "reverse merger" transaction with a now-defunct event planning firm.

The Sylmar-based company, which has a semiconductor wafer facility and employs around 30 people, is now listed on the "over-the-counter bulletin board" exchange in the US. That should give the firm access to greater working capital as it looks to expand operations, which are said to be scalable to 20 million devices per year.

QPC's lasers emit through the surface of the wafer, thanks to a 45° mirror that is etched into the AlGaAs/GaAs epitaxial structure. This approach means that two-dimensional arrays of laser diodes can be made without the need to cleave the wafer into a series of bars.

The company says that it can aggregate hundreds of high-power lasers onto a single semiconductor chip in this way, which enables volume production, inexpensive assembly and simpler cooling.

DARPA has awarded QPC a \$3.1 million subcontract to further develop the lasers under its three-year Architecture for Diode High Energy Laser Systems program. Paul Rudy at the company says that the military program



**QPC is now** working on the third generation of its high-power surface emitters, which the company hopes will find widespread use in the industrial welding sector.

will involve combining the surface-emitting laser technology with QPC's high-power singlemode lasers.

Having launched its first high-power emitters in 2004, QPC is already delivering lasers to the US Army and has also won a multi-year production contract with the Israeli Ministry of Defense. Its third-generation diodes are currently in development, with prototypes targeted at the industrial welding market set for a launch next year.

QPC now says that it has also designed the world's only on-chip wavelength converter. Developing this technology and the third-generation products will rely on the company gaining more funds.

Mark Bernhard of Capital Group Communications, the investment company that oversaw the switch, explained that QPC was acquired by now-defunct corporate event management company Planning Force. The business was based in Spokane, WA, and had nothing to do with semiconductor lasers.

Julie Morin, the CEO and sole employee of Planning Force, received \$250,000 in cash through the deal and promptly resigned, leaving QPC co-founder and CEO Jeffrey Ungar at the helm of the new publicly traded firm.

According to Bernhard, this kind of transaction provides a very low-cost way to take a private company onto a public exchange and is ideal for relatively small companies such as QPC that could not afford a full-blown IPO. He added that QPC would aim for a NASDAQ listing around the end of this year.

QPC has also hired Timothy Franey as its new VP of manufacturing. Franey was previously at JDSU and Lightwave Electronics, which makes high-power laser systems.



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### ...GaN laser ramp in the pipeline

After delaying its spring release, Sony's computer entertainment division has now confirmed that its new games console, the PlayStation 3, will launch in November 2006. According to Japan's *Nihon Keizai Shimbun* newspaper, Sony plans to ship 2 million units initially, with 4 million more by 31 March 2007.

### ...Vitesse execs get the boot

Three of Vitesse Semiconductor's most senior executives have been fired amid an investigation into the timing of the stock options that they were awarded. CEO Louis Tomasetta, CFO Yatin Mody and executive VP Eugene Hovanec were shown the door as the InP chipmaker, which pioneered 6 inch GaAs processing as long ago as 1998, announced that it was expanding its internal investigation to review the company's revenue recognition policies. Vitesse added that it has defaulted on the terms of a loan agreed with the Silicon Valley Bank.

## PHOTONIC POWER

# Chinese OK GaAs power meters

JDSU's photonic systems for measuring electrical current have passed tests set by the Chinese government. The certification could bring about a fast-growing new market for GaAs-based lasers and photovoltaic devices, both of which are fundamental components of the systems.

Working in conjunction with the Zhuhai Cheng-Rui Electric Power Company, JDSU says that it incorporated one of its photonic power systems to demonstrate the benefits offered by all-fiber digital measurement of electric current.

"We expect rapid growth of optically powered current measurement systems," noted Xiao-Li Xu, general manager at the utilities company. He added: "All-fiber systems have now reached the economical level and achieved the reliability to support the future development of Chinese and other Asian electric power markets."

The photonic power systems from JDSU can monitor and protect transmission and distribution grids operating between 100 and 500 kV. And because they are based on pho-

tonics, the current measurement systems are immune to interference from local electric and magnetic fields.

JDSU acquired Photonic Power Systems in June last year, at which time the division employed just eight people. In its laboratories, the unit recently demonstrated a photovoltaic device with greater than 50% electro-optical conversion efficiency – an improvement that will enable more energy-hungry applications such as transducers, transceivers, and sensors to be powered via optical fiber.

The photonic power converters can feature either GaAs or InP-based photovoltaics, typically using 2 × 2 mm chips, and are particularly useful for powering electronic devices that operate in high-voltage or magnetic environments where traditional copper-based power delivery can be problematic.

One such application in the medical field would make device operation viable inside magnetic resonance imaging (MRI) scanners. The strong field inside MRI scanners means that this is impossible with conventional copper-wire powering.



## SOLAR CELLS

# Emcore and Bandwidth get excited about terrestrial solar power prospects

Military and commercial installations of GaAs-based solar power systems are expected to pocket Emcore at least \$30 million in sales over the next year or so.

The compound semiconductor device maker says that it is making good progress towards the deployment of terrestrial solar systems based on the triple-junction cells, and plans to add manufacturing capacity to meet rising demand next year.

"On the terrestrial solar front, we are excited about our prospects," commented Emcore CEO Reuben Richards. "We have bids out on approximately 40 MW of [planned projects], with contracts to be awarded in 2006 and installation beginning in 2007."

Owing to a shortage of polysilicon material for solar cell applications that is showing few signs of becoming resolved, and that material's relative lack of scalability compared with GaAs-based solutions for large commercial projects, Emcore has recently penetrated the terrestrial solar market for the first time.

Richards told investors in a conference call that Emcore stood to make revenue of \$30–\$60 million in the coming year through sales of solar cells and modules.

The contracts include both military and commercial solar installations, and Richards says that at least half of the 40 MW on which Emcore has bids awaiting approval should get the go-ahead very soon. Even if the company does not win all the contracts to supply solar systems, it will more than likely be the key supplier of the cells that are used in those projects, he says. Ultimately, however, Richards sees Emcore's "sweet spot" in the terrestrial solar business at the module level.

Prospects in the terrestrial solar area have further impressed John Lau, an analyst at Jefferies. With Emcore's stock price having tracked up from \$4 to as high as \$12 over the past year, Lau has increased his share-price target to \$16.

"We believe a strong outlook for the company's new terrestrial solar cell businesses should be a significant catalyst for the stock," Lau wrote in his summary of Emcore's update. "The company is bidding on four opportunities in the south-west US for solar cell projects, and has limited competition."

"Furthermore, emerging markets such as India and China should shape up as large markets for GaAs-based cells as opposed to poly-

silicon-based cells," concluded the analyst.

Richards believes that GaAs-based solar systems currently promise to operate at around \$3 per watt output. But with expected improvements to the cells raising efficiency to 50 per cent in the pipeline, that figure could drop to just \$1.50 per watt, which would prompt further market penetration.

In silicon-based photovoltaics, sunlight is directed onto large-area cells and converted into electrical power. However, in modules that are based on III-V technology, a small chip with up to three p-n junctions is used to convert solar energy that is focused onto the cell area via an optical concentrator system.

Because only a small area of III-V material is required, the overall system cost can be reduced compared with the large volumes of silicon needed in conventional photovoltaics.

Now preparing for what is expected to be a

significant ramp-up in production of the devices, Richards says that Emcore will look to add manufacturing capacity some time in 2007 in the form of MOCVD reactors.

Meanwhile, Spire Corporation says that its Bandwidth Semiconductor subsidiary is now offering GaAs-based solar cells for use in terrestrial power applications.

Like Emcore, Spire senses a major opportunity beginning to arise. "With the demand for solar electricity and shortage of polycrystalline silicon, concentrator solar technology has an opportunity to become significant in the marketplace," said Spire CEO Roger Little.

Bandwidth, which will also produce the concentrator cells using MOCVD equipment, is focused on custom device production of a wide range of III-V devices, while Spire already sells a wide range of manufacturing equipment for solar power applications.



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## SIMS Technology Advances at EAG

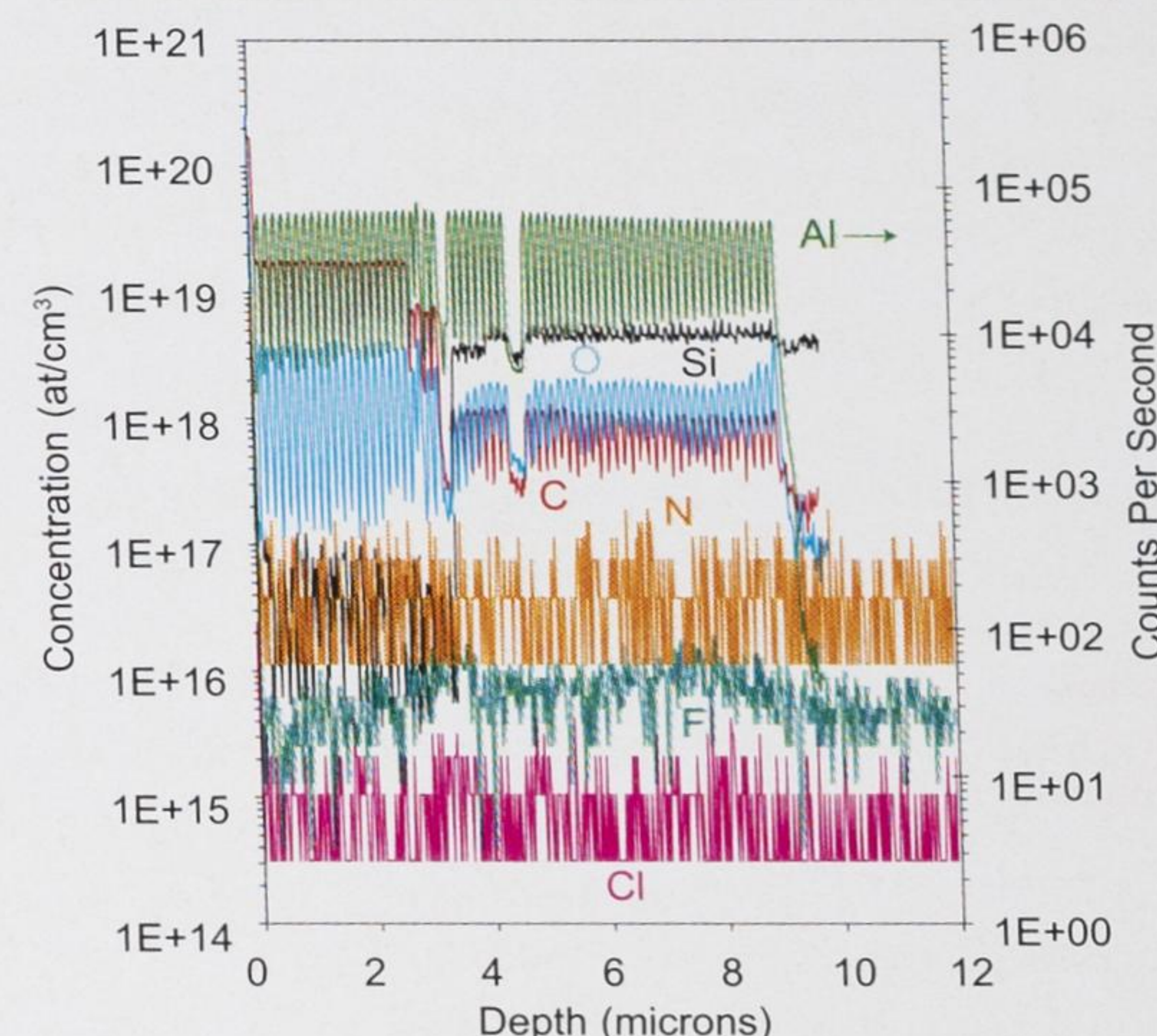
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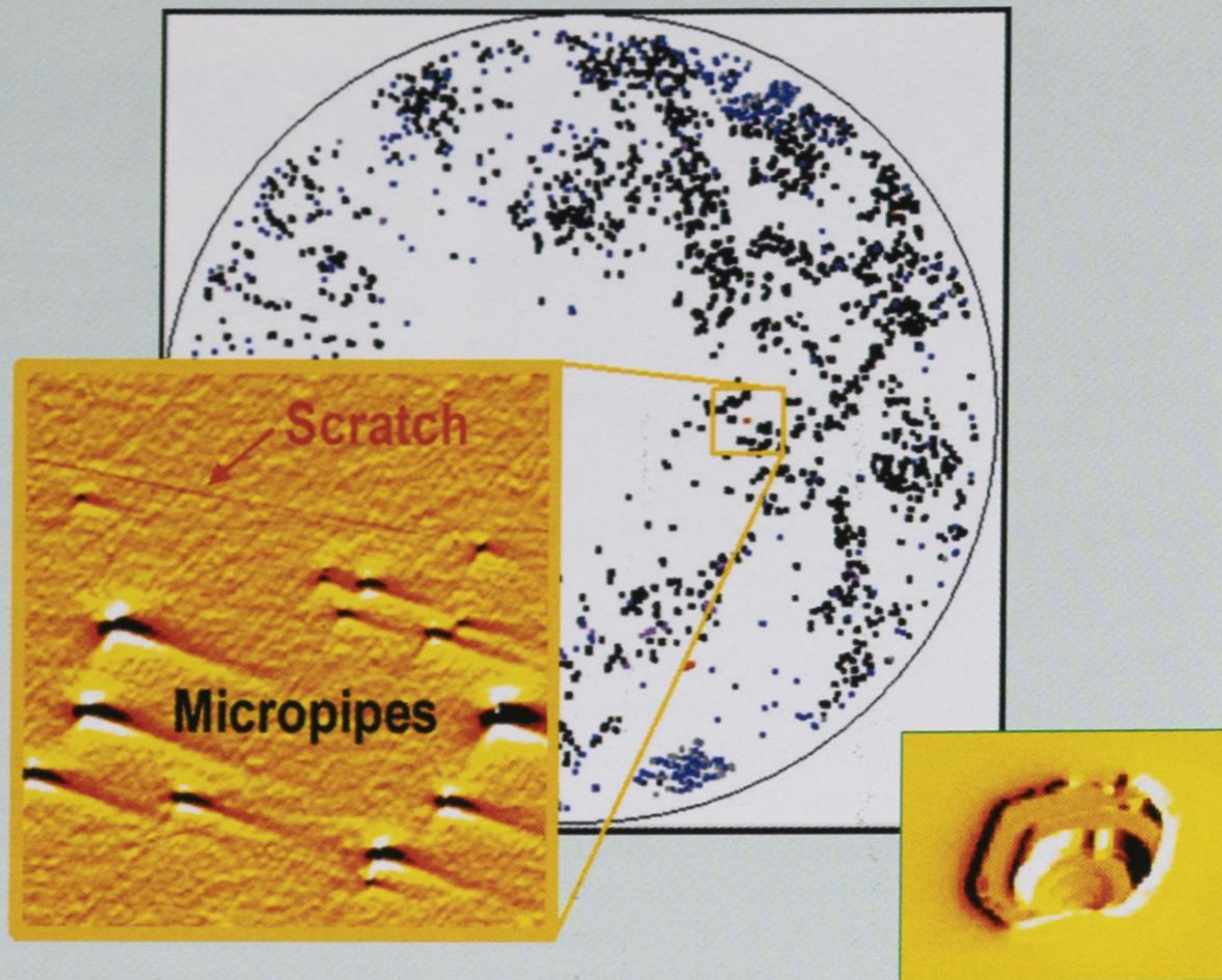
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SKYWORKS

# Skyworks weighs up capacity dilemma

Based in Woburn, MA, Skyworks Solutions plans a dramatic increase in its share of the power-amplifier market and is targeting both high-end and ultra-low-cost applications. Michael Hatcher asks **Kevin Barber** how the company will be able to meet the manufacturing demands.



**Kevin Barber** is senior vice-president and general manager of mobile platforms at Skyworks Solutions.

**MH: What is driving today's high demand for GaAs?**

**KB:** The replacement market for cellphones is increasingly driven by more complex, high-end handsets that have multimode capabilities such as W-CDMA and GPRS, or W-CDMA and EDGE. This increases not only the unit volume but also the GaAs content of PAs, as well as the volume of PHEMT switches.

Occurring simultaneously towards the lower end, the entire market is expanding at a more rapid pace than we've seen in previous years. This is the result of addressing new geographies, such as in developing countries, where cellphone penetration has been relatively low but the infrastructure is already in place. So, we have many underserved markets in the world where if the phone price can be driven to a low enough point, the entire market can expand. That is something that we've begun to see over the past year – particularly with GPRS, but also some low-end CDMA2000.

**MH: How has this affected Skyworks' GaAs fabs?**

**KB:** Utilization has remained at nearly full capacity for quite some time, while we have been increasing that capacity. For HBT products, we use a wafer foundry that

we have had a relationship with for a number of years now. We have introduced a copy-exact process that gives us both second-sourcing capability as well as flexible capacity, and that has been part of our ability to rapidly expand supply to meet demand.

We have ongoing investment [and more equipment] at both of our factories, and we are exploring other forms of capacity expansion beyond that. We have been strategically evaluating all of the alternatives for some time, including 6 inch conversions at our own fabs, as well as broader and deeper foundry relationships, and the possibility of acquiring a fab. But none of those decisions is something that we have ready to make public at this point.

**KB: What are the key issues involved in a switch to 6 inch production?**

**MH:** There are three key parameters. One is the cost of the investment versus return. Second is the time element – none of these projects occurs quickly. Third is continuity of supply – how do we ensure that a project like that satisfies our ongoing requirements? A 6 inch conversion in a wafer fab has the potential to affect our existing production. In the end, it's simply a question of finances, customer satisfaction and timeliness.

**MH: Does the use of 4 inch processing put you at a disadvantage?**

**KB:** No, I think that it is an advantage – we have a fully written-off 4 inch wafer fab. Any investment we were to make in 6 inch would come with a significant increase in our depreciation costs, without necessarily a slam-dunk benefit in terms of lower wafer costs. We have a very advantageous wafer-foundry relationship regarding cost – so we've been able to satisfy a tremendous increase in demand with an outsourced manufacturing strategy, which is balanced with high utilization of our existing low-cost wafer fab. It's hard to beat that cost profile. That's not a disadvantage – it is quite the opposite, and I think that we have a cost-structural advantage over some of our competitors.

**MH: Does the ramp-up of BiFETs strengthen the case for a conversion?**

**KB:** We make our BiFETs in California and production is ramping just now. It's still a minority of our production today, but it will increase over time. The increase in die area is not significant. The idea of larger wafers is really about needing more capacity and what is the most cost-effective and timely path to achieving that – there are many drivers.

**MH: Are you seeing strong demand for products used in ultra-low-cost (\$20–30) handsets?**

**KB:** Absolutely, we have for some time now. We have a 100% share of a Taiwanese ODM for exactly that market today and we'll continue to enjoy that business. Today, a low-end phone is a dual-band GPRS product. Our designs take out costs that are not valued by that segment of the market. Specific products for that market are optimized for dual-band-only applications, which is



"We have been strategically evaluating all alternatives... including 6 inch conversion."



**Wirebonders** in the cleanroom area of Skyworks' back-end facility in Mexicali, Mexico. The company operates two GaAs fabs, one in Newbury Park, CA, where HBTs and BiFETs are produced, and another in Woburn, MA, for PHEMT and MESFET manufacture.

quite a departure from where we were a year ago, when we really saw no value other than to ship only quad-band GPRS PAs because that's what the vast majority of the market valued. But in this very low tier, cost is everything and those additional two bands are less important.

**MH: What market-share target do you have for the PA business?**

**KB:** Our market share is 40–45% currently, and our target is well over 50% in the next two years. Overall suc-

cess will be greatly determined by our success with the top-tier vendors. Our primary focus is on them, and our ability to satisfy demand for the PA, switch and filter in complex FEMs that really address W-CDMA and EDGE. Concurrently, we have to satisfy the low-end of the market with very cost-optimized solutions.

**MH: Do you expect to see CMOS PAs taking share away from GaAs?**

**KB:** Certainly there's been lots of noise in the industry about CMOS PAs over these past couple of years. But there has been no market-share penetration because of performance and reliability, combined with no demonstrable cost advantage with CMOS. We've proved with our low-end PAs that we can deliver price-points at acceptable margins where we compete very nicely with silicon CMOS PAs.

We do see certain applications where silicon-based switches will play a role, and we are addressing that where required. But we will also continue to see PHEMTs have a big role.

**MH: What will drive your GaAs business aside from handsets?**

**KB:** I think you'll see us increasingly participate in WiMAX and wireless LAN, using GaAs technology for each of those applications. WiMAX is exciting for what could eventually be a mobile 4G standard, and you'll see us have more to say about that in the future. Cellular infrastructure has been pretty flat, and although we're hoping to see a recovery it is probably too early to say whether there is one – we'll just have to wait and see.

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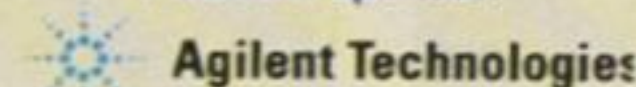
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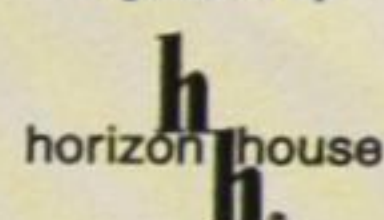
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## SHARE-PRICE SURVEY

# Compound stocks race ahead of NASDAQ

The value of nearly all publicly-owned compound semiconductor companies across the globe has raced upwards over the past year. But, asks **Michael Hatcher**, which stock outperformed the rest with a seven-fold increase in just 12 months?

## Compound semiconductor share-price leaderboard

| Rank | Company                         | Ticker          | One year ago<br>(\$ unless specified) | May 9 2006<br>(\$ unless specified) | % appreciation<br>(May 05–May 06) |
|------|---------------------------------|-----------------|---------------------------------------|-------------------------------------|-----------------------------------|
| 1    | Anadigics*                      | ANAD            | 1.26                                  | 9.06                                | 619.0                             |
| 2    | Finisar                         | FNSR            | 1.15                                  | 5.25                                | 356.5                             |
| 3    | Emcore                          | EMKR            | 3.06                                  | 12.39                               | 304.9                             |
| 4    | AXT                             | AXTI            | 1.15                                  | 4.25                                | 269.6                             |
| 5    | Riber                           | RIB (Paris)     | €0.71                                 | €2.60                               | 266.2                             |
| 6    | JDSU                            | JDSU            | 1.35                                  | 3.41                                | 152.6                             |
| 7    | IQE                             | IQE (London)    | £0.065                                | £0.161                              | 147.4                             |
| 8    | RF Micro Devices                | RFMD            | 3.77                                  | 9.07                                | 140.6                             |
| 9    | Hittite Microwave**             | HITT            | 17.50                                 | 37.95                               | 116.9                             |
| 10   | Avanex*                         | AVNX            | 1.10                                  | 2.36                                | 114.5                             |
| 11   | Veeco Instruments               | VECO            | 13.14                                 | 27.29                               | 107.7                             |
| 12   | TriQuint Semiconductor          | TQNT            | 2.90                                  | 5.47                                | 88.6                              |
| 13   | Kopin                           | KOPN            | 3.06                                  | 5.50                                | 79.7                              |
| 14   | Bookham*                        | BKHM            | 3.00                                  | 4.83                                | 61.0                              |
| 15   | Optical Communications Products | OCPI            | 1.60                                  | 2.19                                | 36.9                              |
| 16   | Aixtron                         | AIX (Frankfurt) | €2.55                                 | €3.46                               | 35.7                              |
| 17   | Skyworks Solutions              | SWKS            | 5.25                                  | 6.96                                | 32.6                              |
| 18   | Cree                            | CREE            | 24.00                                 | 31.12                               | 29.7                              |
| 19   | <b>NASDAQ composite</b>         | <b>Index</b>    | <b>1962.77</b>                        | <b>2337.83</b>                      | <b>19.1</b>                       |
| 20   | Endwave                         | ENWV            | 30.00                                 | 16.10                               | -46.3                             |

\*have made major share offerings in the past 12 months; \*\*Hittite's initial public offering was in July 2005. Source: Yahoo Finance.

As our “leaderboard” shows, all but one of the listed stocks has outperformed the NASDAQ composite index of technology companies (itself up 19%) over the past year. The companies are ranked according to share-price appreciation between May 9 2005 and May 9 2006. More than half the stocks doubled in value, while three of them more than quadrupled. For IQE, Riber and Aixtron, no adjustment for currency fluctuations have been made.

After a generally dismal performance following the false dawn of late 2003 to early 2004, compound semiconductor stocks suddenly seemed to be one of the hottest investments in town until a widespread sell-off hit the markets in late May.

Admittedly, many of those stocks could not have fallen much further without prompting the interest of NASDAQ's de-listing enforcers, but it is fair to say that a dollar invested in almost any stock relating to compound chip technology one year ago would have brought excellent returns and, in most cases, investors would have doubled their money.

The one exception is Endwave, the RF sub-system specialist based in southern California, whose value peaked in mid-2005 and then crashed as Northrop Grumman, its major shareholder, sold off vast quantities of stock. Each dollar invested in Endwave in early May 2005 was worth only 54 cents a year later, although the company's finances now appear to be improving with solid orders from wireless infrastructure divisions at major players including Siemens, Nera Networks and Nokia.

But Endwave is very much the exception. At the other end of the scale, any investors in RFIC maker Anadigics will have been very happy with their return. After miss-

ing the HBT boat back in the late 1990s, the Warren, NJ, firm – which outsources its epitaxy – has at last begun to recover that lost ground in the cell-phone market following the recent strong uptake of high-end handsets. Anadigics' fab is now filling up fast to produce integrated transistor structures with combined HBT and PHEMT processes, as the devices find widespread use in multi-band power amplifiers and switches.

As our leaderboard shows, Anadigics was comfortably the III-V industry's top-performing stock from May 2005 to May 2006. Every dollar invested would have brought a return of more than seven as the stock price reached the dizzy heights of \$9.18. Although that value was almost seen in early 2004, you have to go back four years to June 2002 to find the last time that the stock breached \$10. And even though the widespread tumble in the stock market has hit all the III-V valuations since May 9, Anadigics has stayed strong.

The second-best performer in our league, Finisar, has proved to be the outstanding supplier in the ever-turbulent fiber-optic components market, and, like Anadigics, its value has risen steadily over the past 12 months to reach a four-year high. During that time the Finisar business has changed massively, through the acquisition of



Every dollar invested in Anadigics would have brought a return of more than seven.

Honeywell's Advanced Optical Components division, the world's top 850 nm VCSEL producer, and much of Infineon's former fiber-optic unit.

That metamorphosis has seen the Fremont, CA, firm, which has two compound semiconductor fabs, emerge as a key player in the datacoms sector of the optical components business. Growing demand for datacoms parts to meet the requirements of bandwidth-devouring applications like video delivery over IP networks is the chief reason for this, and Finisar has now indicated it is investing in extra capacity at its InP fab in Fremont as a result.

Back in early March, Finisar's stock soared in value with better-than-expected financial results. This seemed to have a favorable knock-on effect on fellow component makers Avanex and Bookham. In fact, if we'd conducted our survey from April 2005 to April 2006, Bookham's stock would have been the top performer. Unlike Finisar's sustained increases, Bookham's spike to nearly \$10 proved short-lived, and its value had halved at the time of writing after it revealed that profit margins had been hit by a shift in its product sales mix. The distinction between Finisar and Bookham is one of the subtleties of the fiber-optic communications business. Demand for components used in datacoms is quickly filling Finisar's fabs, whereas Bookham's InP facility remains largely underutilized because demand for components used in longer-haul telecom applications is rather slack in comparison. And fab utilization is seen as the biggest factor determining financial health for any III-V device manufacturer.

Nevertheless, good vibes surround communications

in general, as applications such as voice-over IP, video on-demand and internet TV delivery begin to take root in public consciousness, and 3G phones sell like hot cakes. The bigger market picture looks good for the likes of Bookham, and investors in the firm will have seen an increase of 60% in share value over the past year, despite the more recent knock-back. The big question for Bookham investors now is whether it can fill its chip fab by exploiting the growing market with convincing product launches that can be scaled up to volume production.

This revival in fortunes – in terms of share valuations and market capitalization, if not quite yet in revenue and profit figures – is not limited to device manufacturers. The top-five performers listed in our survey include substrate manufacturer AXT and French MBE equipment vendor Riber, both of which have near-quadrupled in market value. Emcore, whose rapid ascent was charted in our March 2006 "Portfolio", has continued its upward trend and in early May it sailed past the \$12 target price set by Jefferies and Company analyst John Lau, before it was hit by the dip in mid-late May.

With Emcore benefiting from the surge in demand for both its GaAs HBT material and fiber-optic components, as well as the buzz of expectation surrounding terrestrial photovoltaics, Lau revised his target to \$16.

Increased share valuations often precede a period of good financial performance where it really matters – on the bottom line. Though wary of another "bubble", most investors in III-V stocks will be rubbing their hands in anticipation of further gains.



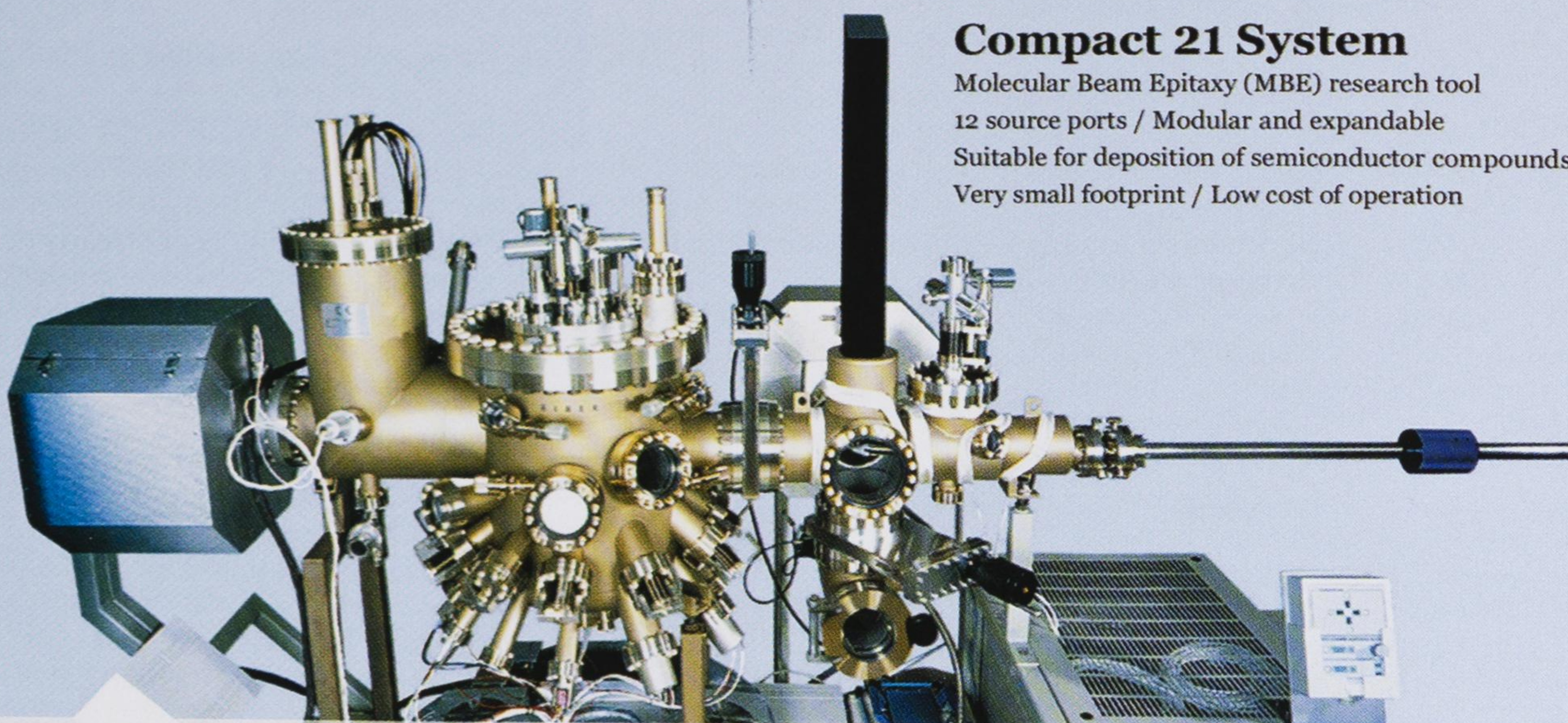
**Michael Hatcher**

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

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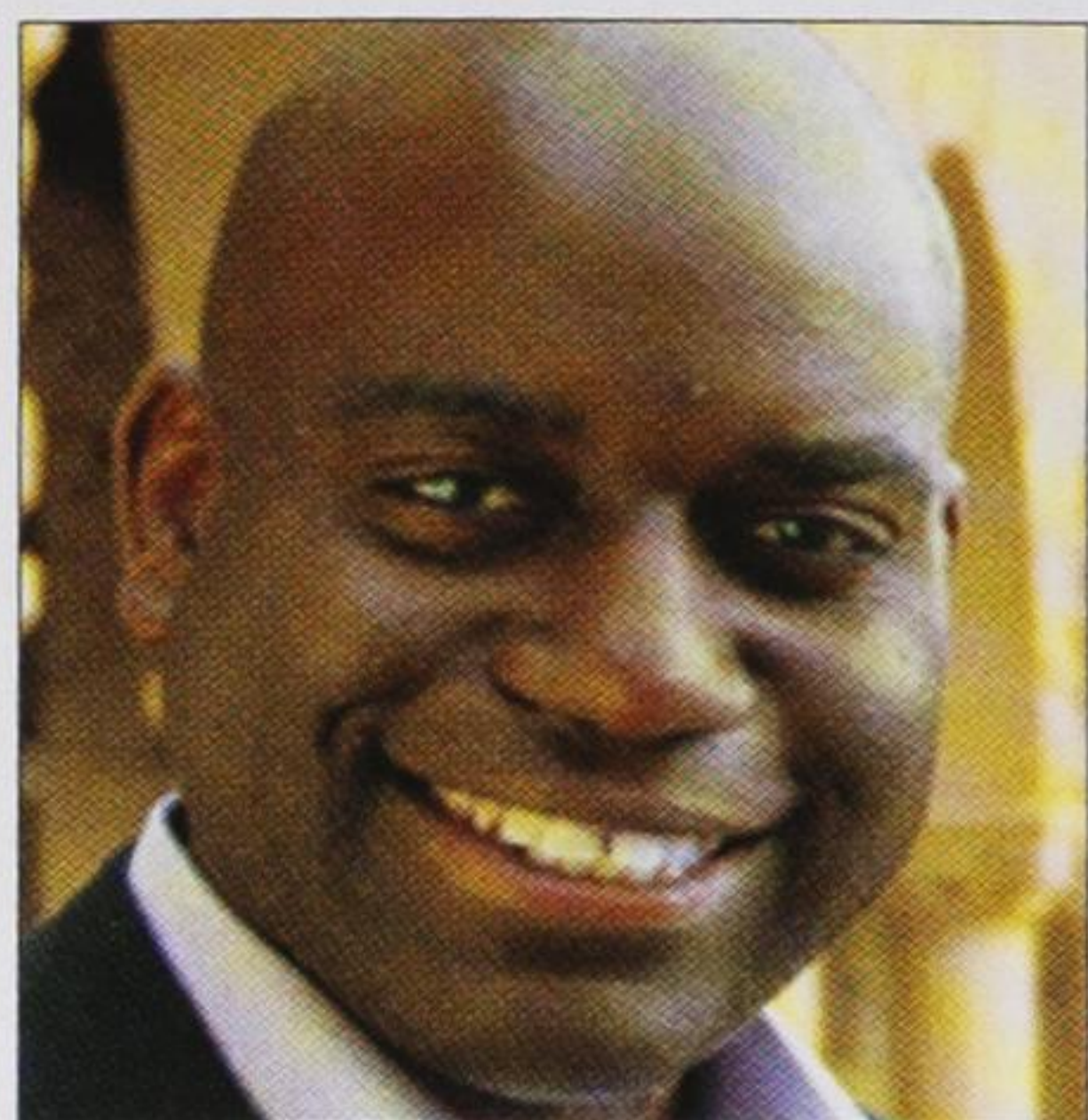
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## START-UPS

# Self-funding: building a business without the venture capitalists



## Felix Ejeckam: the CV

**1992** Electrical and computer engineering degree, Rice University.

**1994** Electrical engineering masters degree, Cornell University.

**1997** Electrical engineering PhD, Cornell University.

**1997–1998** Associate at McKinsey & Company.

**1998** Co-founder and CEO of Nova Crystals.

**2003** Nova Crystals acquired by Gemfire; co-founder and CEO of Group4 Labs.

Want to start up a new company, but worried about taking on financing from venture capitalists? **Felix Ejeckam** from GaN-on-diamond specialist Group4 Labs offers some words of advice.

When I was asked to write a column on building a business without venture capital, I thought it might directly and erroneously imply that we were already massively successful and have no need for continued funding. But then I realized that a lot of budding young entrepreneurs out there might benefit from our experience at Group4.

Three years since first registering Group4 Labs, LLC in California, our story is still unfolding. Though absolutely froth with the risky perils that plague all small companies, we have managed to become a successful, self-funded business without the benefits of traditional venture capital. In the US, venture capital (VC) is an incredible business-building tool that is almost without parallel in its ability to create substantial value quickly, efficiently and effectively. For those companies without the targeted billion-dollar market size, ace management team, all-cancer-curing product, or access to Svengali VCs, there are some funding alternatives to consider, while retaining the option to go out for VC funding later.

Our first source of financing in 2003 was (and still is) the would-be customer. We decided early on that we would not commence product development unless we could find a potential customer interested in co-funding it at an early stage. Our reasoning was simple: if we couldn't find a seed customer, we likely had one or more of a number of problems. Perhaps our proposed product was not strategically valuable enough. This might be due to a long product development time (five to seven years). The product may only be slightly more valuable than existing products, in which case a lump-sum investment for development would be unnecessary, too risky, or too small compared with expected returns.

A second possibility is that the market potential is limited, so what better time to get this direct and valuable feedback for a product idea than at the inception of its development? Thirdly, when there is significant competition in the market for the proposed product, the customer may still say: "Yes, please do develop such and such; we'll buy it." This off-handed remark may belie their knowledge of fast-encroaching competitors who are poised to quickly bring their product to market.

At Group4, we found that development funding from a would-be customer is a very good way to test their product adoption appetite. Many of our early product ideas were rejected outright by customers for development funding even though they liked the product. We always insisted that funding be paid according to a milestone-pegged plan, so that the risks for both parties could be reduced. In one regrettable instance, we stopped prod-

uct development after the customer had already begun funding because our due diligence revealed that we could not ultimately penetrate valuable market segments.

We have found that keeping the funding requests to \$100,000–\$200,000 per customer works well. The smaller the amount the easier it is for large companies to secure management approval. Several of these deals then aggregate to a substantial sum. But an important question arises: what does the customer get for funding development at this early stage? Typically, we have offered exclusive sourcing for a year or more, joint ownership of future intellectual property, substantially discounted pricing terms for one to two years, small quantity sampling for small funding amounts, etc. In other instances we simply asked the customer what they would prefer and negotiated.

Our second funding source has been the US government's various small-business initiatives (e.g. the small-business innovation research programs from the National Institutes of Health [NIH], the US Air Force, etc) and DARPA programs. This can be a slow way to get started, as lead times to fund can be months to years. However, once good development progress is made, further support is reasonably assured. In securing government funding we were keen to find strong overlaps between the needs of various government agencies, the commercial market needs, and Group4's particular products and strategic objectives. We also liked the government's investments because it might also become a customer. We did receive a lot of rejection early on, but we applied often and spoke with numerous program managers. In time, we received positive award letters and did our best to deliver on the original promise.

Our other focus has been on spending. In other words, we worked hard to be lean. If we received only \$500,000 in a year, we had to be highly critical about how to spend those funds to achieve development objectives as well as lay solid foundations for growth. Talented hires in this phase are more meagerly-paid guru prophets than fully-paid principal engineers. Since there is no VC, ample equity is available for recruiting. Lean firms also force heroic levels of creativity in product innovation and manufacturing. Such creativity can pay huge dividends later when spend budget grows.

Today, we're growing rapidly and grateful for all the support we've received over the last few years from our strategic partners and the US government. We expect to enter into more creative and strategic deals in the months and years to come, as we unveil more ground-breaking extreme materials for advanced electronics markets.

Group4 Labs came out of stealth mode in February 2006, and has since publicly announced three GaN-on-diamond wafers for commercial and military applications. Visit [www.group4labs.com](http://www.group4labs.com) for more details.



# Interferometry speeds sur

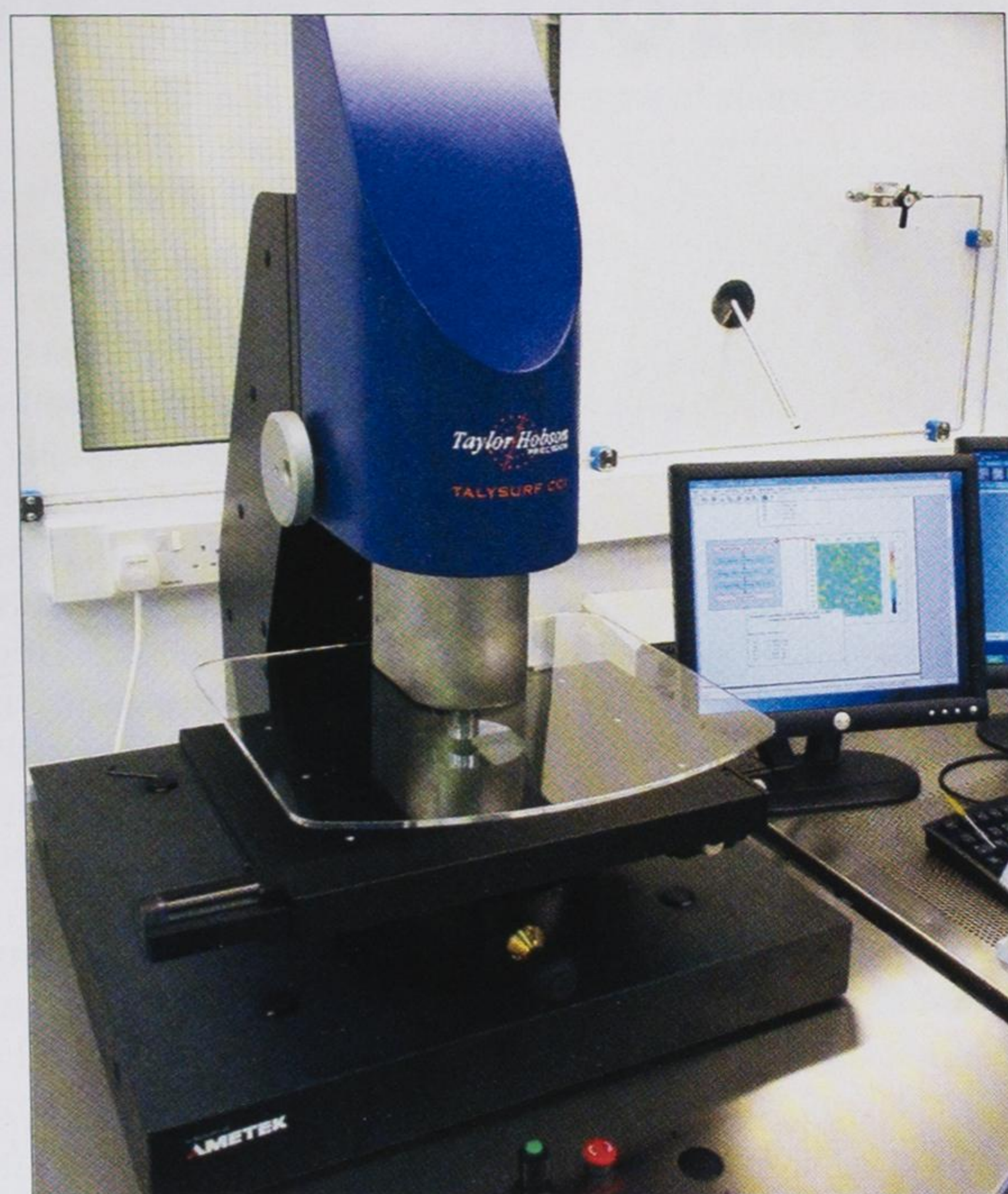
Atomic force microscopy is the standard technique for determining semiconductor surface roughnesses. But there is an easier-to-use alternative, white-light interferometry, which can deliver the same height resolution while imaging larger areas at far faster rates, argues IQE's **Roy Blunt**.

Surface roughness is an important parameter for gauging semiconductor material quality, but it is rarely measured quantitatively. This is because the technique often used for quantitative analysis – atomic force microscopy (AFM) – is poorly suited to production environments if we discount the expensive fully automated systems that are only practical in large silicon device lines. So instead, assessments are usually carried out with either qualitative techniques such as Nomarski interference microscopy, or inferred from optical scatterometry methods.

However, there is another technique that can routinely provide quantitative roughness measurements and surface images – white-light interferometry (see “White-light interferometry” box on p21 for a detailed explanation). This method is well established and has been used for many years to obtain contactless measurement of step height or similar parameters (see figure 1). However, recent advances in instrumentation software have improved the height resolution of today's white-light interferometers to a level comparable with that of an AFM.

For example, the Taylor Hobson CCI 3000A interferometer we have employed at IQE can determine the surface position with a vertical resolution of 0.01 nm by using a patented correlation algorithm to locate the coherence peak and phase position of an interference pattern produced by a white light source. This coherence correlation interferometry (CCI) technique is sufficient to measure roughness levels on many semiconductor samples, since these materials have a roughness of typically 0.1–1 nm. Lateral resolution is still significantly inferior to an AFM and is diffraction-limited to 0.35  $\mu\text{m}$ , which defines the maximum lateral magnification. However, for practical production measurements of semiconductor samples this limitation is not significant, while it is an advantage to be able to measure larger areas than those imaged by an AFM.

We assessed our Taylor Hobson interferometer by mounting it on a passive anti-vibration table and using it to image GaAs and InP-based substrates and epi-wafers. All these measurements used a “ $\times 50$ ” objective lens with a working distance of 3.4 mm. This magnification provides the maximum lateral resolution over an imaged area of 280  $\mu\text{m}$  when using a 1024  $\times$  1024 pixel CCD array. The instrument can also be used with lower

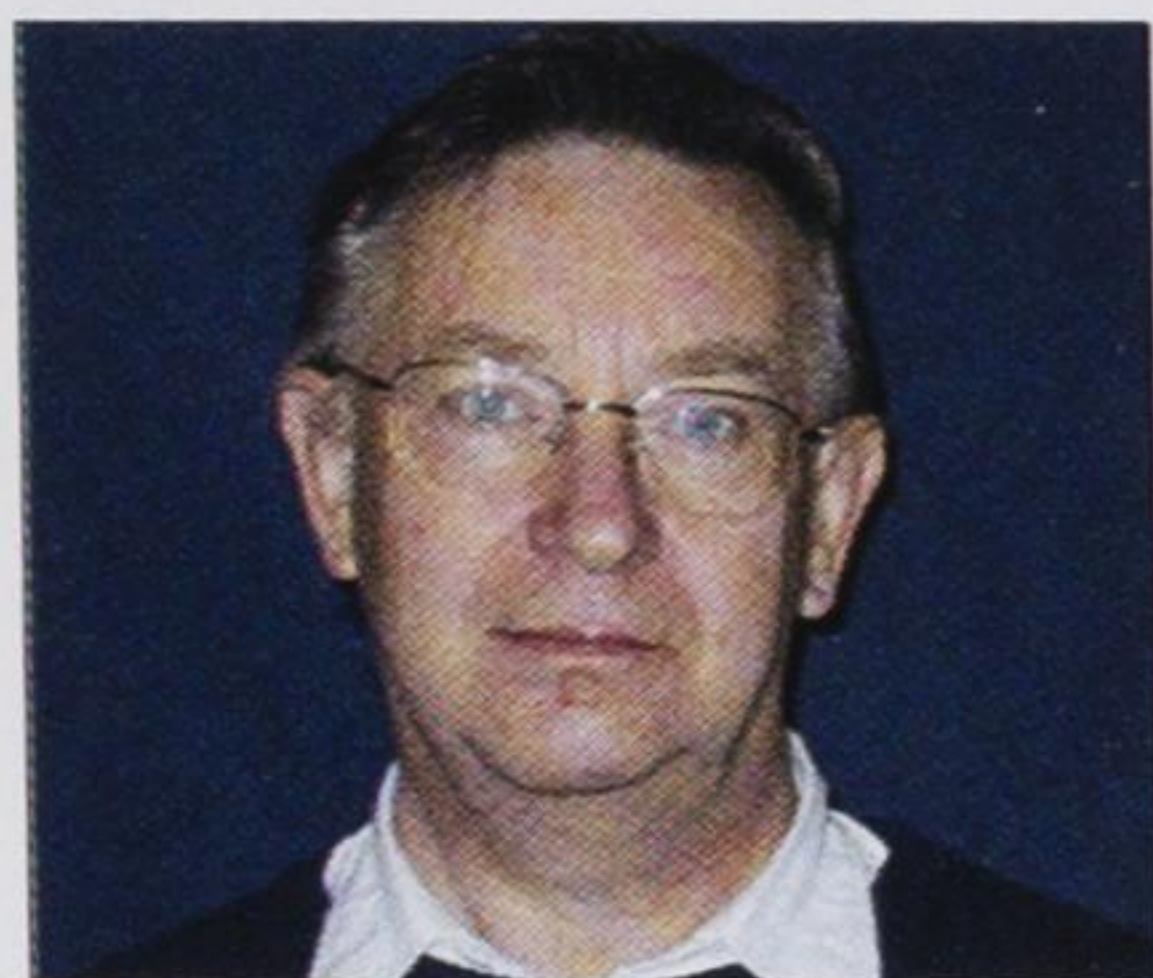


**The Taylor Hobson** white-light interferometer is similar in size and shape to a high-quality microscope, and can produce surface-roughness measurements on a wide variety of semiconductor samples with a height resolution of 0.01 nm.

magnification lenses to image areas up to 7 mm  $\times$  7 mm, but this reduces the lateral resolution.

Plan-view images of both a part-polished and a fully polished GaAs semiconductor substrate are shown in figure 2. They reveal the residual damage left on the part-polished GaAs substrate by the sawing process that creates individual substrates from the bulk single crystal. This part-polished substrate has a root mean square (RMS) roughness of 0.36 nm, and distinctive, pronounced sharp features associated with saw damage. The fully polished production substrate (see figure 2b) has a much lower RMS surface roughness of 0.16 nm. This image is indicative of most high-quality conventional semiconductor surfaces – a blotchy background with a few sharp features.

The method used for acquiring these images is straightforward, and the skills required are similar to those needed for operating a normal optical microscope. Setup time is short and the images in figure 2 took just 90 seconds to acquire. In comparison, an AFM image on a smaller area of a similar sample would have required approximately 15 minutes of measurement time and a similar setup time. It would have also involved contact between the sample and probe, and required a skilled and experienced operator to ensure a trustworthy result.

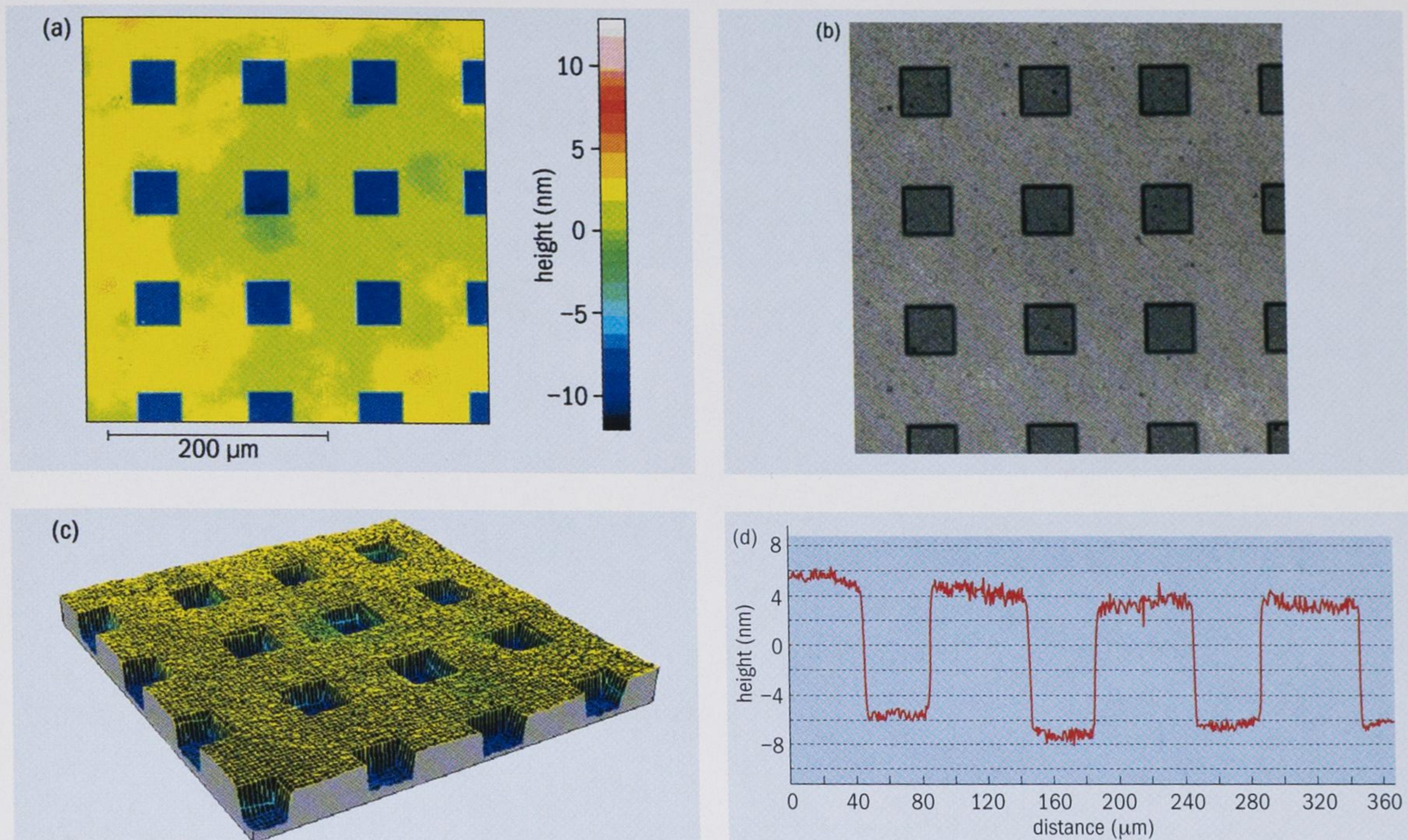


#### About the author

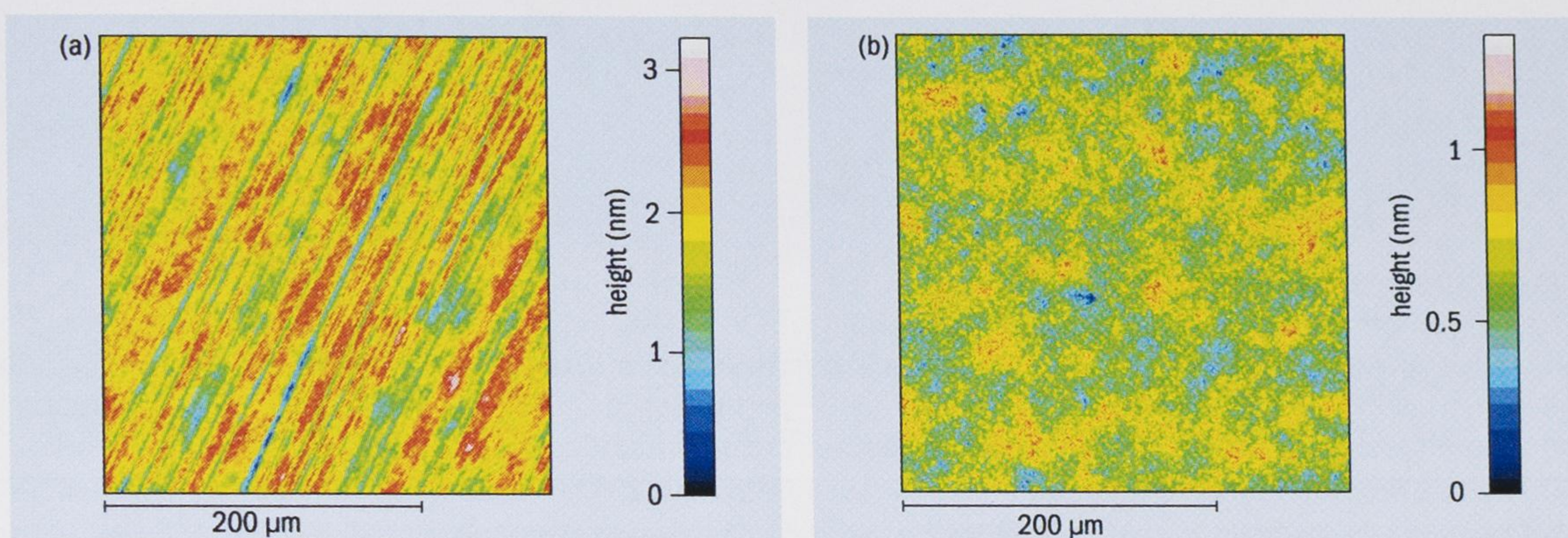
**Roy Blunt (Rblunt@IQEP.com)** was a member of the original start-up team at Epitaxial Products International (EPI) Cardiff, now IQE Europe, and currently manages the company's characterization projects. Prior to joining IQE he worked at Plessey Research in Caswell, UK, for 19 years.



# Surface-roughness analysis



**Fig. 1.** White-light interferometry instruments have been used for many years to produce contactless images of step height, and can provide images of 10 nm-deep etched pits in a semiconductor sample in 10 seconds. A false-color plan image of the surface, the basic image type produced by white-light interference microscopy, is shown in (a). This image contains all the vertical and lateral data required to describe the surface completely, so it can also produce a simulated microphotograph of the surface (b), a computed three-dimensional image (c), and a profile across the horizontal center of the image (d).



**Fig. 2.** White-light interferometry can reveal the scratches in the part-polished substrate left by the sawing process that is used to cut individual substrates from the crystal boule (a). These imperfections can be removed by a chemical-mechanical process, to leave an atomically flat surface (b).

## Imaging PIN structures

High-quality epitaxial layers, particularly if they are thin, produce only small changes in surface characteristics compared with the underlying platform when grown on production-quality substrates. For example, the surface roughness of an InP/InGaAs/InP PIN structure with a total thickness of 5  $\mu\text{m}$  is very similar to that of its substrate (see figure 3a, p21). The low-roughness surfaces are produced by maintaining growth conditions within required, carefully chosen limits. However, any significant variation in the growth conditions, or a switch to inferior substrates, can impair the surface quality and increase its roughness (see figure 3b, p21).

White-light interferometry can also reveal the details

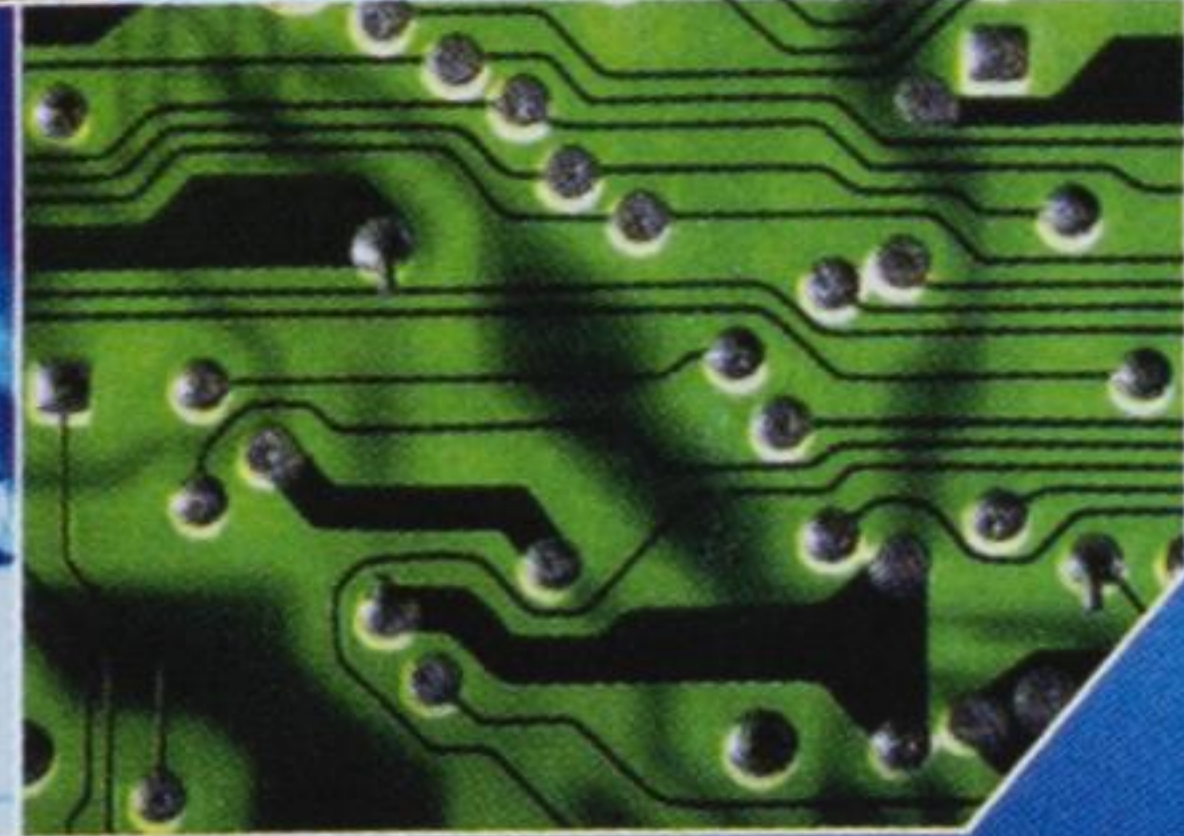
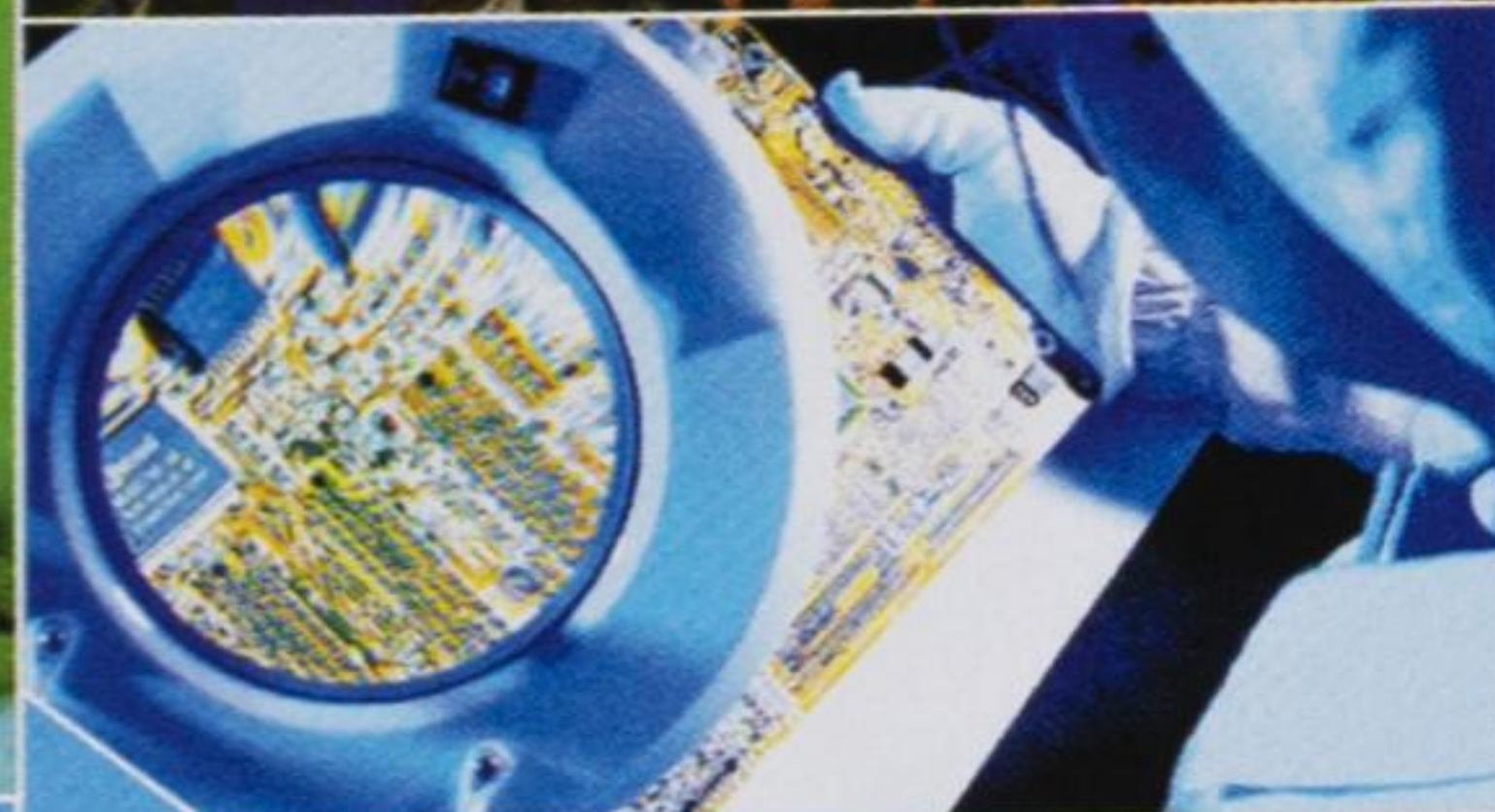
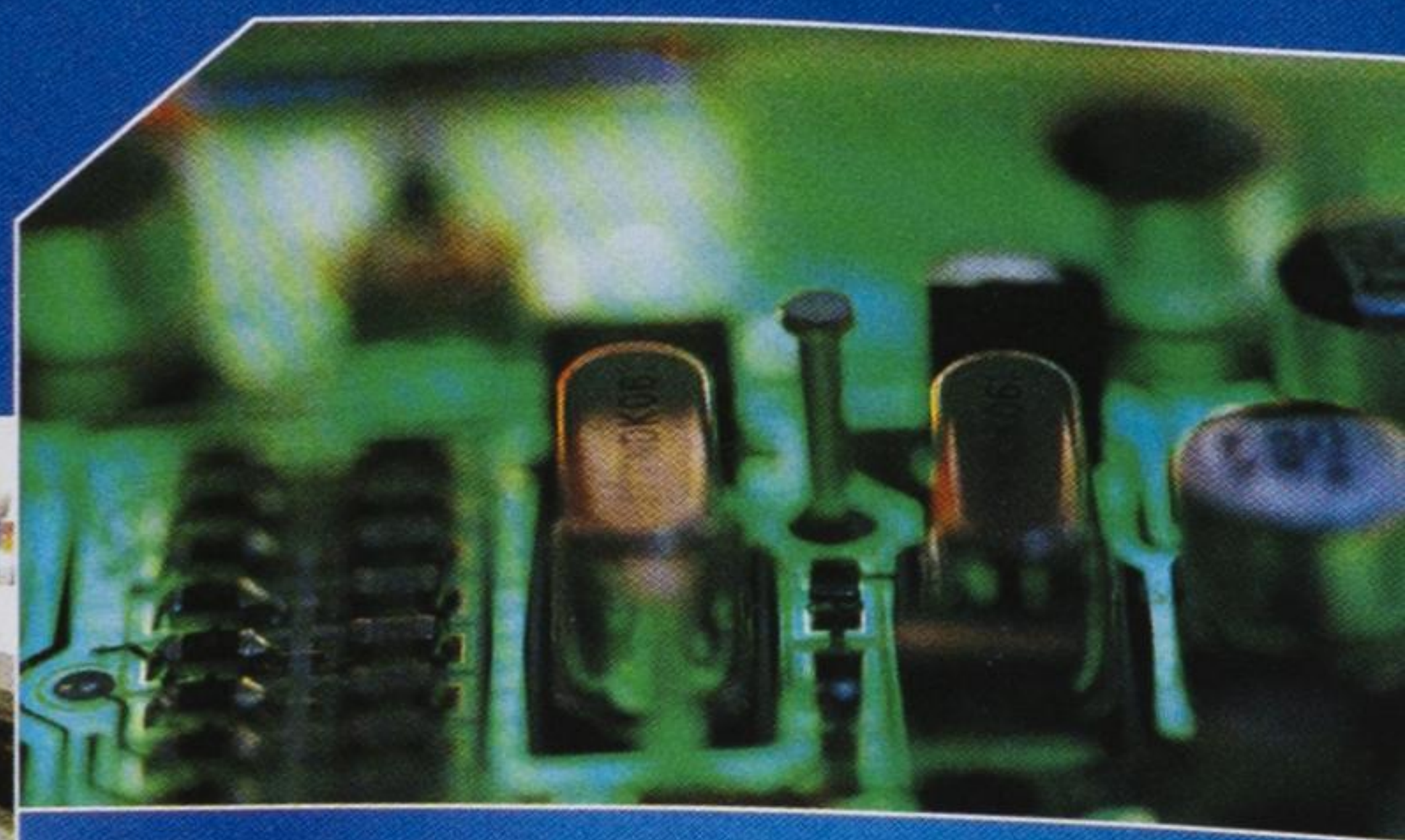
in the surface of structures incorporating material with a higher strain. For example, the technique can expose the orthogonal features in relaxed lattice-mismatched long-wavelength (2.2  $\mu\text{m}$ ) InGaAs PIN structures grown on InP substrates.

Direct quantitative comparisons between the surface-roughness measurements produced by AFM and white-light interferometry is difficult. Each technique has its own advantages and disadvantages, and produces its best results with different-sized lateral areas. For example, the white-light interferometry measurements presented here have been taken over  $280 \times 280 \mu\text{m}$  areas – 30 times larger than the standard maximum area for AFM measurements ( $50 \times 50 \mu\text{m}$ ). In addition, each method has a different lateral resolu-



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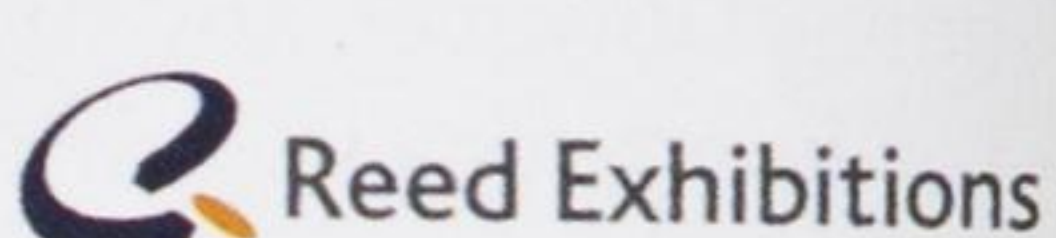
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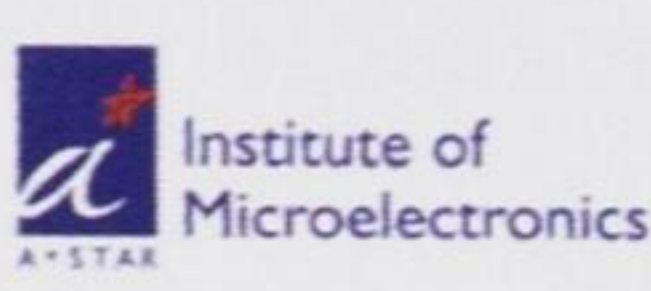
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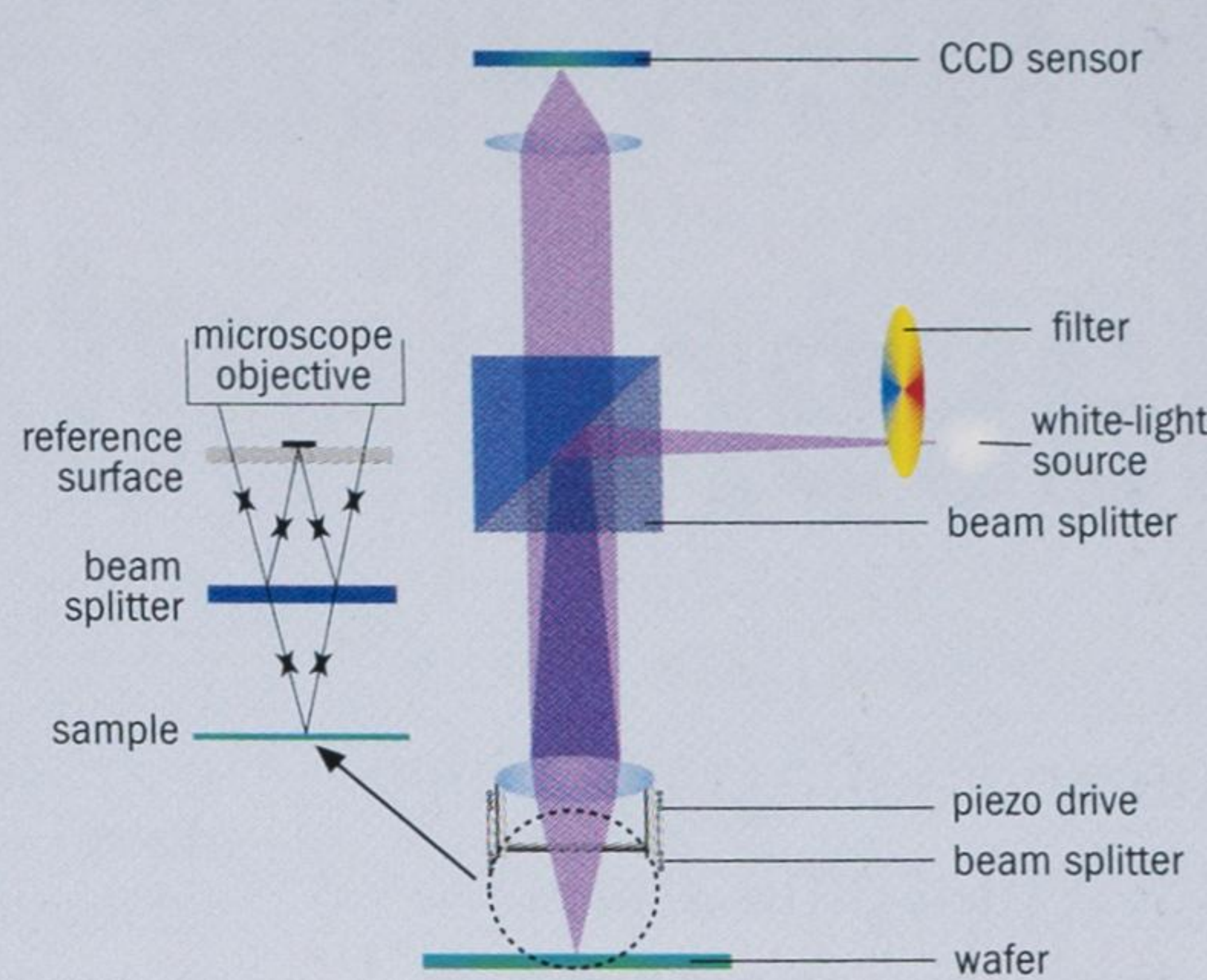


## White-light interferometry

Interferometry involves splitting a single beam of light into two sources. One beam, known as the sample beam, is either passed through or reflected from the object to be measured, while the other, the reference beam, follows a known and constant optical path. These beams are then recombined to produce light with an intensity that depends on the phase difference between the two optical paths.

This effect is responsible for the “Newton’s rings” that are produced when a convex lens is placed on a flat glass surface and observed from above using monochromatic light. The different optical path lengths taken by rays of light reflecting from the curved bottom surface of the lens and the flat glass surface produces alternating light and dark concentric rings centered on the point of contact.

Interferometers operate in a very similar fashion, with the bottom surface of the lens replaced with a sample and the flat glass swapped for a reference surface. However, there is no physical contact between the key components. This approach can provide surface height variation measurements across a whole wafer that normally involve little, if any, lateral magnification of the images. The downside of this method is that it is not absolute – it only



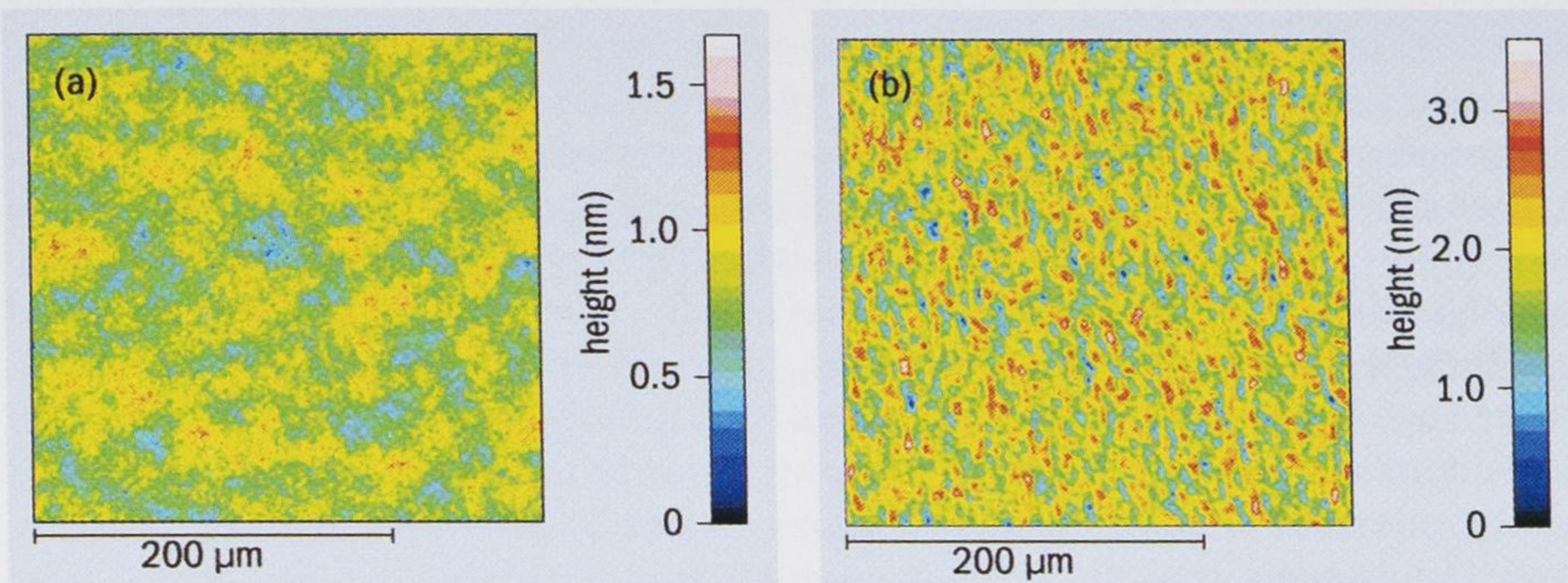
compares the flatness of the sample with that of a reference surface, which means that the reference surface must be much flatter than the sample.

The same principle can be used in a microscope arrangement (see image above). Here, a light source provides a beam that is reflected by the upper beam splitter into the objective lens. The lower beam splitter divides and combines the light beams reflected from the sample surface and the reference surface using a “Mirau” interferometer arrangement. This produces an interference pattern of light and dark fringes, known as an interferogram, which is

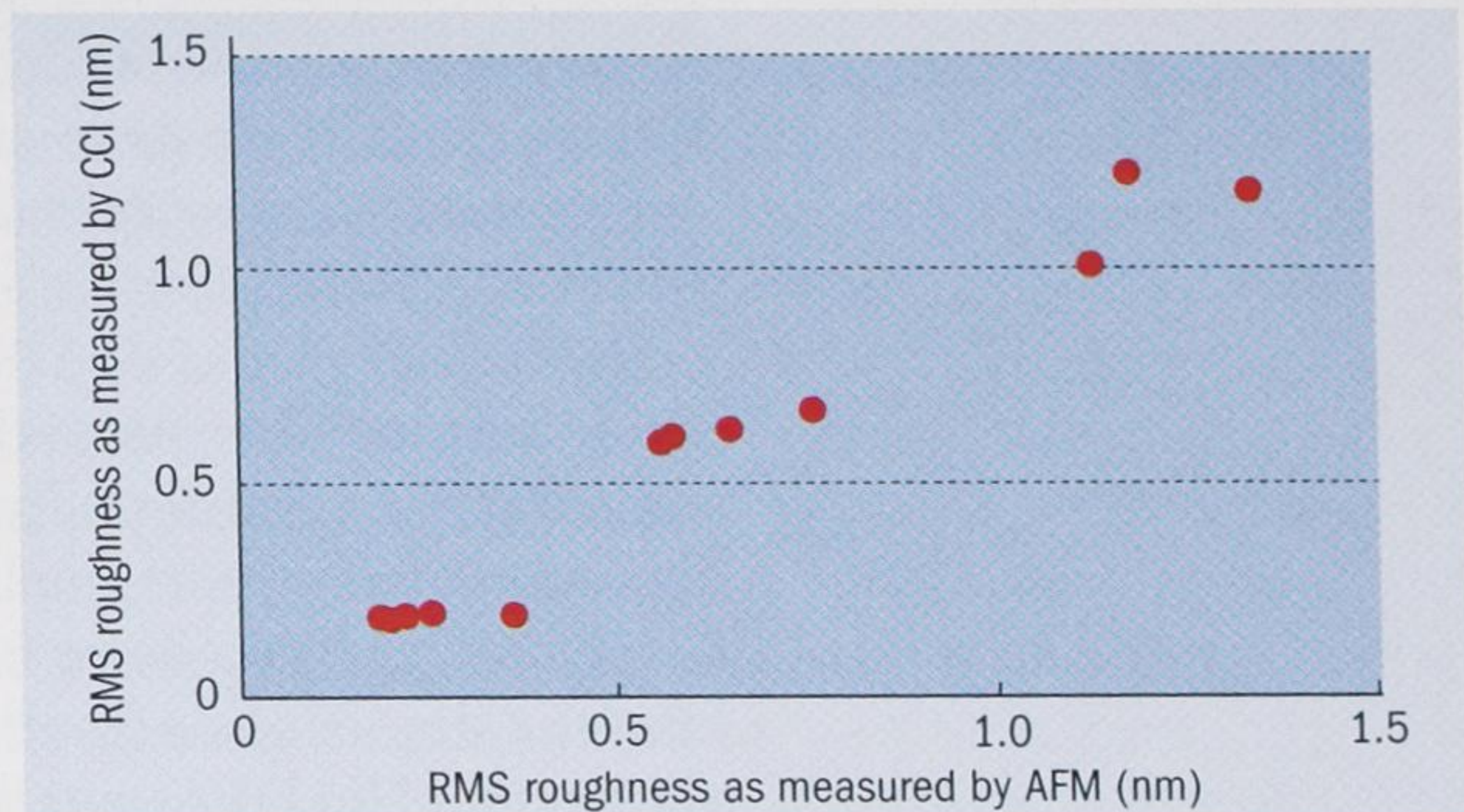
magnified by the microscope optics and imaged onto the CCD camera.

This image would not be particularly useful in itself, because it would only reveal differences in the distance between the reference and the sample. However, if the objective lens assembly is scanned vertically using a piezoelectric drive, then it is possible to find the point at which maximum constructive interference occurs and the image is at its brightest. Provided the movement of the lens can be accurately tracked, it is possible to generate a three-dimensional map of the sample surface by measuring the lens position required to produce the brightest image at each point on the CCD array.

This approach could be carried out with monochromatic light, such as that from a laser, but there are several different heights that correspond to a maximum in the signal. However, if multiple wavelengths are used, with white light providing the ultimate broadband source, the system can then be configured to produce a maximum optical signal at just one point. The only factor then limiting the height resolution is the quality of the measurement algorithm to define the maximum brightness (or, in most cases, peak intensity modulation), which in turn defines the surface position.



**Fig. 3.** If the growth conditions for the production of InGaAs-based PINs on InP substrates are maintained within carefully chosen limits, then epiwafers can be produced with very smooth surfaces (a). Deviation from these limits impairs the surface and increases the RMS surface roughness from 0.14 to 0.35 nm (b).



**Fig. 4.** The good correlation between surface-roughness measurements obtained by atomic force microscopy (AFM) and white-light interferometry (CCI) supports the validity of the latter technique.

tion, data analysis and filtering techniques, making rigorous comparisons very complex.

Despite these drawbacks, we found good agreement between AFM and white-light measurements using the CCI technique for a range of semiconductor samples with a roughness between 0.1 and 1.5 nm (see figure 4). Because CCI measurements, unlike those made by AFM, are completely contactless, repeated measurements can also be made to establish reproducibility. These measurements have been very stable with time, showing a  $\pm 0.01$  nm deviation on an average roughness of 0.15 nm that befits a production-worthy technique.

This stability, allied to a height resolution that is

comparable to that of an AFM, but with a faster, non-contact approach, makes the technique well suited to a cleanroom production environment.

### Acknowledgements

This work is part of a project entitled “Semiconductor and Optical Layer Analysis and Definition using Interference Microscopy (SOLADIM)”, which is funded by the UK Department of Trade and Industry’s Micro- and Nano-Technologies Applied Research Program. The other partners in the project are Applied Multilayers, Taylor Hobson, the Centre for Precision Technologies at the University of Huddersfield and the National Physical Laboratory.



# Nichia eyes new markets with expanded laser-diode portfolio

Nichia has developed ultraviolet, blue and aquamarine high-power laser diodes that offer compact replacements for mercury lamps and argon-ion lasers and have the same structure as its 405 nm emitters. **Richard Stevenson** reports.



**Nichia's research and development** facilities include single-crystal growth equipment, scanning electron microscopes, Auger electron spectroscopy systems, and LED reliability test racks.

Over a decade has passed since Nichia first demonstrated pulsed emission from an InGaN laser diode. In the intervening years the lifetime and output of these violet emitters has been improved, to such an extent that the devices are finally set to enter volume production for HD DVD and Blu-ray Disc players, as well as Sony's PlayStation 3 games console.

Nichia is obviously keen to grab a large share of this market, but it has also been developing laser diodes that span from the ultraviolet to the aquamarine region of the spectrum. This could dramatically increase the number of addressable markets for the company's high-power diodes, as 365 nm ultraviolet emitters can be used for curing applications that have previously been served by high-pressure mercury lamps, while blue lasers can feature in full-color laser displays, and aquamarine diodes can offer a more compact alternative to argon-ion lasers that are often used for spectroscopy.

All of these laser diodes have the same basic structure, which is shown in figure 1. They were first grown on sapphire substrates using the epitaxial layer over growth (ELOG) technique to reduce defect density, but more recently they have been fabricated with a mixture of Nichia's own and commercially available n-

type free-standing GaN substrates. This switch has produced several benefits for high-power laser diodes, including lower resistance and more straightforward processing, as laser cavities can be formed by cleaving instead of reactive ion etching.

The benefits of using native substrates can be seen in the improved performance of many of Nichia's lasers diodes, including the company's 365 nm emitters. These ultraviolet sources have trailed the performance of their 405 nm cousins, because the additional aluminum content that is needed to shift the emission wavelength increases the strain in the epiwafers, generating cracks and dislocations.

The latest UV lasers feature a buried-ridge geometry, reflective coatings on the front and rear facets, and an n-type electrode that is formed by evaporation onto the bottom of the n-type substrate. The devices produce 20 mW continuous-wave output under a drive current of 76 mA and an operating voltage of 5 V. The lifetime, which is defined as the time taken for the diode's operating current to reach 1.3 times its initial value, has been estimated at more than 10,000 h following device operation lasting 1500 h. In comparison, the GaN-on-sapphire devices had a lifetime of only 2000 h when delivering 3 mW at 25 °C.

Nichia has also been improving the performance of its blue laser diodes. These devices are needed to complete the line-up in full-color laser display systems that can feature high-power red emitters, and green lasers created through second-harmonic generation that are already commercially available. Until recently, blue laser diodes operating in the 440–460 nm window were unable to deliver the output power and reliability for this application, but Nichia has recently demonstrated 445 nm emitters producing 200 mW and it will release lasers operating at this wavelength later this year. Encouragingly for this emerging application area, surface-emitting laser developer Novalux has sealed a supply deal with display giant Epson. Its red, green and blue chips will be used to power the Japanese company's market-leading LCD projectors.

## Blue to aquamarine

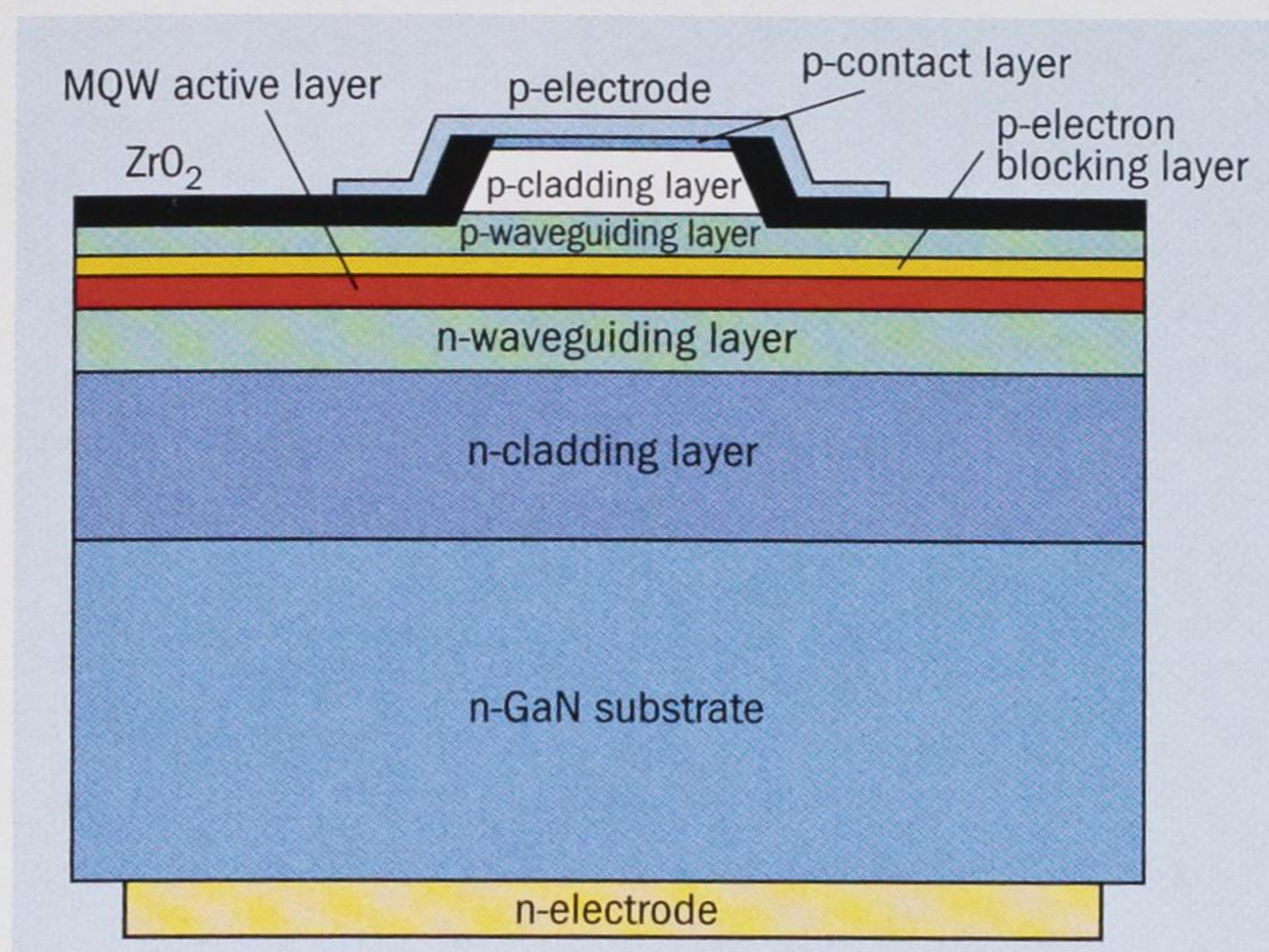
Nichia has been developing both single-transverse-mode and multi-transverse mode formats of its 445 nm emitters. The singlemode devices have a  $2 \times 1 \mu\text{m}$  aperture, can deliver a continuous-wave output of 50 mW at room temperature, and have an estimated lifetime of more than 10,000 h. Their multimode coun-



## Nichia's laser-diode structures

| Regions of the device     | Ultraviolet lasers (375 nm)                                                                                                                                                               | Violet lasers (405 nm)                                                                                      | Blue lasers (445 nm)                                                                                                                                                                                                 |
|---------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| p-contact layer           | 15 nm GaN                                                                                                                                                                                 | 15 nm GaN                                                                                                   | 15 nm Mg-doped GaN                                                                                                                                                                                                   |
| p-cladding layer          | a superlattice of 100 pairs of 2.5 nm-thick Mg-doped $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ and undoped 2.5 nm-thick $\text{Al}_{0.13}\text{Ga}_{0.87}\text{N}$                       | a superlattice of 100 pairs of 2.5 nm-thick Mg-doped AlGa <sub>N</sub> and undoped 2.5 nm-thick GaN         | a superlattice of 100 pairs of 2.5 nm-thick Mg-doped GaN and 2.5 nm-thick undoped $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$                                                                                         |
| p-waveguide               | 0.15 $\mu\text{m}$ -thick undoped $\text{In}_{0.06}\text{Ga}_{0.94}\text{N}$                                                                                                              | 0.15 $\mu\text{m}$ undoped GaN                                                                              | 0.3 $\mu\text{m}$ $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$                                                                                                                                                           |
| p-electron blocking layer | 10 $\mu\text{m}$ p-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$                                                                                                                         | 10 nm p-doped AlGa <sub>N</sub>                                                                             | 10 nm Mg-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$                                                                                                                                                              |
| active region             | InGa <sub>N</sub> quantum well and AlGa <sub>N</sub> barrier                                                                                                                              | InGa <sub>N</sub> MQW                                                                                       | InGa <sub>N</sub> MQW                                                                                                                                                                                                |
| n-waveguiding layer       | 0.15 $\mu\text{m}$ undoped $\text{Al}_{0.06}\text{Ga}_{0.94}\text{N}$                                                                                                                     | 0.15 $\mu\text{m}$ GaN (undoped)                                                                            | 0.3 $\mu\text{m}$ GaN                                                                                                                                                                                                |
| n-cladding layer          | 0.7 $\mu\text{m}$ $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$<br>0.15 $\mu\text{m}$ $\text{In}_{0.05}\text{Ga}_{0.95}\text{N}$<br>2 $\mu\text{m}$ $\text{Al}_{0.02}\text{Ga}_{0.98}\text{N}$ | 2 $\mu\text{m}$ AlGa <sub>N</sub><br>2 $\mu\text{m}$ AlGa <sub>N</sub><br>2 $\mu\text{m}$ AlGa <sub>N</sub> | 1 $\mu\text{m}$ Si-doped $\text{Al}_{0.06}\text{Ga}_{0.04}\text{N}$<br>0.15 $\mu\text{m}$ Si-doped $\text{In}_{0.05}\text{Ga}_{0.95}\text{N}$<br>1 $\mu\text{m}$ Si-doped $\text{Al}_{0.02}\text{Ga}_{0.98}\text{N}$ |

All of Nichia's lasers use the same basic structure (see figure 1). The aquamarine laser diodes are not shown in the table, but have very similar characteristics to the 440 nm blue emitters. The only changes are a switch to modulation-doped InGa<sub>N</sub> layers for the n- and p-type waveguiding layers, and an adjustment to the active layer.

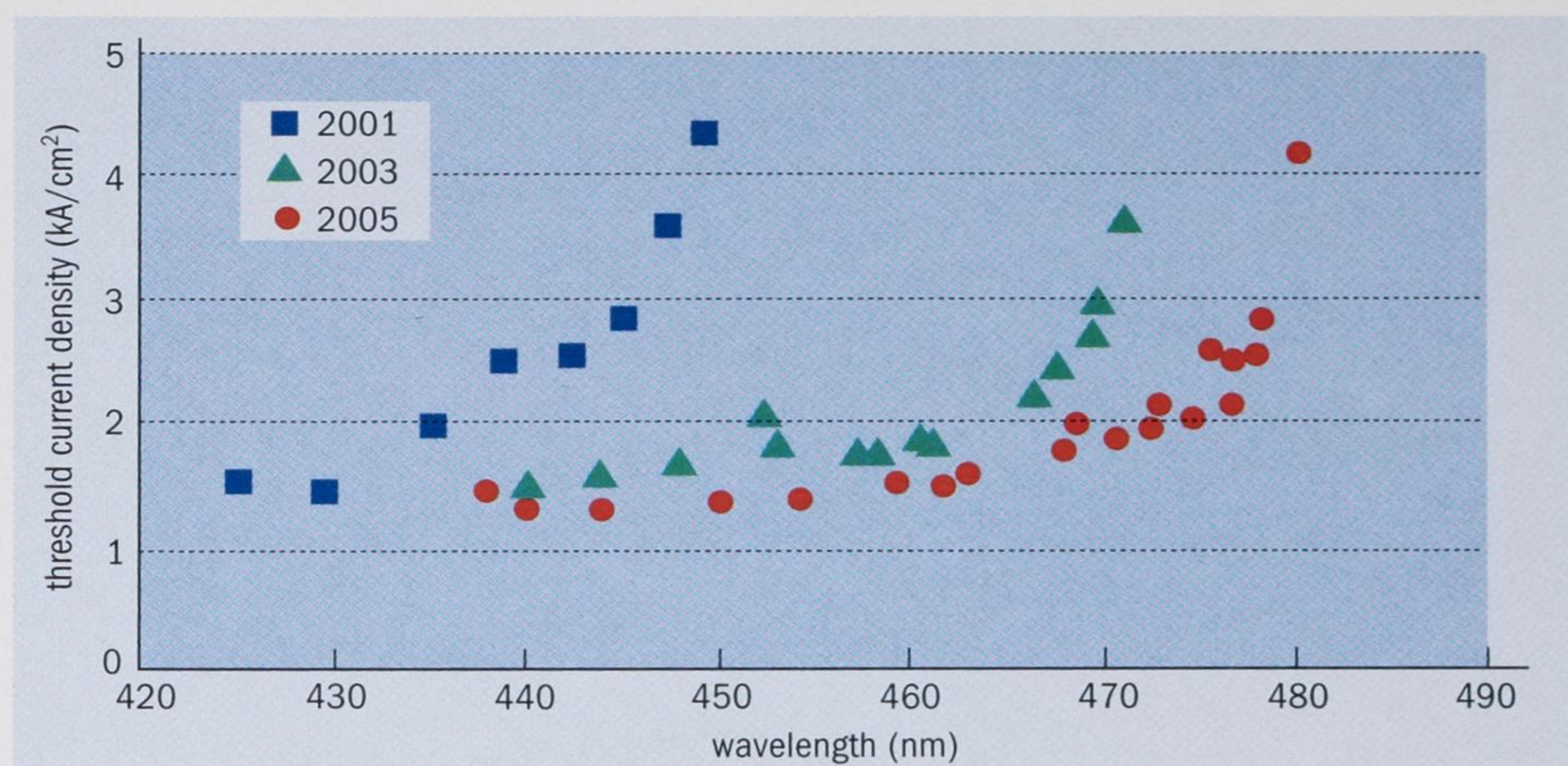


**Fig. 1.** Nichia's laser diodes share the same separate confinement heterostructure multi-quantum well design that features a buried ridge-waveguide, and are fabricated on n-type free-standing GaN substrates with a threading dislocation density of  $10^5$ – $10^6 \text{ cm}^{-2}$ .

terparts have the same estimated lifetime, but have  $7 \times 1 \mu\text{m}$  apertures and produced 300 mW under the same conditions.

The threshold current density of these blue-emitters is strongly dependent on the lasing wavelength (see figure 2). At longer wavelengths the threshold current density is higher because the additional indium content in the InGa<sub>N</sub> quantum wells that is required to increase the lasing wavelength also produces dislocations in the epilayers. However, these problems can be addressed by modifying the growth conditions and the device structure, which has allowed Nichia to extend the emission wavelength and make lasers that it describes as aquamarine. These efforts have produced 5 mW room-temperature emission at 482 nm, which is believed to be the longest wavelength ever reported for III-V GaN current-injection laser diodes.

Nichia is also continuing to develop its violet laser diodes operating at 400–410 nm, and is focusing on increasing the output power of these devices so that they are suitable for high-speed recording in high-density optical-disk systems and industrial applications. The company has already fabricated single-transverse-mode



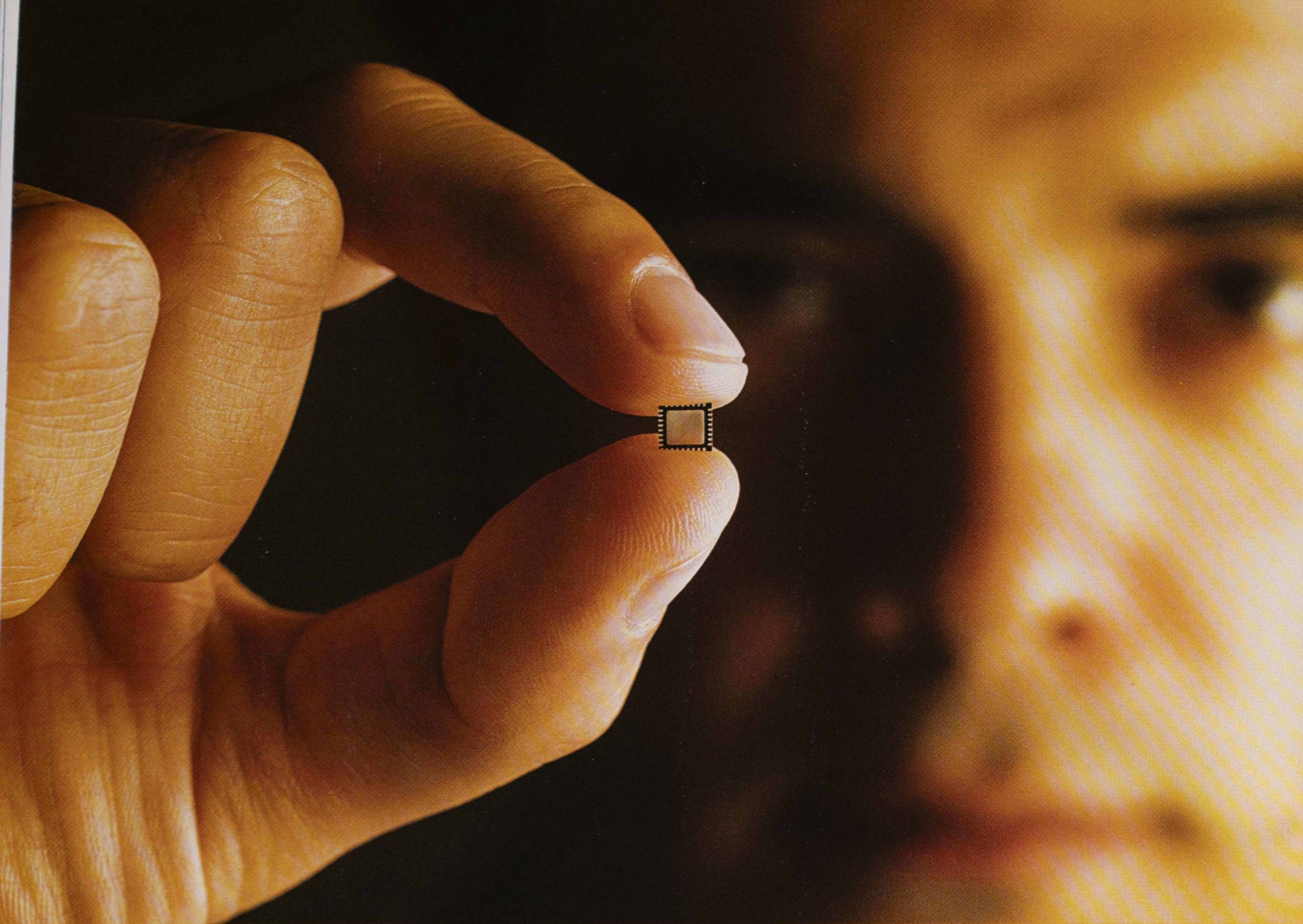
**Fig. 2.** Nichia is continuing to make steady progress in extending the emission wavelength of its laser diodes from the blue to the aquamarine, and will reveal more developments later this year.

405 nm lasers producing 200 mW at room temperature, and will release a commercial version of this device next year. These diodes can operate at up to  $80^\circ\text{C}$ , and were lifetime-tested at this temperature when delivering 160 mW output in pulsed-mode (a 30 ns pulse width and a 50% duty cycle). This examination revealed a steady degradation in the operating current, which increased by typically 7–8% over 1000 h.

The company has also built multimode versions of the violet-emitting devices that are targeting industrial applications such as the processing of printed-circuit boards. These lasers have  $7 \times 1 \mu\text{m}$  apertures and also show a steady degradation of the operating current when subjected to a lifetime test. In this case the diodes showed a typical increase in operating current of 20% over the 3000 h of operation.

Nichia's development program for high-power laser diodes emitting in the ultraviolet, violet, blue and aquamarine has equipped the company with a portfolio of devices delivering between tens and hundreds of milliwatts. And while the Japanese outfit will expect to reap the rewards of a ramp in sales of consumer electronics deploying 405 nm emitters, the company is also now in the position to chase business from many other types of application.





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TOURISM VANCOUVER

# Optimism returns to CS Mantech

The most upbeat mood in years was in evidence at this year's CS Mantech, with delegates as well as exhibitors feeling the benefits of surging sales of the latest phones. **Richard Stevenson** reports.

The Vancouver sunshine that greeted delegates at this year's CS Mantech was only part of the reason for all the smiling faces. A feel-good factor had also returned, as the effects of rising handset sales and an increase in the average GaAs content per phone had filtered through to all points in the supply chain.

This positive outlook was particularly evident at the conference's exhibition, where many company representatives talked about the improving business climate. Signs of the good times included strong growth in sales of 6 inch semi-insulating substrates at Hitachi Cable, and plans for capacity expansion at microelectronic epiwafer suppliers Visual Photonics Epitaxy and Pico-giga. The upbeat mood had even extended to equipment suppliers, with Aixtron hoping that the sale of two of its multi-wafer MOCVD reactors to Kopin will signal the return of significant sales to RF chipmakers.

A global perspective on this boom was provided by Asif Anwar, director of Strategy Analytics' GaAs and compound semiconductor technologies service, during a presentation at CS Vision, a co-located one-day meeting. According to Anwar the worldwide GaAs microelectronic device market, which is dominated by handset components, grew from \$2.6 billion in 2004 to \$2.8 billion in 2005, and will exceed \$3 billion this year. This surge has even surprised Anwar, who did not expect the strong growth in the handset-replacement market in Europe, America and Korea that has been led by Motorola's RAZR range of mobile phones.

Anwar says that the increased chip production has also driven strong growth in GaAs semi-insulating sub-

strate sales, and fab utilization among the crystal growers has reached an average of 80%. Revenue from this business is expected to hit \$600 million this year and \$863 million in 2010. According to Anwar, 6 inch material is the "incumbent standard" enjoying two-thirds of the market, with recent gains arising from RFMD's switch from 4 to 6 inch material. This size will remain the most popular choice for production, says Anwar, as the bad memories associated with the 2001 downturn will hamper development of 8 inch wafers.

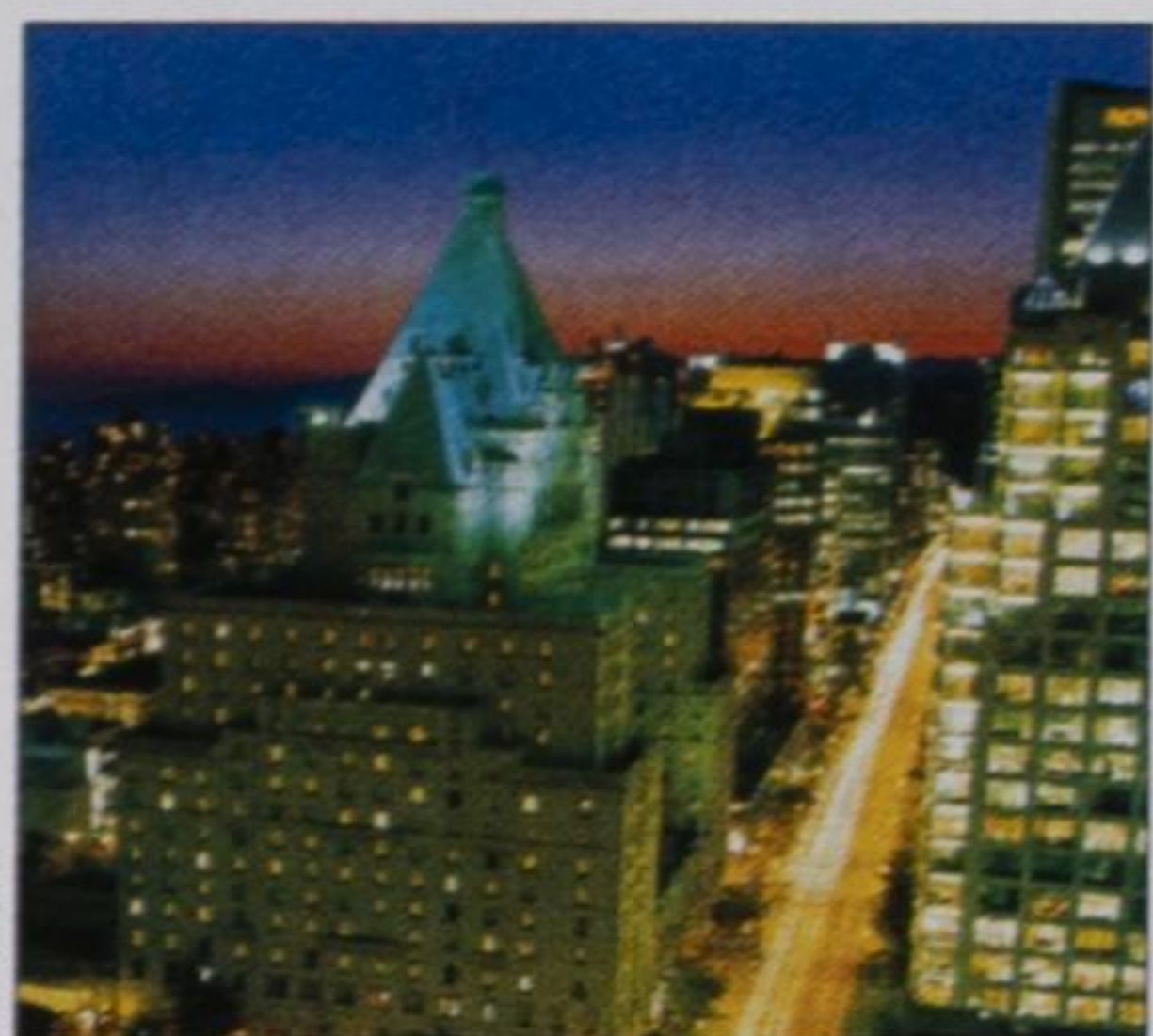
Global sales of GaAs microelectronic epiwafers are also on an upward curve. In 2004 the sector generated \$200 million, last year the figure was \$261 million, and throughout the remainder of the decade near double-digit annual growth is expected. The merchant market continues to be dominated by companies deploying MOCVD growth, says Anwar, while MBE is used by nearly all of the players in the captive market.

In Anwar's opinion, the surge in sales of GaAs substrates, epiwafers and microelectronic components is mainly due to a move towards 3G handsets. "3G is marvelous. It was supposed to be a unifying format, but it isn't and what we've got are multimode, multi-band requirements that can't be met with silicon." Migration towards handsets featuring five or even six bands will further increase the GaAs content in phones that is already worth 31% of the total component cost. This increase in radio content will deliver a further blessing for GaAs chip manufacturers, as increasingly complex switches are needed to cater for all these bands. In the past these switches were built with silicon, but now



The 2006 International Conference on Compound Semiconductor Manufacturing Technology was held in Vancouver, Canada, and attracted 285 delegates and 65 exhibitors. Between 24 and 27 April 68 papers were presented in 15 sessions on topics such as high-voltage FETs, HBTs, high-speed technologies, and the recent progress in GaN development programs.





**CS Mantech 2006** was held in the luxurious Fairmont Hotel Vancouver, located in the heart of the city. Conference chair Deb Green was presented with an award for her efforts by Chun-Lim Lau of Booz Allen Hamilton.



companies such as RFMD and Skyworks are building these components using GaAs PHEMT technology.

Anwar reiterated his positive outlook for the GaAs microelectronic industry at the CS Mantech panel session that discussed the threat that compound semiconductor technology faces from silicon. During this discussion he claimed that by 2010 GaAs will account for 90% of the semiconductor content in mobile phones, thanks to a need for components operating at higher frequencies and data rates for the delivery of emerging services such as mobile TV.

### The WLAN battleground

Anwar believes that the move towards higher-frequency, dual-band wireless LANs will also play into the hands of the compound semiconductor market, and he expects the power amplifiers in these modules to be dominated by GaAs-based components by 2010.

However, at the lower frequencies such as 2.4 GHz Anwar believes that silicon-based technology will continue to hold the largest share of the market. Freescale's engineering manager of compound semiconductor products Monte Miller agrees, claiming that silicon LDMOS technology is better than its rivals at fulfilling the needs of customers who want low-cost, best-in-class performance, reliability and product consistency. He says that the high-frequency performance of silicon LDMOS is also improving, with gain increases in the

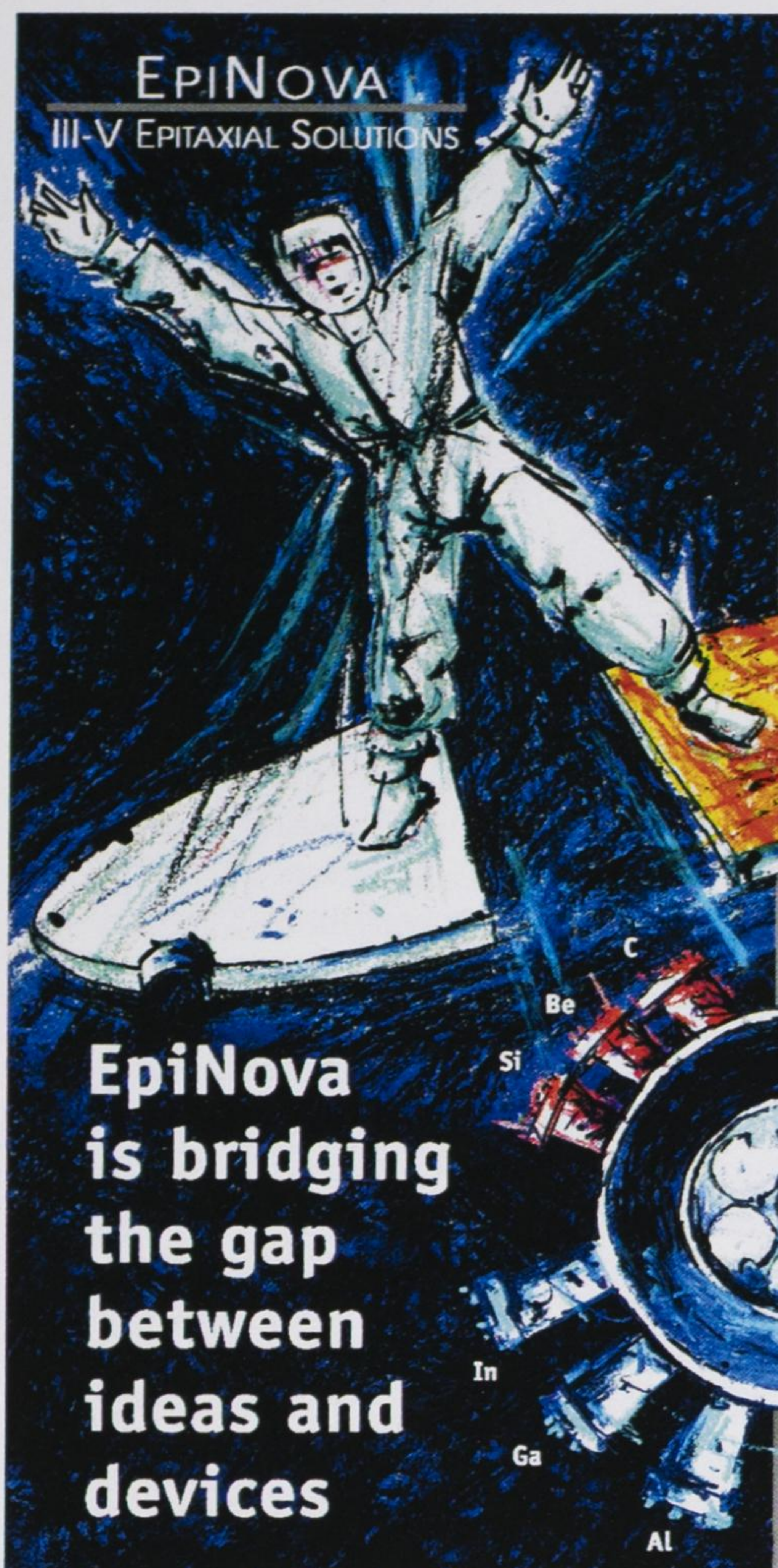
4–6 GHz regime, and at Mantech he warned GaAs manufacturers viewing those frequencies as their territory against complacency. However, he added: "Compounds have the advantage that they can do it today."

Miller believes that the biggest challenge facing GaAs and GaN devices are high costs. "Which markets will drive GaN epi costs down?" he asked, before questioning the long-term reliability of this technology. He cannot see GaN ever competing for market share, claiming that "silicon is almost free by comparison".

As expected, this view was not shared by Nitronex's integration engineering manager Allen Hanson, whose GaN-on-silicon products are already being shipped into the 3.5 GHz market. "We feel that the process is in a fair state of maturity," said Hanson, who gives the large number of wafers shipped as one reason for the firm's success: it has about 1500 wafer starts per year.

The panel also discussed WiMAX, which Anwar sees as a complementary technology suiting customers unable to receive data via cable or ADSL. Miller expects the market to take off soon; Freescale was surprised by the number of customers in late 2005 that were buying high-power GaAs components for this protocol.

This was further good news for many at the conference. After years of discussing the pros and cons of the foundry model, they felt they had every right to smile now that sales of GaAs substrates, epiwafers and chips were all on the up.



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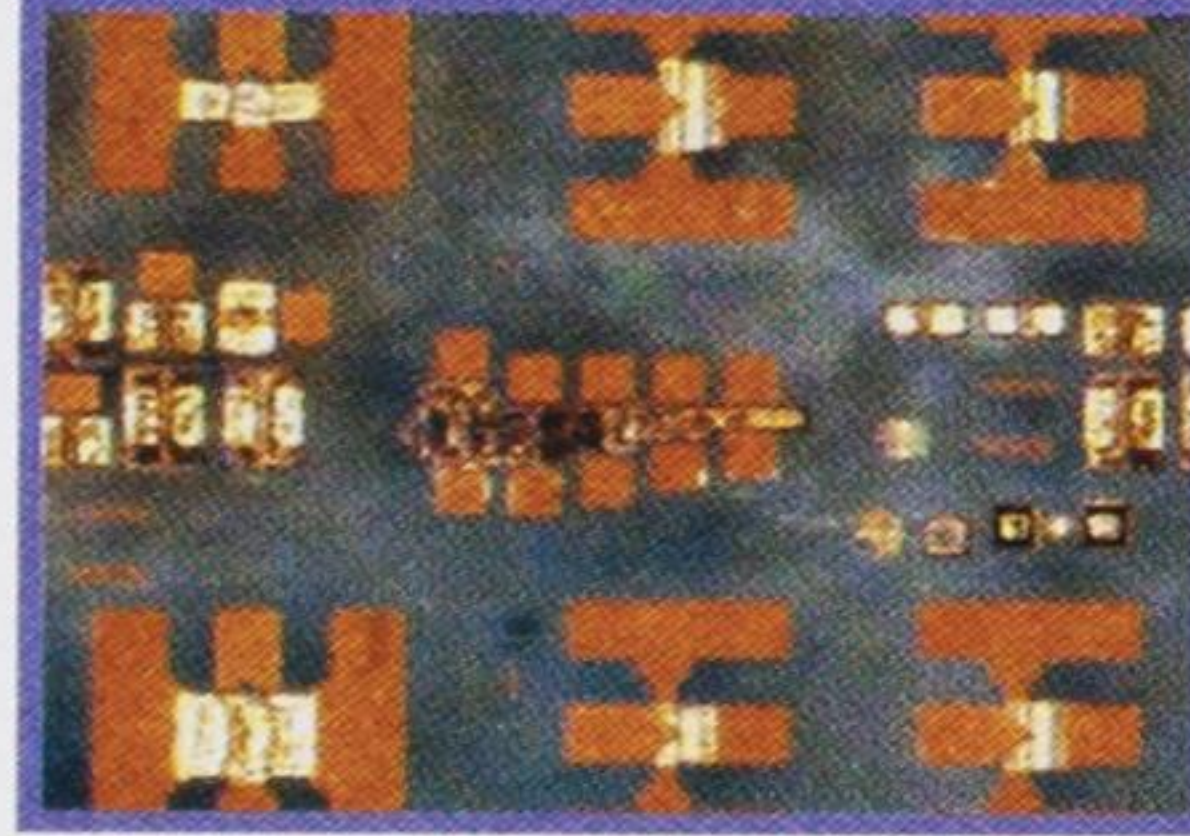
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# AlGaN provides filter-free detection

Arrays of filter-free AlGaN-on-sapphire detectors that are unaffected by sunlight and deliver high sensitivity, high operability and excellent uniformity could be used in all sorts of commercial and military applications, say **Marion Reine**, **Philip Lamarre** and **Allen Hairston** from BAE Systems.

AlGaN has some unique material properties that are ideal for high-performance ultraviolet (UV) detectors. They include a high optical absorption coefficient and a direct bandgap that can be tuned from 200 to 365 nm. This allows the bandgap to be tailored to produce “solar blind” detectors that operate at wavelengths below 280 nm. These devices are “blind” to solar radiation – at such short wavelengths the Sun’s emission is strongly absorbed by atmospheric ozone, and so it is relatively straightforward to detect the emission from artificial sources such as UV lamps in daylight.

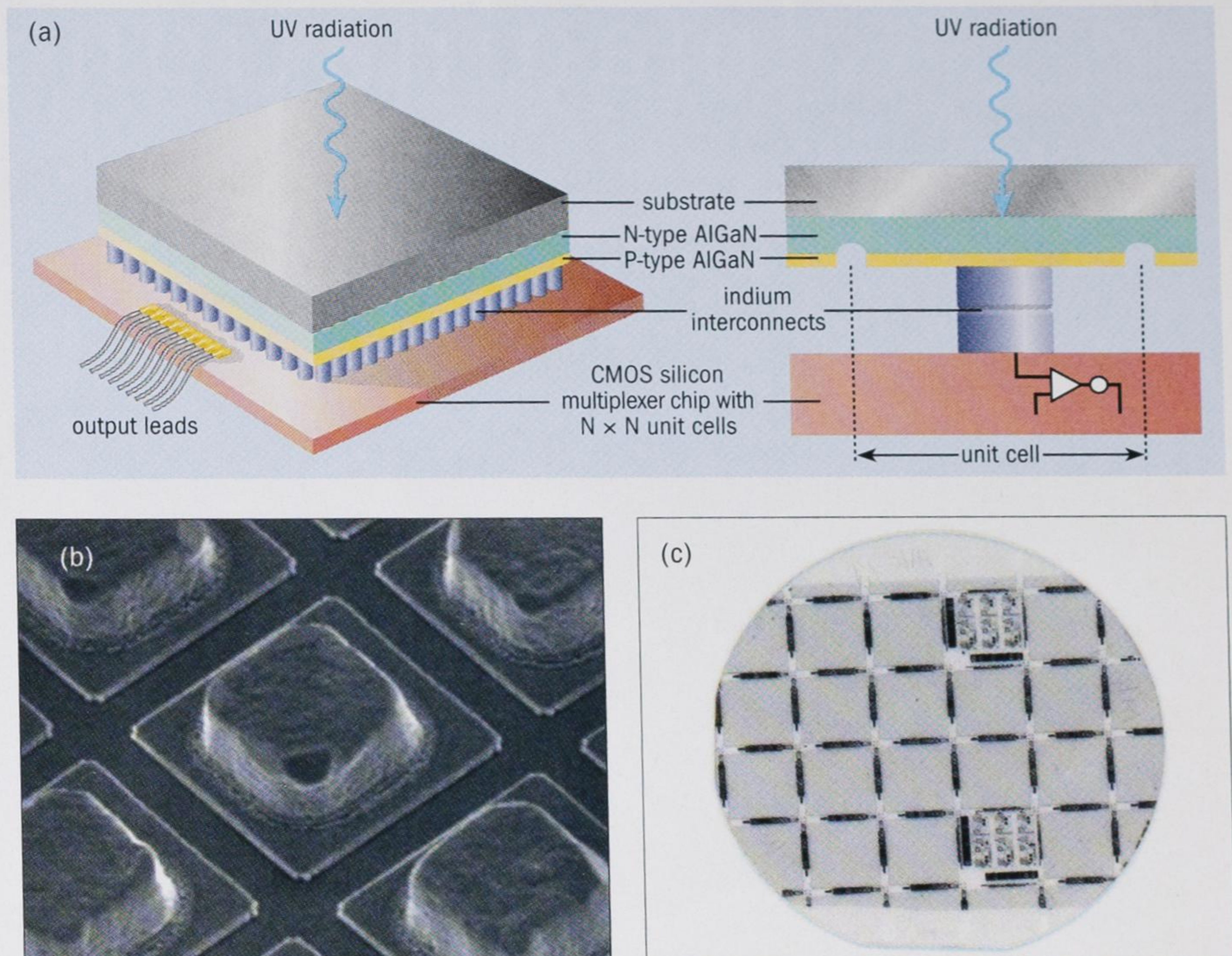
A wider bandgap gives these solar-blind detectors a much lower thermal noise than those built using narrower bandgap material such as silicon. Additionally, the filters required by the narrower bandgap alternatives to reject solar wavelengths cause drawbacks in terms of extra cost, size and weight. AlGaN is also radiation hard, able to withstand high temperatures, and can be grown n-type or p-type by MOCVD or MBE onto various substrates, including those that are UV transparent. In addition, the material’s quality is constantly improving through the enormous investment in AlGaN-based visible and UV emitters and RF electronic components.

These AlGaN detectors could be used for a wide range of tasks, including atmospheric ozone-level monitoring, UV astronomy, flame detection, combustion monitoring, medical imaging, missile warning, and biological agent detection and identification.

Prior to our efforts, there were only two reports of GaN-based hybrid focal-plane arrays (FPAs) – a  $256 \times 256$  FPA fabricated by the NASA Goddard Space Flight Center, which employs GaN photoconductors, and a  $32 \times 32$  FPA featuring a back-illuminated PIN photodiode built by Honeywell, North Carolina State University, and the US Army Night Vision and Electronic Sensors Directorate. In both cases a GaN absorber layer gave the FPA a cutoff wavelength of 365 nm, meaning that these detectors were visible blind but not solar blind.

## From visible blind to solar blind

At BAE Systems, Lexington, MA, we have developed the first solar-blind  $256 \times 256$  AlGaN back-illuminated hybrid UV FPAs under a program sponsored by the Defense Advanced Research Projects Agency (DARPA). Our detector arrays, which are built using epiwafers from Cree, Emcore and the University of Texas at Austin (UT), have  $30 \mu\text{m} \times 30 \mu\text{m}$  unit cells, a photosensitivity in the 260–280 nm waveband, and



**Fig. 1.** BAE Systems has developed hybrid ultraviolet (UV) focal-plane arrays consisting of a back-illuminated AlGaN detector array on a UV-transparent sapphire substrate, connected with indium bump interconnects to a silicon CMOS readout integrated circuit chip (a). These devices benefit from being operated at zero bias voltage, as this leads to negligible current flow through the device and eliminates “1/f” noise. Scanning electron microscope images reveal the details of the  $30 \mu\text{m} \times 30 \mu\text{m}$  unit cells, each with an indium bump (b). These AlGaN-based PIN devices were grown on 2 inch film on a sapphire substrate and processed into  $256 \times 256$  pixel arrays with an area of  $8 \text{ mm} \times 8 \text{ mm}$  (c).

a quantum efficiency of more than 50% at 270 nm. They are formed by attaching a back-illuminated AlGaN detector array to a matching silicon CMOS readout integrated circuit (ROIC) chip with indium-bump interconnects (see figure 1).

Grown on UV-transparent sapphire substrates, the detectors are based on the back-illuminated PIN heterojunction architecture reported by Honeywell. However, we have replaced the GaN absorber layer in the Honeywell design with a wider-gap  $\text{Al}_{0.47}\text{Ga}_{0.53}\text{N}$  layer that has the cut-off wavelength of 280 nm required for solar-blind detection (see figure 2, p29), and the composition of the n-doped window layer has been switched from  $\text{Al}_{0.28}\text{Ga}_{0.72}\text{N}$  to  $\text{Al}_{0.6}\text{Ga}_{0.4}\text{N}$  to give a cut-on wavelength of 260 nm.

The increased aluminum content required to advance from visible-blind to solar-blind detectors has demanded significant AlGaN materials develop-



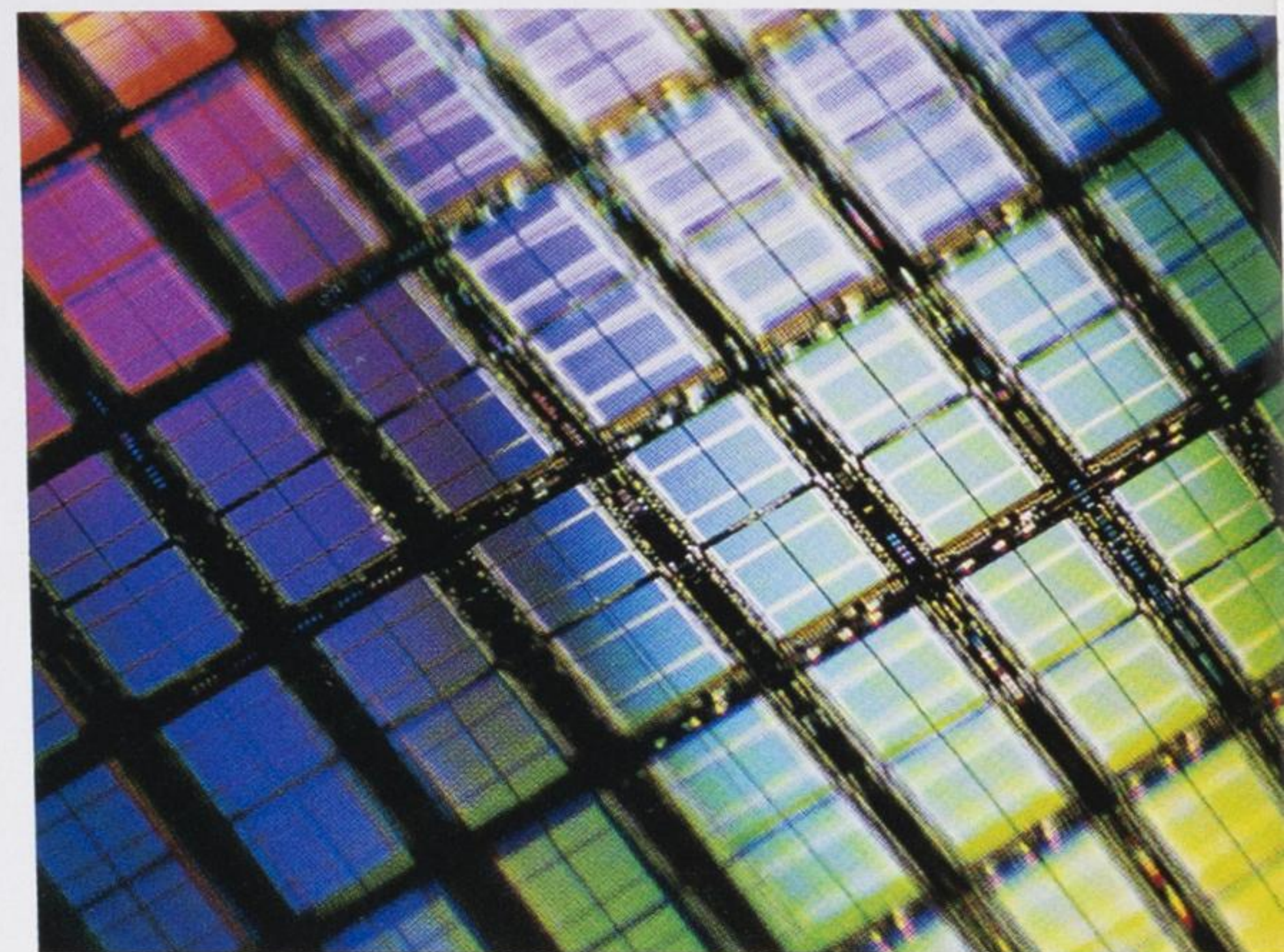


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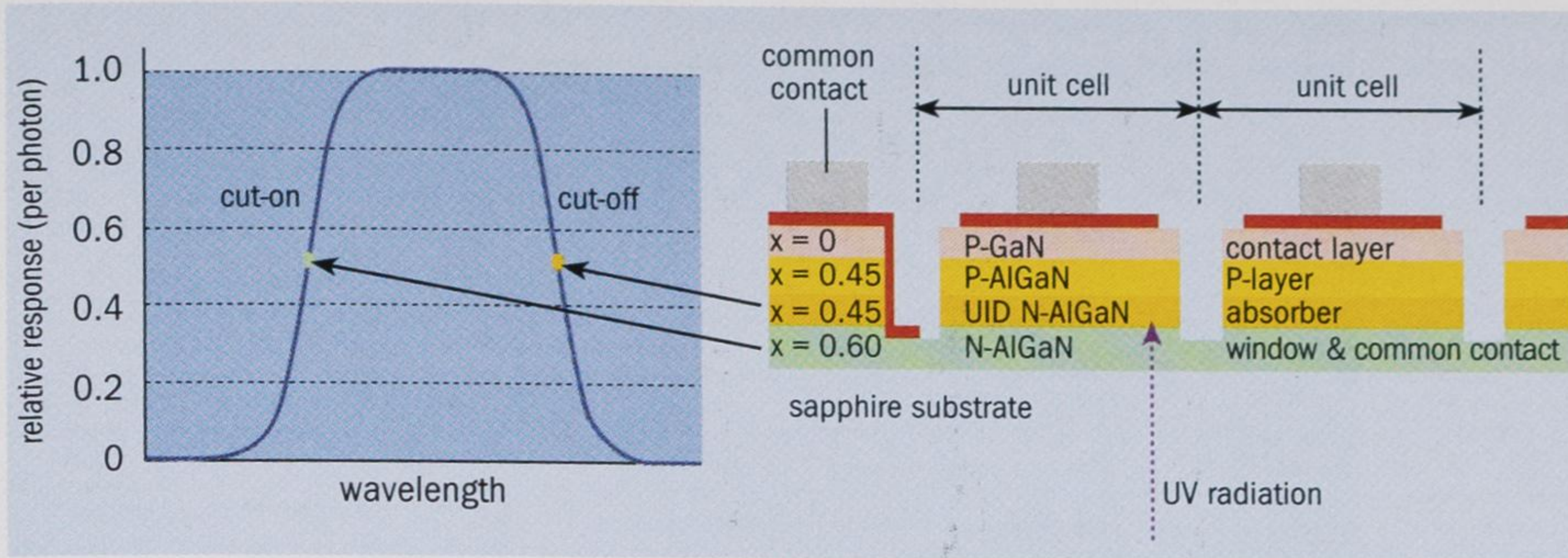
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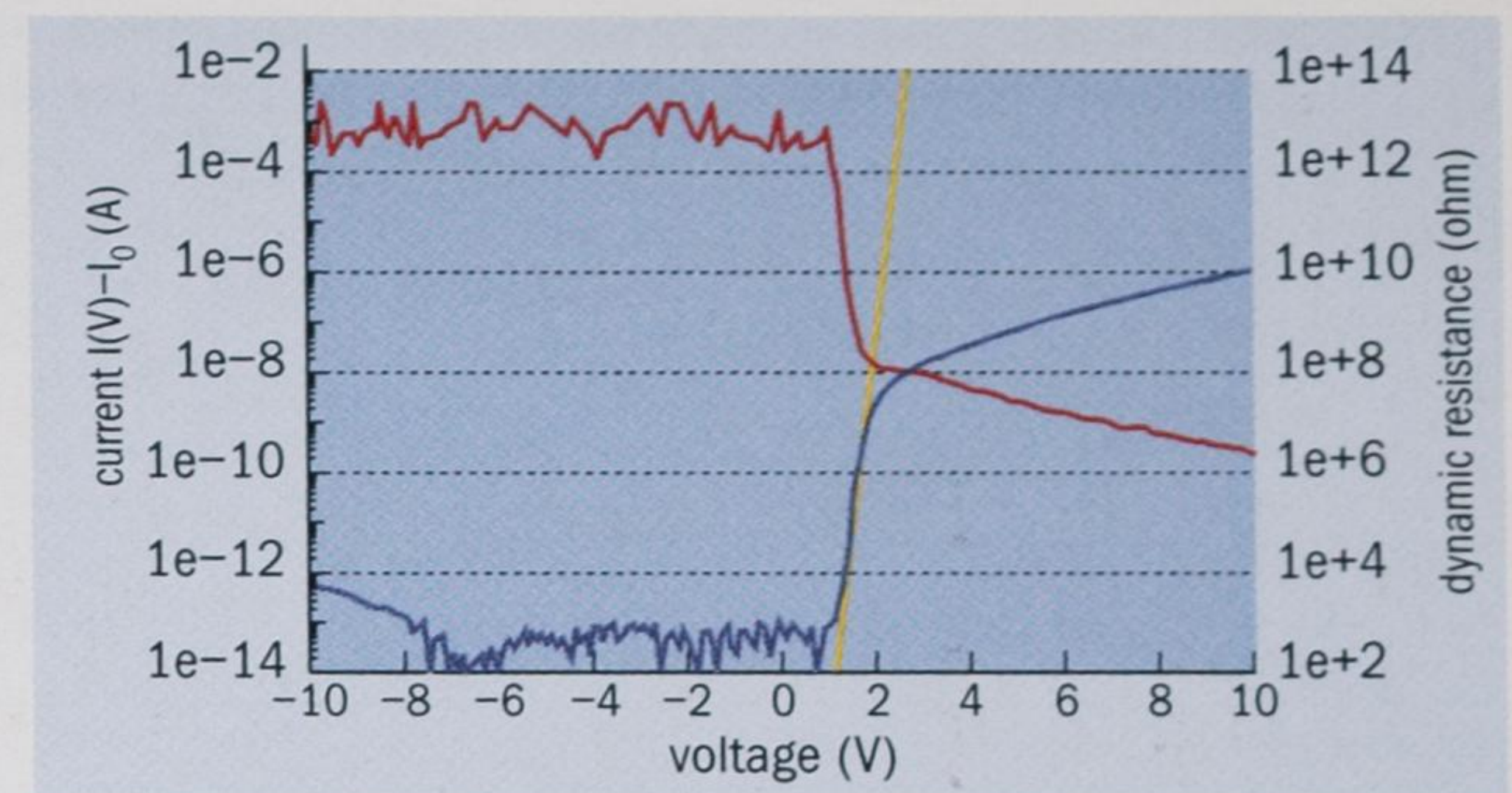


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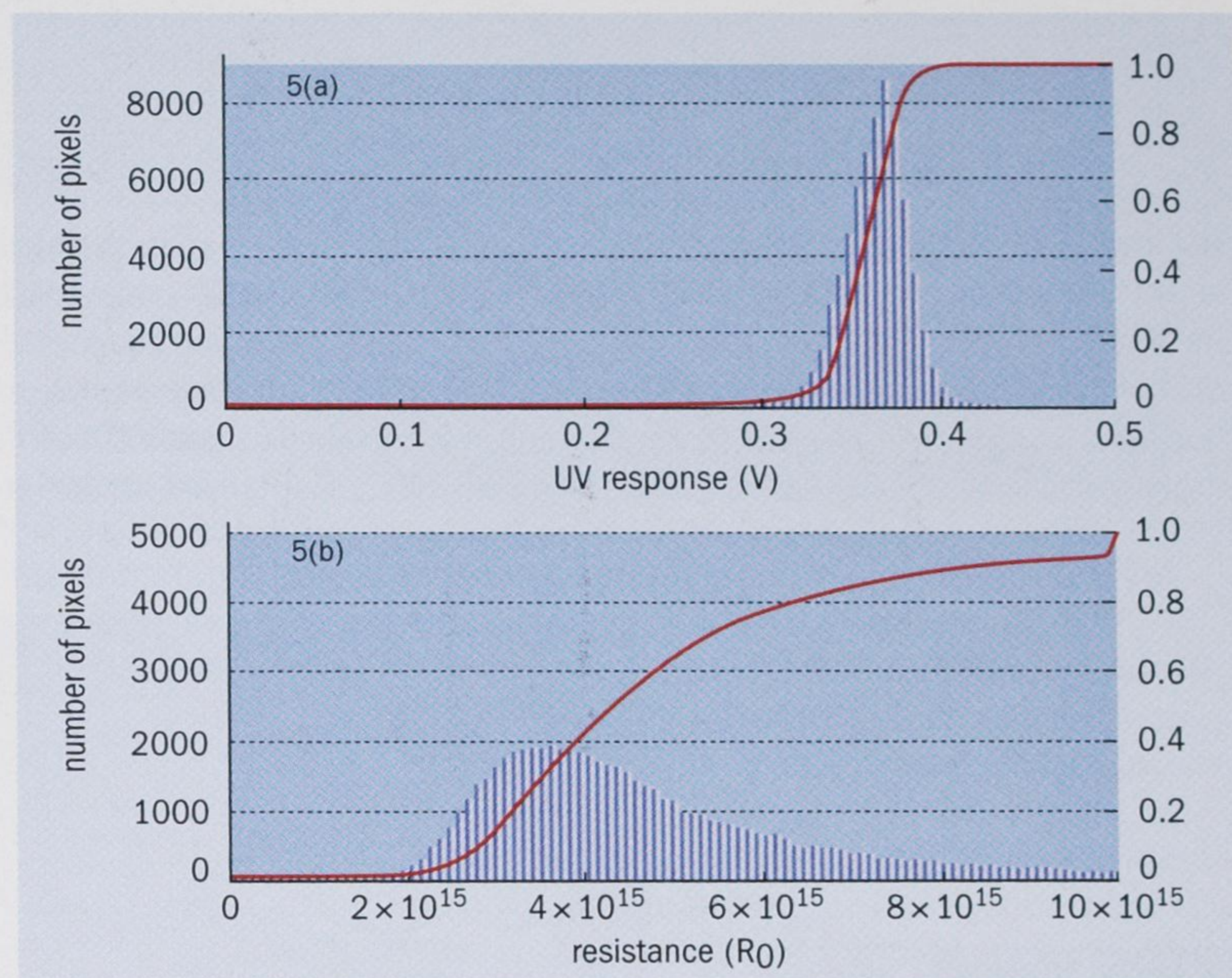
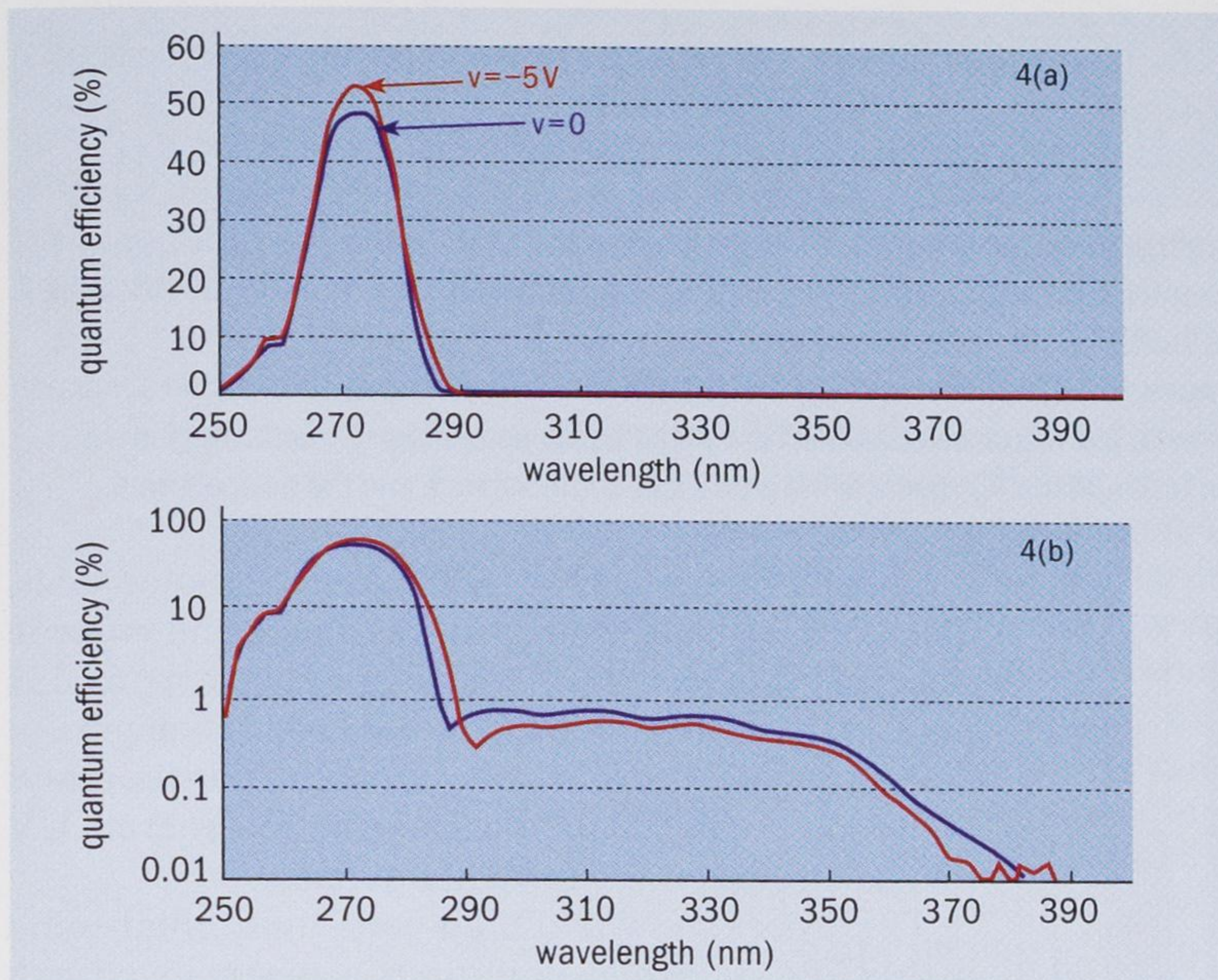




**Fig. 2.** BAE Systems' back-illuminated AlGaIn PIN photodiode uses high aluminum content layers to produce a spectral response over a small window of ultraviolet wavelengths. The cut-off and cut-on wavelengths are determined by the composition of the unintentionally doped n-type AlGaIn absorber layer, and the silicon-doped n-type AlGaIn window layer that acts as the common n-side contact for all elements in the array, respectively. Magnesium is used for p-doping of the top two epilayers.



**Fig. 3.** Room-temperature measurements of the photodiodes that were produced using material from the University of Texas at Austin have extremely low leakage currents and an ideality factor of 2.3. These results are similar to those obtained on photodiodes fabricated using epiwafers from Cree and Emcore.



**Fig. 4 (left).** Photodiodes produced with material from the University of Texas at Austin (a, b) have a slightly higher quantum efficiency when the bias voltage is increased to 5 V. The films have an out-of-phase response at the GaN cut-off wavelength of 360 nm – see the semilog plots. This effect is caused by a photocurrent of opposite polarity from a Schottky barrier unintentionally formed by the p-contact metal on the p-type GaN surface, and can be reduced or eliminated by increasing the doping in the GaN p-side contact. **Fig. 5 (right).** The response histogram of FPA 208 (a), fabricated from UT material, shows a narrow distribution ( $\sigma/\mu = 6\%$ ), which demonstrates the excellent uniformity of the response of the FPA. The array has a median zero bias resistance,  $R_0$ , of  $4.3 \times 10^{15} \Omega$ , which demonstrates the low thermal noise of these detectors (b).

ment. MOCVD growth conditions had to be established and optimized for growing crack-free layers of high-quality AlGaIn on sapphire, including the development of an innovative buffer. In addition, an approach for producing the silicon-doped  $\text{Al}_{0.6}\text{Ga}_{0.4}\text{N}$  window layers with sufficiently high conductivity had to be developed. Both improvements had to be delivered while producing material capable of extremely low leakage currents and high quantum efficiencies when used in back-illuminated PIN photodiodes.

The AlGaIn epiwafers were grown on 2 inch c-plane double-side-polished sapphire substrates by MOCVD and featured the basic back-illuminated PIN structure (see figure 2). The  $256 \times 256$  arrays were fabricated using a four-mask process, with mesa etching carried out by inductively coupled plasma chlorine-based dry etching at Boston University Photonics Center.

Material from all three suppliers produced photo-

diodes with extremely low leakage currents and correspondingly high resistances at zero bias voltage (see figure 3). High resistance is important because the thermal noise is inversely proportional to the square root of the zero-bias resistance. The leakage current at near-zero bias voltage is too small for us to measure in our laboratory, and a reverse bias of several volts is required to raise this current above the probe station's noise floor of  $1 \times 10^{-13}$  A. Under forward bias, the current increases exponentially over three-to-four orders of magnitude and is limited by series resistance at higher voltages.

Our photodiodes have high quantum efficiencies. Figure 4 shows a typical response for a UT photodiode with a 48% peak quantum efficiency at zero bias. None of the devices featured any antireflection coating on the back surface of the sapphire substrate, and without the reflection loss at the air-sapphire interface the UT diode's quantum efficiency would have been 52.3%.

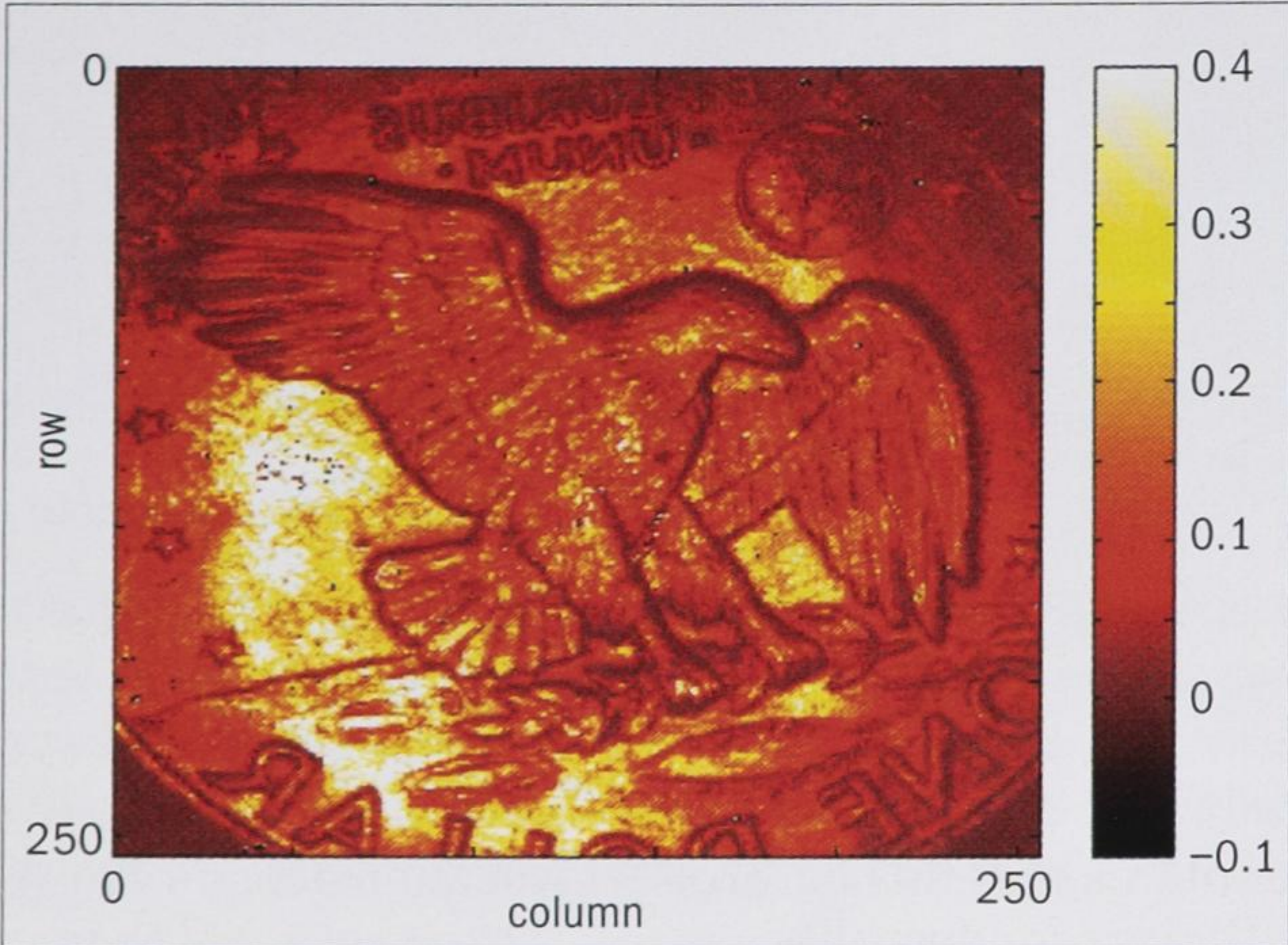


| The properties of UV solar-blind detectors built with material from Cree, Emcore and the University of Texas |          |                        |                         |                      |          |             |                          |                                      |                             |                                          |
|--------------------------------------------------------------------------------------------------------------|----------|------------------------|-------------------------|----------------------|----------|-------------|--------------------------|--------------------------------------|-----------------------------|------------------------------------------|
| FPA                                                                                                          | Film     | Cut-on wavelength (nm) | Cut-off wavelength (nm) | $\Delta\lambda$ (nm) | QE (V=0) | QE (V=-5 V) | Response operability (%) | Response uniformity $\sigma/\mu$ (%) | $R_0$ (median) ( $\Omega$ ) | $R_0A$ (median) ( $\Omega\text{ cm}^2$ ) |
| Emcore films, processed at BAE Systems                                                                       |          |                        |                         |                      |          |             |                          |                                      |                             | Visible blind                            |
| 202                                                                                                          | R3497    | 341                    | 362                     | 20                   | 51.4     |             | 98.5                     |                                      |                             |                                          |
| 204                                                                                                          | M1674    | 282                    | 309                     | 27                   | 13.5     |             | 90                       |                                      |                             |                                          |
| 205                                                                                                          | M1678    | 296                    | 328                     | 33                   | 22.8     | 56.9        | 98.5                     | 8                                    | 4E+15                       | 3E+10                                    |
| 206                                                                                                          | M1702    | 279                    | 287                     | 8                    | 24.8     | 29.3        | 97                       |                                      |                             |                                          |
| 207                                                                                                          | M1704    | 276                    | 289                     | 12                   | 37.6     | 43.3        | 99.4                     | 4.8                                  |                             |                                          |
| University of Texas at Austin films, processed at BAE Systems                                                |          |                        |                         |                      |          |             |                          |                                      |                             | Solar blind                              |
| 208                                                                                                          | UT-M2608 | 262                    | 278                     | 16                   | 44.5     | 54.7        | 99.8                     | 6                                    | 4E+15                       | 3E+10                                    |
| 209                                                                                                          | UT-M2608 | 261                    | 278                     | 17                   | 47.5     |             | 95                       |                                      | 6E+12                       | 4E+07                                    |
| 212                                                                                                          | UT-M2609 | 264                    | 282                     | 18                   | 46.6     |             | 99.6                     | 3.1                                  | 1.5E+15                     | 1.1E+10                                  |
| University of Texas at Austin film, processed at the University of Texas                                     |          |                        |                         |                      |          |             |                          |                                      |                             | Solar blind                              |
| 213                                                                                                          | UT-M2510 | 265                    | 282                     | 17                   | 58.1     | 64.5        | 85                       |                                      | >1E+16                      | >7E+10                                   |
| Cree films, processed at Cree                                                                                |          |                        |                         |                      |          |             |                          |                                      |                             | Solar blind                              |
| 210                                                                                                          | A(k1068) | 261                    | 281                     | 20                   | 43.4     | 56.5        | 99.4                     | 2.5                                  | 5E+15                       | 4E+10                                    |
| 211                                                                                                          | C(k1071) | 265                    | 284                     | 19                   | 38.2     |             | 99.4                     | 5.5                                  | 1E+16                       | 7E+10                                    |

The best 256 × 256 AlGaIn ultraviolet (UV) focal-plane arrays (FPAs) made with material from Emcore, the University of Texas at Austin and Cree all have high operability, high sensitivity, excellent uniformity and good quantum efficiency (QE). The FPAs were attached at BAE Systems to specially designed low-noise silicon CMOS 256 × 256 ROIC chips, and any noise measured in the resulting detectors came from the ROIC and the test set, not the AlGaIn photodiodes. Defectivity ( $D_\lambda^*$ ) values as high as  $2 \times 10^{13}\text{ cm}^{-2}\text{ Hz}^{1/2}/\text{W}$  at 272 nm were measured for the best elements of selected FPAs. The UV response was measured with a broadband deuterium lamp to provide unfocused UV radiation at normal incidence. Photodiode resistances were measured under dark conditions at a 100 Hz frame rate. The response operability is defined as the percentage of pixels that have a response greater than half the average response value. The  $R_0$  value is the resistance at zero bias and the  $R_0A$  figure is the product of this resistance and the device's area.



**About the authors**  
**Marion Reine (marion.reine@baesystems.com)** is a principal engineering fellow at BAE Systems, with extensive experience in the design and development of HgCdTe infrared detectors and AlGaIn UV detectors. **Philip Lamarre** develops advanced processing technology for quantum detectors at BAE Systems, including advanced photolithography. He is founder and president of Photronix, an electro-optics company in Fairhaven, MA. **Allen Hairston** has more than 20 years' experience at BAE Systems in the design of silicon CMOS ROIC chips for advanced sensors, including HgCdTe infrared FPAs and AlGaIn UV FPAs.



**Fig. 6.** BAE Systems' solar-blind detector featuring Cree's material has been used to generate a UV reflection image of a dollar coin. It was taken using UV radiation from a deuterium lamp at near-normal incidence, a F/3.5 Nikon lens and an integration time of 10 ms.

Quantum efficiency increased at a small reverse-bias voltage, such as 5 V. Analytical modeling and numerical simulations suggest that this increase is caused by incomplete depletion of the unintentionally doped absorber layer at zero bias. This allows rapid recombination of photocarriers in the undepleted part of this layer, which is located next to the higher bandgap window layer. A reverse-bias voltage pushes the edge of this depletion region towards the window layer and increases the number of photocarriers collected.

The best 256 × 256 AlGaIn photodiode arrays were attached to low-noise 256 × 256 ROIC chips at BAE Systems that were specifically designed to match the

ultra-high-resistance low-noise AlGaIn photodiodes. The UV response, dynamic resistance and noise in selected FPAs was then measured for each of the 65,536 pixels (see table above). There was a high degree of uniformity of the pixel's performance within the arrays (see figure 5, p29), and their ability to generate UV images of objects is shown in figure 6.

These data show that high-sensitivity solar-blind hybrid FPAs with high uniformity can be realized with AlGaIn PIN photodiode arrays grown by MOCVD on sapphire. Material improvements to AlGaIn layers incorporating a high aluminum fraction, which includes strain management through innovative buffer layers, have driven record quantum efficiencies at cut-off wavelengths as short as 280 nm. These advances are a solid basis to explore more ambitious AlGaIn detectors and arrays, such as devices with avalanche gain with the potential for single-photon counting.

**Acknowledgments**  
This work was funded by the DARPA Solar Blind Detector Program, through an Office of Naval Research contract. The work at Cree was funded by the Air Force Research Laboratory. We thank our collaborators Milan Pophristic, Shiping Guo, Boris Peres and Ian Ferguson at Emcore; Rajwinder Singh and Charles Eddy at Boston University; Uttiya Chowdhury, Michael Wong and Russell Dupuis at UT; and Ting Li and Steven DenBaars at Cree.

**Further reading**  
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## ALUMINUM NITRIDE

# LED breakthrough highlights AlN promise

The availability of 2 inch aluminum nitride substrates and the development of an LED that is based on doped epilayers of the same material marks the dawn of a new era in III-N technology, writes **Michael Hatcher**.

## The lowdown on AlN

**First synthesized:** 1877

**Crystal structure:**  
hexagonal

**Electrically insulating ceramic**

**Melting point:** 2200 °C

**Boiling point:** 2517 °C

**Bandgap (300 K):**  
6.026 eV

Source: Wikipedia/  
Ioffe Institute.

Two developments within the last month promise to unlock the potential of a relative newcomer to the compound semiconductor business – aluminum nitride (AlN). At just over 6 eV, the wurtzite AlN structure has the widest bandgap among semiconductors, and obvious potential for light emitters and detectors operating in the deep-ultraviolet portion of the spectrum.

But AlN is a very tough nut to crack. An electrical insulator with a melting point of 2200 °C and a boiling point only 317 °C higher, forming usefully-sized single crystals of the material for electronic applications has proved impossible until recently.

In the May 18 issue of the leading academic journal *Nature*, researchers at Japan's NTT reported the shortest-wavelength LED ever seen. Yoshitaka Taniyasu and co-workers doped epilayers of AlN to form the p-type and n-type parts of the device, which emitted 210 nm photons.

Although extremely inefficient and with a hefty operating voltage of 25 V, the LED made at NTT's Basic Research Laboratories represents a crucial first step towards the development of very low wavelength emitters that could be used to detect or destroy harmful biological species. So, just how did the NTT team do it?

In the *Nature* paper, the group describes how it used a refined doping strategy using silicon and magnesium to make the PIN LED. Their precise approach is the critical element of the work – until now, researchers had been unable to control the doping of the n-type and p-type layers of AlN precisely enough to demonstrate an LED.

“By reducing the dislocation density and finely controlling the silicon doping level, we were able to boost the room-temperature electron mobility,” wrote Taniyasu.

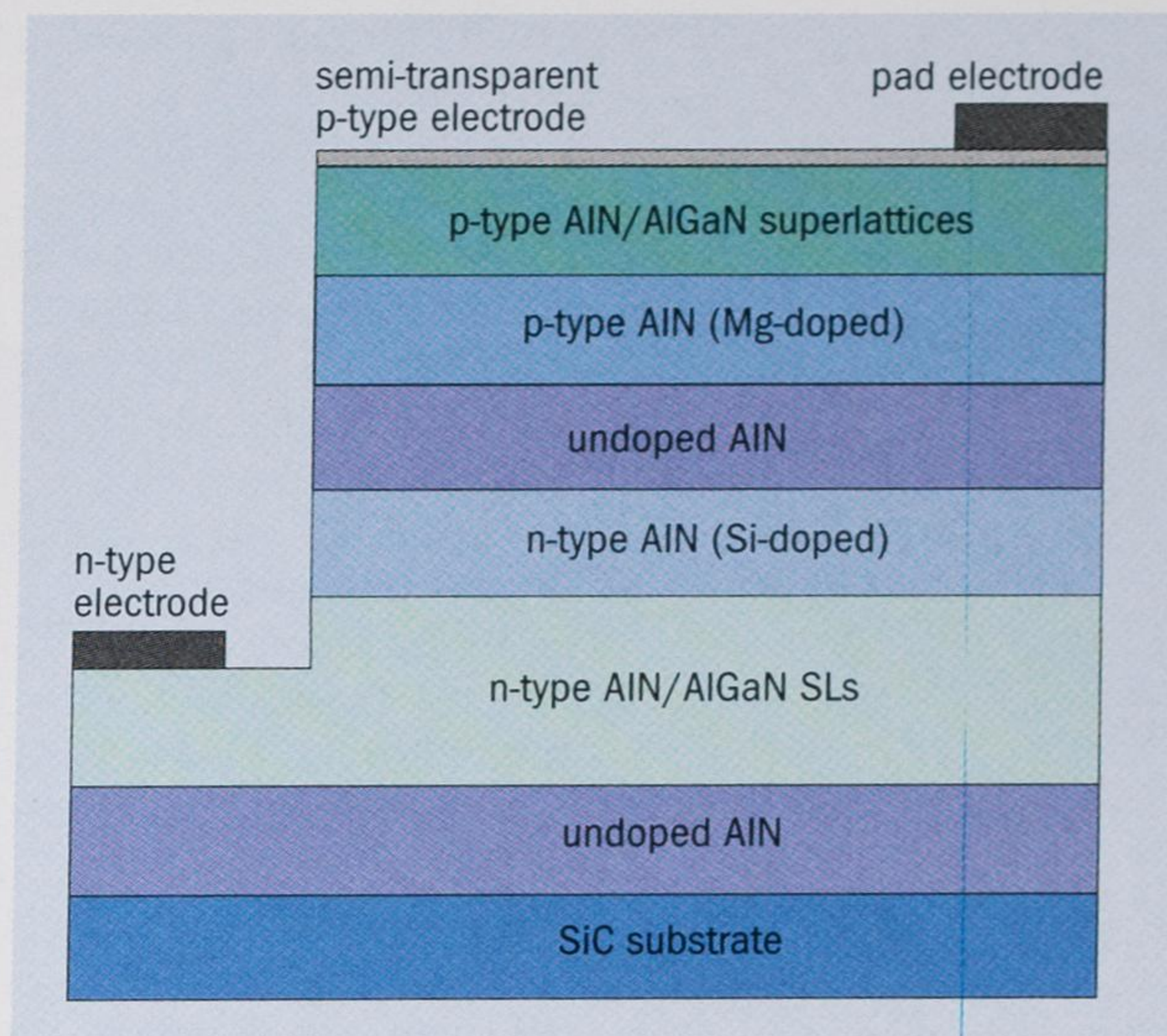
III-N expert Asif Khan at the University of South Carolina (USC) in the US explains that this careful doping control means that sufficient conductivity can be imparted to the layers of AlN to form both p-type and n-type layers, which sandwich the undoped AlN layer in the device. As a result, enough electrons and holes can recombine to produce a useful number of deep-ultraviolet (UV) photons.

LEDs based on AlGaIn that emit down to 244 nm are already available. In fact, Khan's own research group at USC has made such devices using a technique called migration-enhanced MOCVD, developed in collaboration with Sensor Electronic Technology, and is now working to refine their extraction efficiencies.

## Tough nut

But doping AlN has proved much more troublesome. “Unfortunately, as the aluminum fraction increases, so too does the doping difficulty,” wrote Khan in *Nature*. “It is hardest of all for AlN – which is in fact an insulator.”

At present, the 210 nm LED reported by the NTT team is nowhere near good enough for any real-world



**Precisely controlled** doping of the n-type and p-type layers of aluminum nitride (AlN) was the critical stage that enabled researchers from NTT to fabricate a 210 nm LED. Using native AlN instead of SiC substrates, as well as different dopants in the key epilayers, should improve both defect levels and conductivity.

applications such as water or air purification systems. The primary challenge facing the researchers now is to increase device efficiency and improve on the tiny output power – just 0.02  $\mu$ W.

Reducing the number of dislocations in the structure will be the most effective way to do this. Since the NTT LED was fabricated on a SiC substrate, the lattice mismatch between the two materials yielded relatively high dislocation densities of  $10^9 \text{ cm}^{-2}$ .

That level ought to be greatly reduced by using native AlN substrates, which coincidentally have recently become available on the open market thanks to the US companies Crystal IS and The Fox Group. They hope that this will help to spur the commercialization of AlGaIn-based devices for both optoelectronic and micro-electronic applications. According to Tim Bettles, the new vice-president of sales and marketing at Crystal IS, the huge market for water filtration products could become a lucrative one in the long term, while swimming pools may also one day use deep-UV semiconductor emitters to ensure sterilization of nasty bugs.

The release of 2 inch single-crystal AlN substrates with a 50% usable area from Crystal IS should prove to be particularly beneficial for AlGaIn-based optoelectronics, if not necessarily for LEDs with active AlN epilayers.

In the very long term, other applications such as optical data storage may present an opportunity for deep-UV lasers based on similar structures, although the pace



## "We are following in the footsteps of silicon carbide."

### Ding Day

CEO, Crystal IS

at which hard disk, flash memory and Internet storage technologies are advancing suggests that a sufficiently large market to justify their costly development may never materialize. Either way, making reliable lasers based on AlN would require epitaxial growth of semiconductor layers with even lower defect densities.

Crystal IS CEO Ding Day told *Compound Semiconductor* that his latest substrates have a defect density of less than  $10^4$  defects per  $\text{cm}^2$ , although Crystal IS also produces custom material for its clients with different specifications, and levels as low as  $10^3$  defects per  $\text{cm}^2$  have been shown.

"Alternative techniques to produce 'quasi-bulk' AlN substrates do exist, but these all involve growing on non-native materials and result in high defect densities that are more than 100,000 times that of the native substrate," explained Day. "We are following in the footsteps of silicon carbide, [but] aluminum nitride is a very challenging material."

### Crystal challenge

Growing a single crystal of AlN to form a boule from which AlN wafers can be sliced is the biggest challenge. Crystal IS has been awarded US patents that detail the use of a tungsten crucible to do this. The method quoted in US patent 6,770,135 describes how the growth chamber is first evacuated and then pressurized to about 1 bar with a gas mixture consisting of 95% nitrogen and 5% hydrogen. A polycrystalline AlN seed is then placed in the growth chamber and heated to around 1800 °C,

resulting in a crystal that can be grown at 0.6–0.9 mm per hour.

Although using a native substrate should help to increase the internal conversion efficiency of the 210 nm LED by up to two orders of magnitude, Khan reckons that a great deal more work is required before any commercial application becomes plausible, and warns that it will not be a straightforward development path.

"For high-aluminum compounds, one can surely benefit from AlN substrates," said Khan. "For [AlGaIn-based] 245 nm devices, efficiency can potentially be doubled by reducing defects by a factor of 10."

"However, for AlN LEDs the problem will be to find a compatible material with a bandgap larger than AlN," he added. "This will be needed to form quantum wells for efficient carrier capture."

Apart from an increase in efficiency by a factor of at least a million, the 210 nm LEDs need a reduction in operating voltage to well below 25 V for commercial use. To achieve the latter, the room-temperature conductivity of the AlN layers must be increased – probably by developing more efficient doping methods.

Taniyasu suggests that this could be achieved partly by using elements such as carbon, beryllium, zinc or cadmium instead of magnesium to dope the p-type layer, and partly by depositing carrier confinement structures such as quantum wells.

Although these are very early days for AlN, the recent advances made by both the NTT and Crystal IS teams suggests that its time will come.

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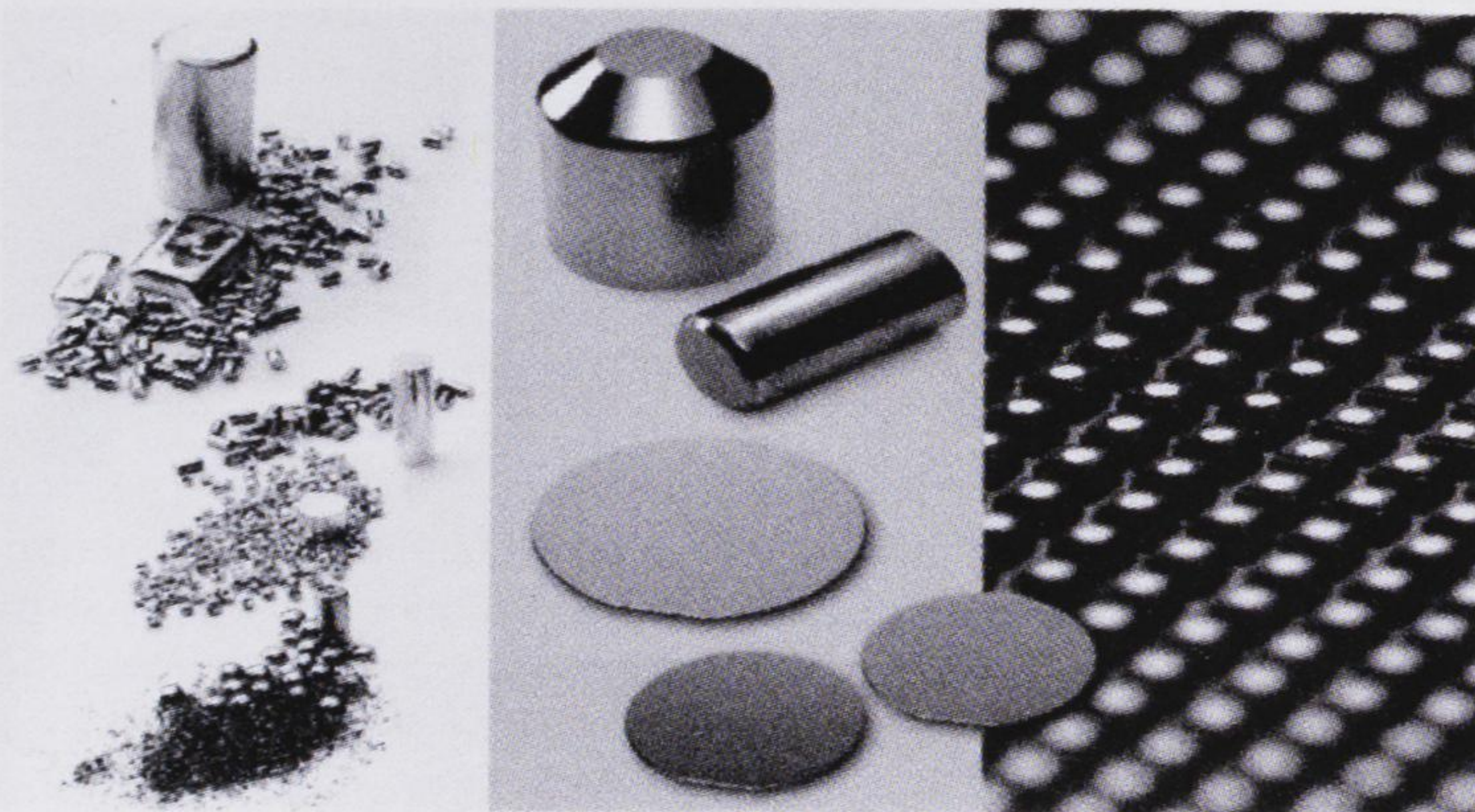
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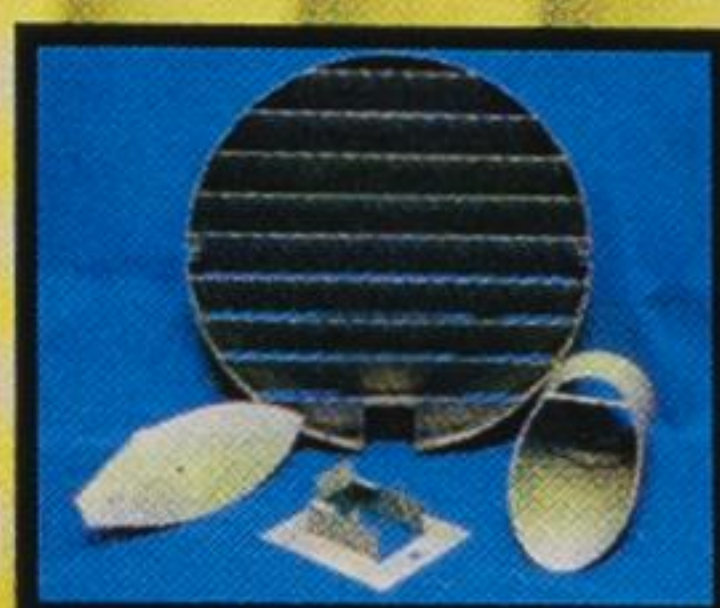


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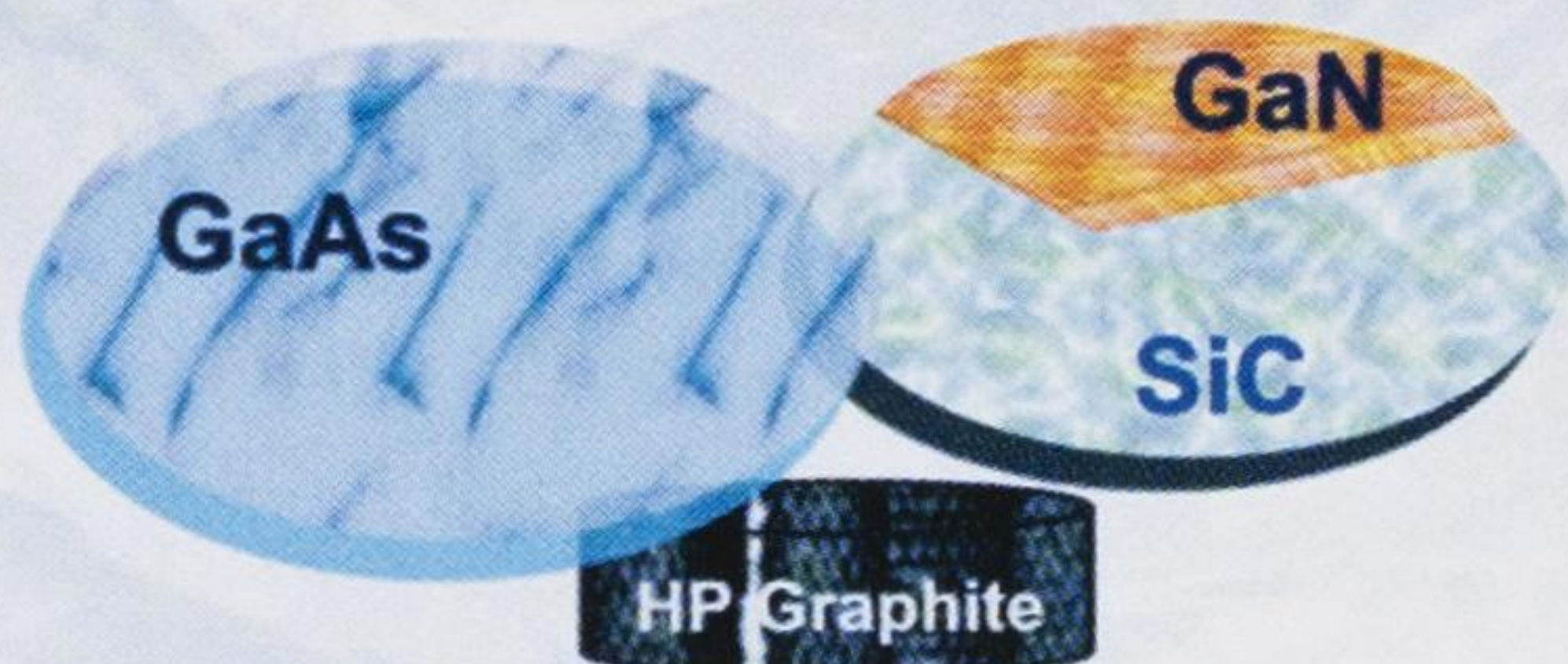
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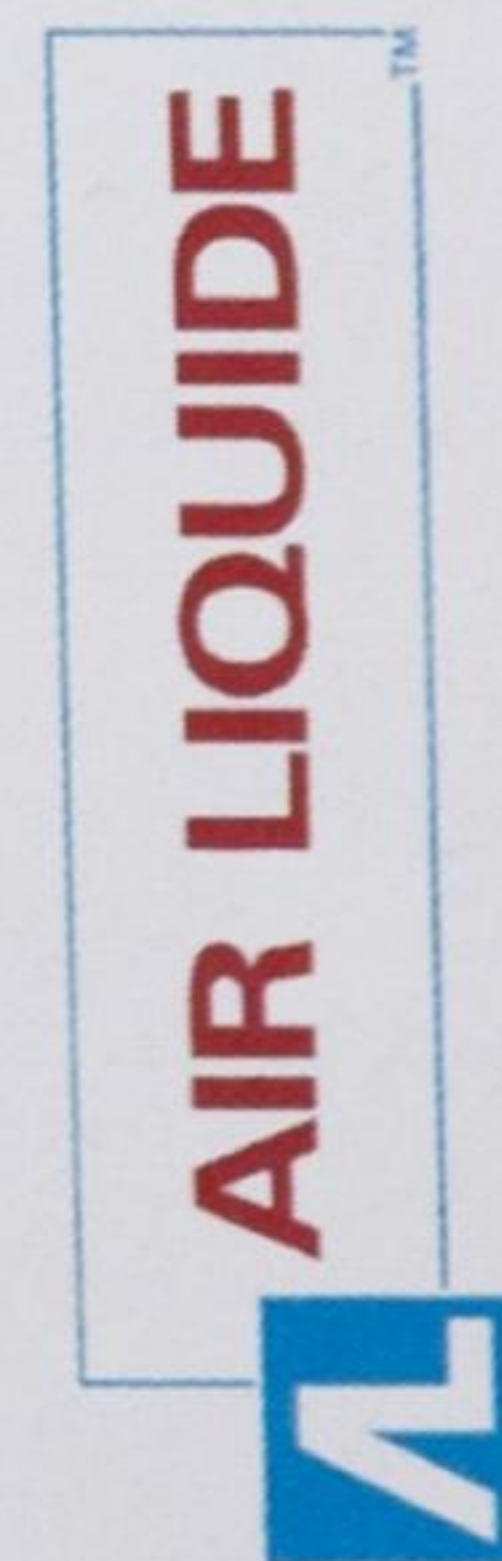
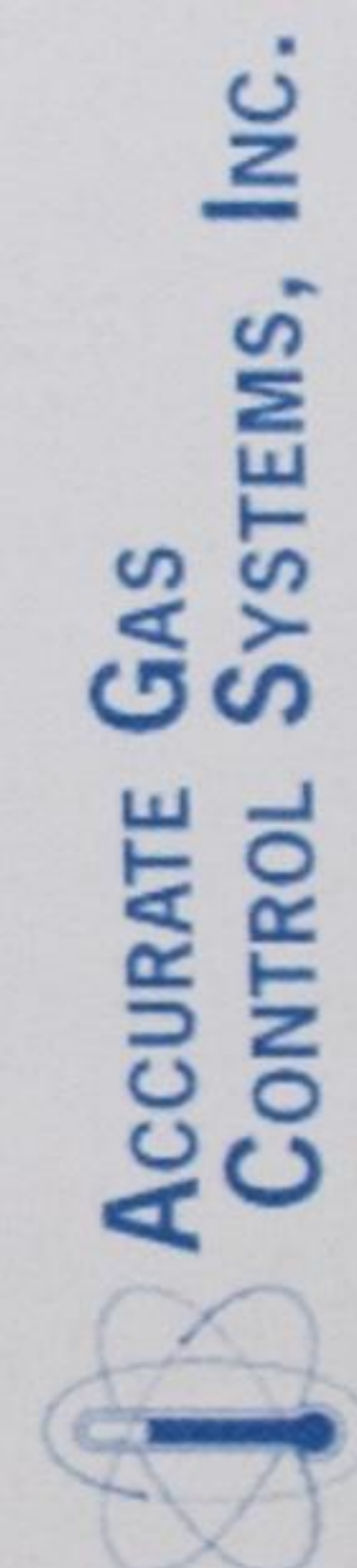


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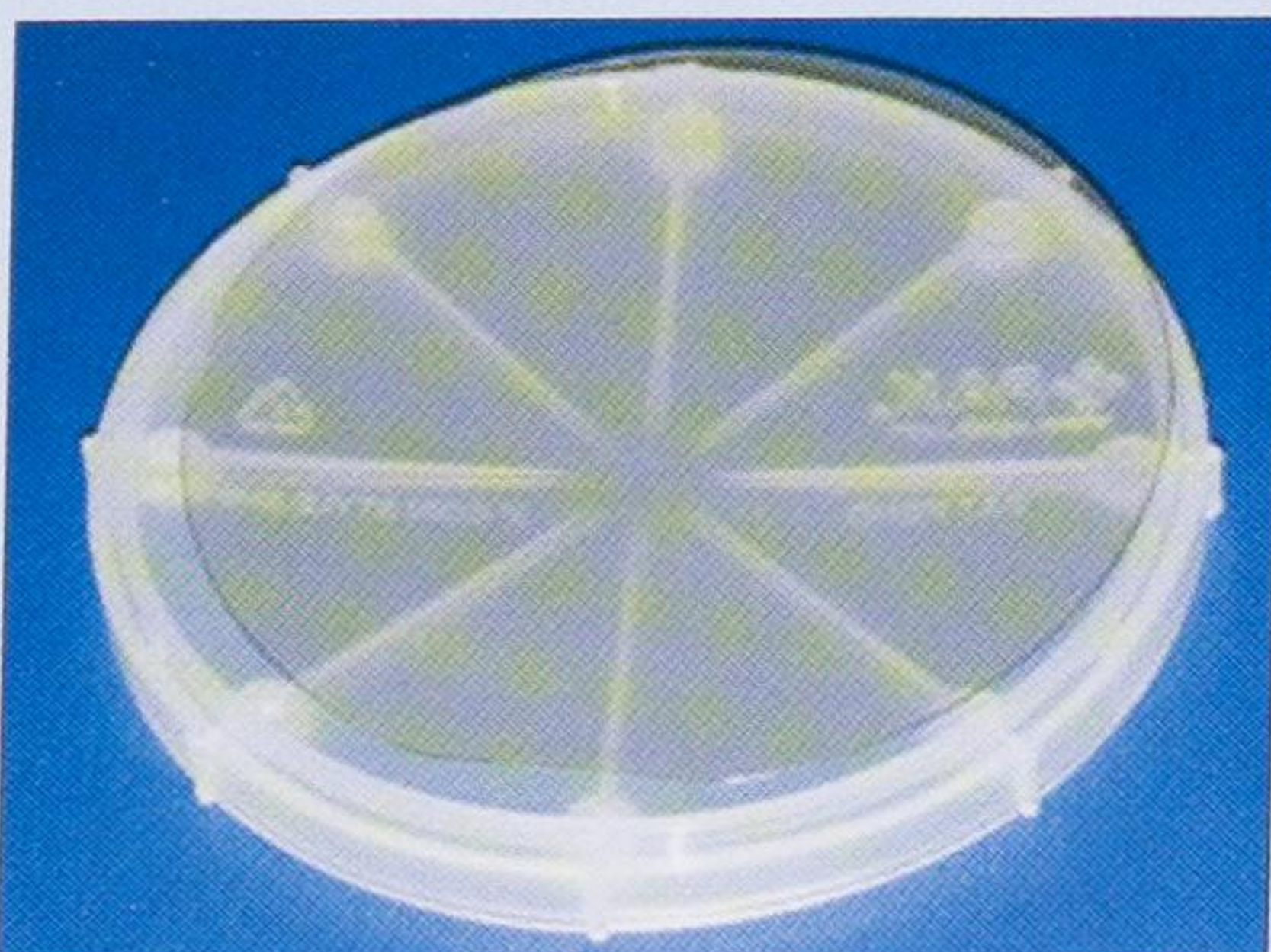
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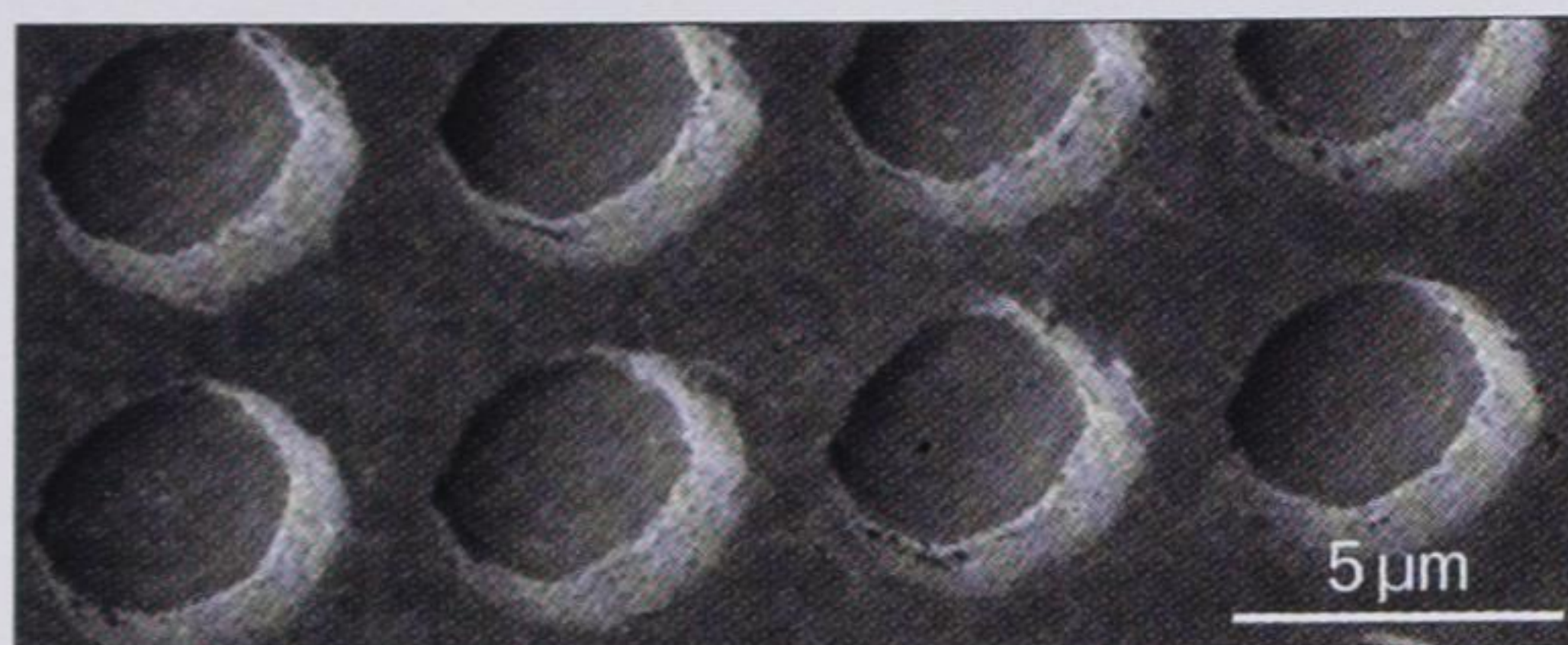
## DEVICE DESIGN

# Micropillars increase output from LEDs

Researchers at National Chung Hsing University in Taichung, Taiwan, have made micropillar 409 nm LEDs that deliver 39% more output power than conventional devices. The team says that this improvement arises because a large proportion of light generated from most LEDs is trapped by total internal reflection at the semiconductor–air interface.

The LED fabrication process is based on a patterned sapphire substrate and a laser lift-off technique. This eliminates surface defects caused by plasma etching and combines the lower dislocation densities produced by growth on patterned sapphire with the high thermal conductivity of a copper substrate.

Fabrication begins by using inductively coupled plasma to etch an array of 1  $\mu\text{m}$ -deep holes in a sapphire substrate that are 3  $\mu\text{m}$  in diameter and spaced 3  $\mu\text{m}$  apart. The initial GaN layer (see figure, top), the n- and p-doped cladding layers and the InGaN/GaN active region are then deposited by MOCVD. Copper electroplating of 100  $\mu\text{m}$ -thick films onto the epiwafers creates the metallic substrate, before laser lift-off removes the sapphire to leave an



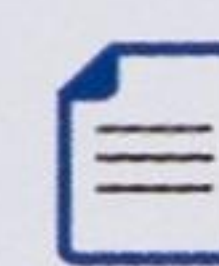
**Cross-sectional** transmission electron microscopy of dislocations in the GaN layers grown on the patterned sapphire substrate (top) and (bottom) scanning electron microscopy of the morphology of the micropillar array.

array of circular bumps (see figure, bottom). Finally, a photoassisted potassium hydroxide chemical etch removes the undoped GaN layer, and a Ti/Al n-type contact is added by electron-beam evaporation.

The technique produced 1  $\times$  1 mm LED chips with a peak emission at 409 nm. At an injection current of 350 mA, these devices delivered an output power that was 39% higher than that of some conventional LEDs that the team fabricated and used as a benchmark. At 20 mA the forward voltage of both types of device is very similar, which shows that the fabrication process does not adversely affect the quality of the n-doped layer.

When the micropillar LEDs were incorporated into an epoxy-containing package, the output was only slightly higher than that of the standard LED. The team's Dong-Sing Wu says that this is because the refractive index of the epoxy affects the external efficiency.

The team aims to increase the efficiency of LED extraction by texturing the micropillar surface and decreasing the micropillar size and spacing to 2  $\mu\text{m}$ . Ray-tracing calculations show this to be the best size for high output.



## Journal reference

Wang et. al. 2006 *Appl. Phys. Lett.* **88** 181113.

## OPTOELECTRONICS

## MBE-grown GaN lasers receive a lifetime boost

By Richard Stevenson in Montpellier, France

Valerie Bousquet of Sharp Laboratories of Europe (SLE) told delegates at the International Conference on Blue Lasers and LEDs (ISBLLED) that her team has extended the lifetime of its MBE-grown nitride lasers to 3 h. Although still much shorter than that of the

MOCVD-grown nitride lasers that will feature in the first generation of HD-DVD and Blu-ray Disc players, this represents a significant improvement on the 3 min figure reported by the same team last June.

The company has pursued this technology because it believes that the approach offers advantages over MOCVD in terms of more accurate doping profiles, lower consumption of source materials and the possibility of *in situ* growth monitoring.

The latest SLE lasers, which are grown on free-standing substrates produced by Sumi-

tomo Electric and Lumilog, deliver a continuous-wave output of 14 mW at a drive current of 450 mA, with a threshold voltage of 6.5 V.

This represents a 2 V improvement in the threshold voltage compared with previous attempts, and is due to a 15  $\Omega$  decrease in the resistance of the p-doped region. Bousquet and colleagues achieved that by switching from a superlattice structure to a bulk region.

Bousquet believes that the threshold voltage will need to drop by a further 1.5 V, accompanied by a similar fall in the threshold current density, to improve laser lifetime further.

## Research in brief...

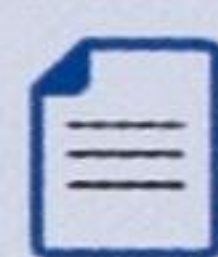
### ...Mirrors cut catastrophic damage

Engineers at Quintessence Photonics, CA, have more than doubled the output power of InAlGaAs laser diodes by using non-absorbing mirrors that reduce the impact of catastrophic optical damage (COD). The research could lead to an improvement in the performance of near-infrared laser diodes, because the output of these devices is limited by COD that occurs when the facet temperature reaches the melting point of the semiconductor.

The team used a process that involves the growth of a single-well separate confinement structure, followed by masking with  $\text{SiO}_2$ , etching of the unprotected active region and

then growth of the n- and p-doped regions.

The improvements resulting from this process were revealed by comparing the performance of two 808 nm lasers with 50 nm apertures – the laser incorporating the non-absorbing mirrors had continuous-wave output of more than 6 W, while the benchmarking conventional device failed at 2.3 W.



## Journal reference

*Electron. Lett.* 2006 **42** 535.

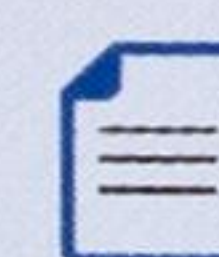
### ...NEC breaks output power record

A team at NEC, Japan, claims that it has broken the output power record for a compound

semiconductor metal-insulator-semiconductor (MIS) FET with an AlGaIn/GaN structure featuring a recessed gate.

The team puts its success down to the improved field concentration in the gate insulator, which results from a recessed-gate structure with a field-modulating plate.

The 48 nm-wide recessed transistor, grown by MOCVD on semi-insulating SiC, delivered a continuous-wave output of 141 W at 2 GHz, with a linear gain of 7.6 dB, a power-added efficiency of 56% and a drain bias of 40 V.



## Journal reference

*Electron. Lett.* 2006 **42** 489.





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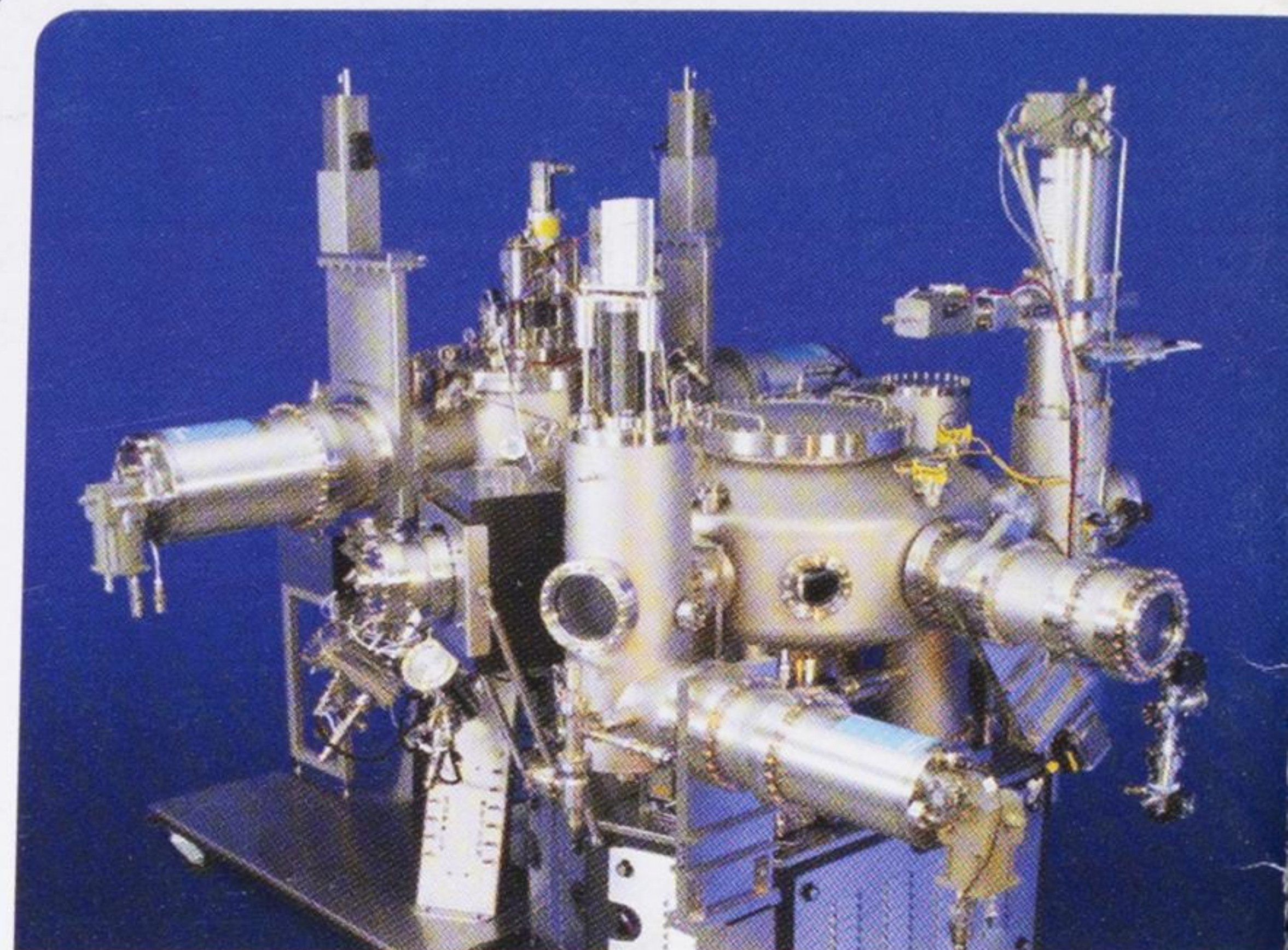


Photo of Veeco Silicon-Style Cluster Tool.

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