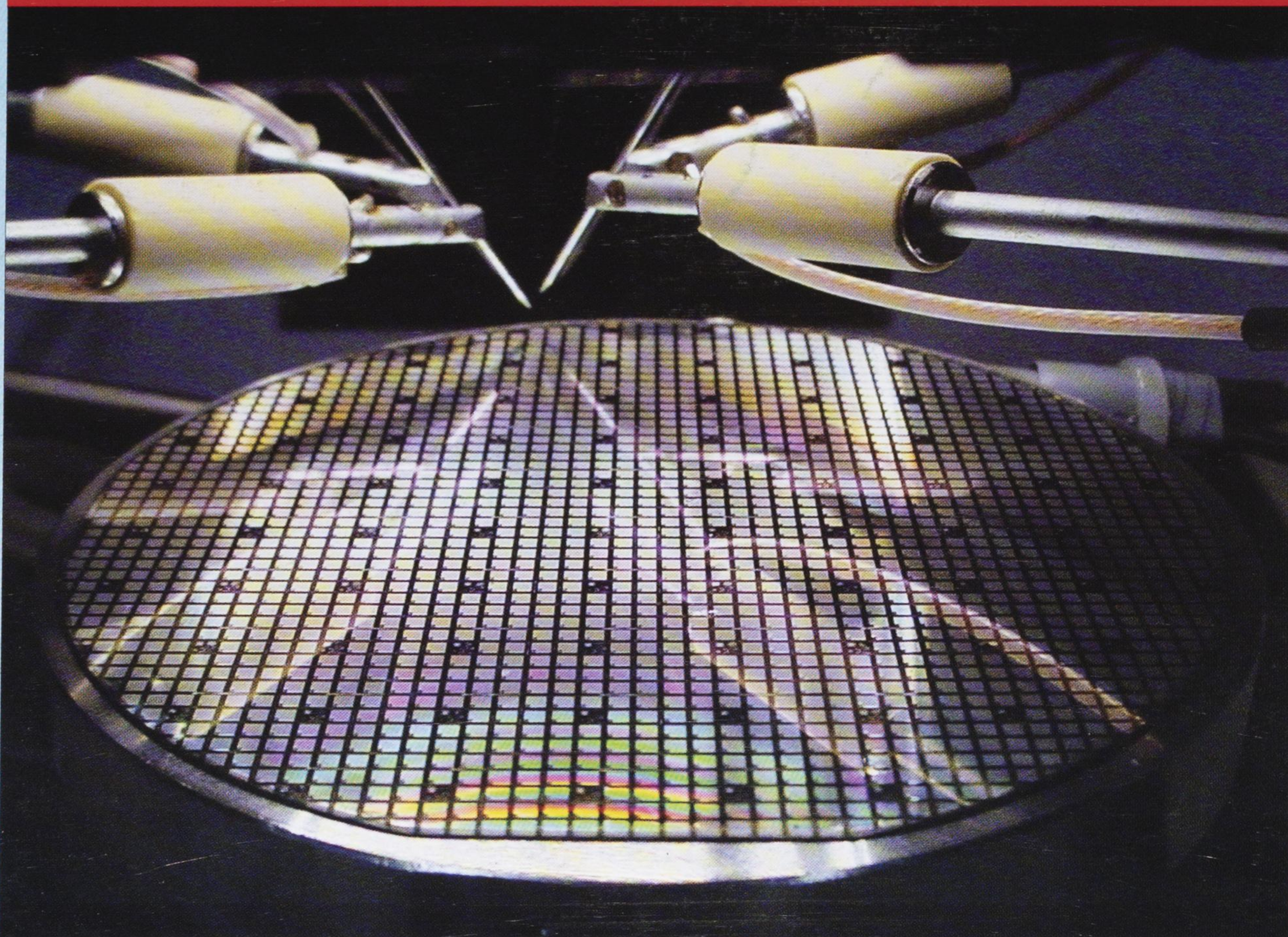


COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

November 2004 Volume 10 Number 10



SILICON CARBIDE

**Updates on epitaxy, devices
and application markets**

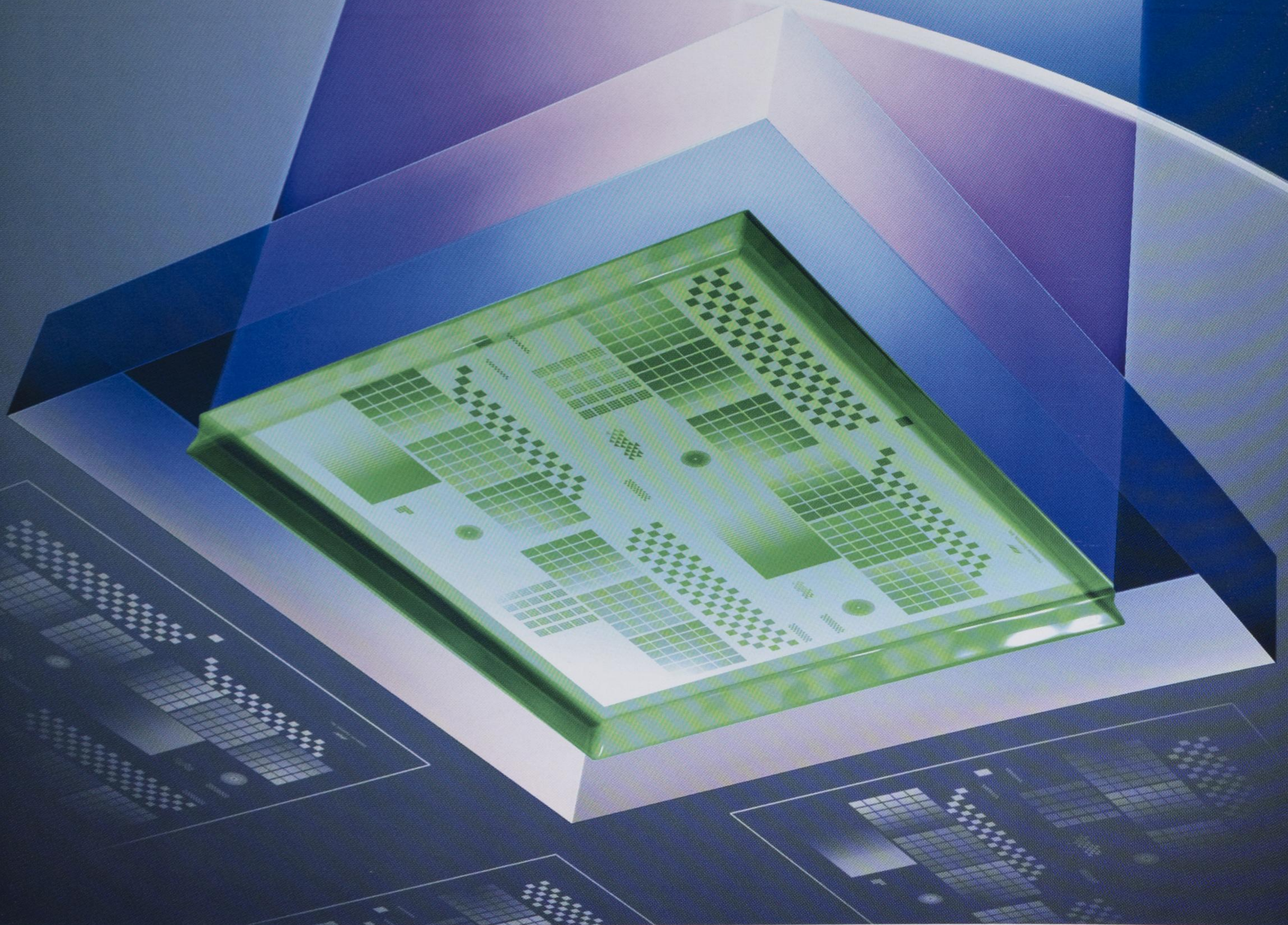
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**Xindium parts with
technical team**

**Blue-laser DVD
battle warms up**

**US backs compounds
on high-risk projects**

Sub-50nm features at low cost. Dreaming? Not anymore.

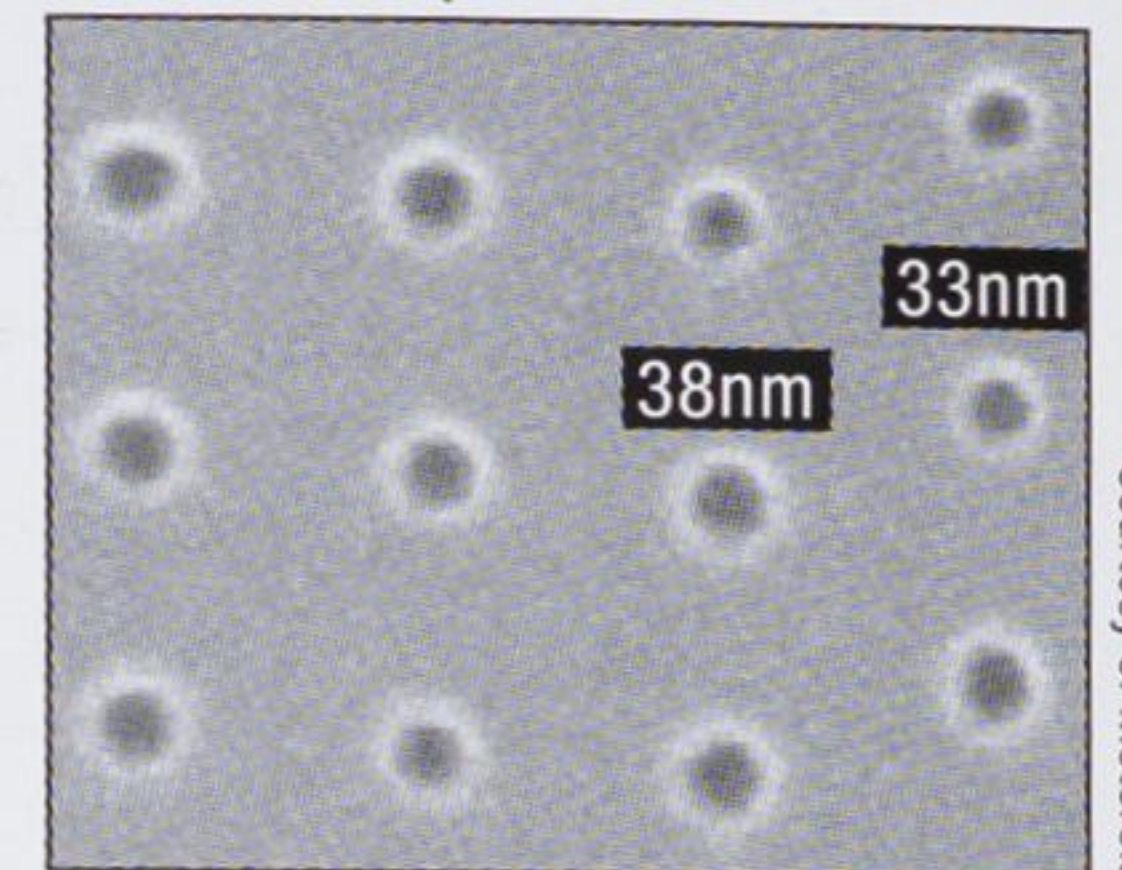


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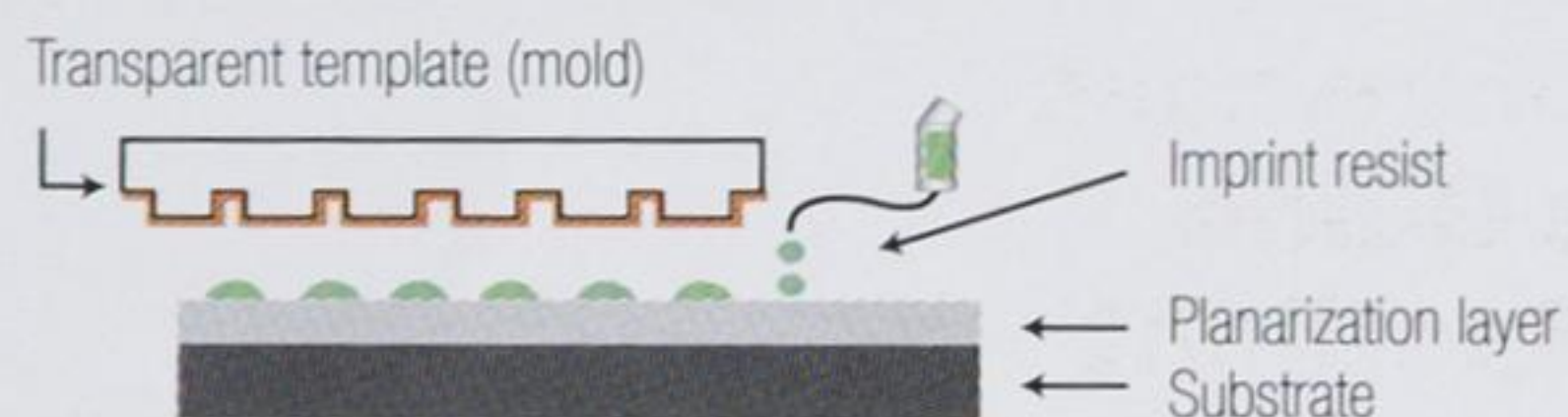
35nm imprinted contacts



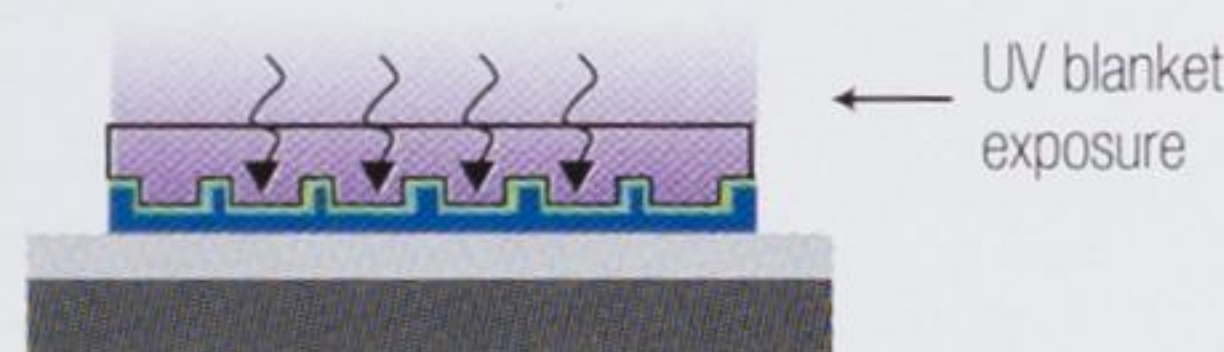
Courtesy of Motorola

The Step and Flash Imprint Lithography process:

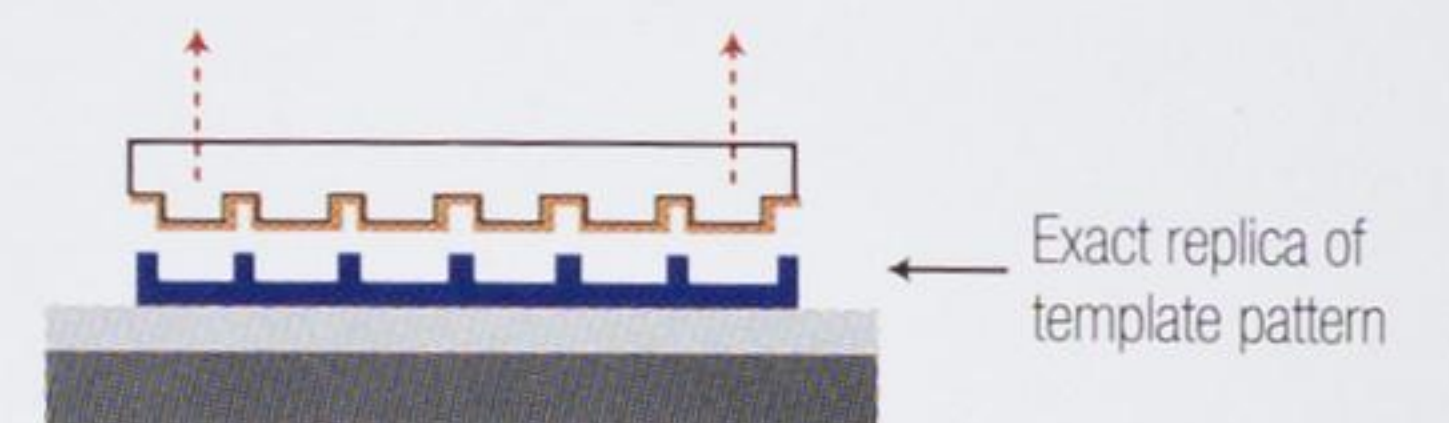
Step 1: Dispense drops of liquid imprint resist



Step 2: Lower template, fill pattern, and polymerize imprint fluid with UV exposure



Step 3: Separate template from substrate



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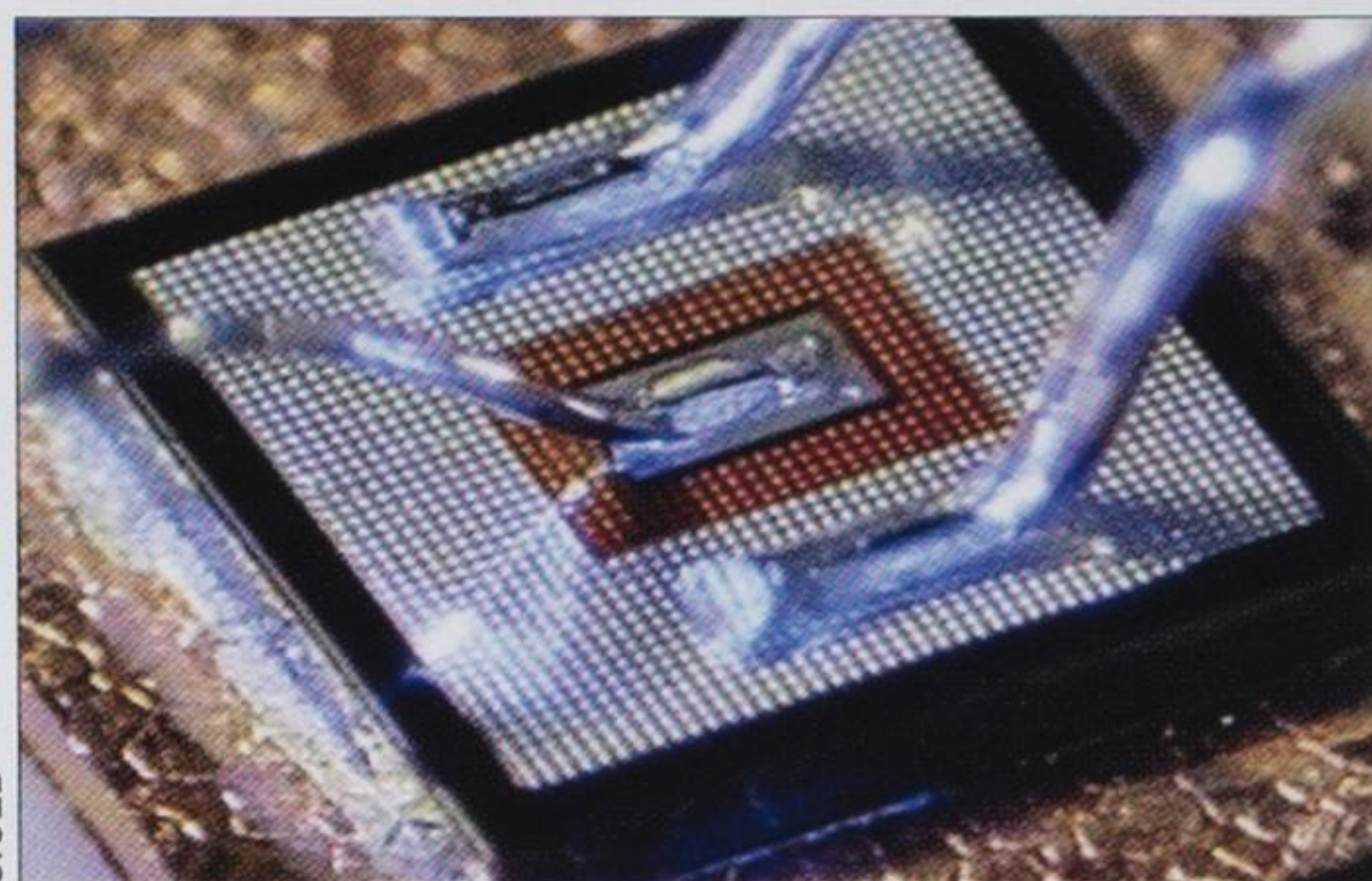
Three-Fives and Silicon Heterostructures

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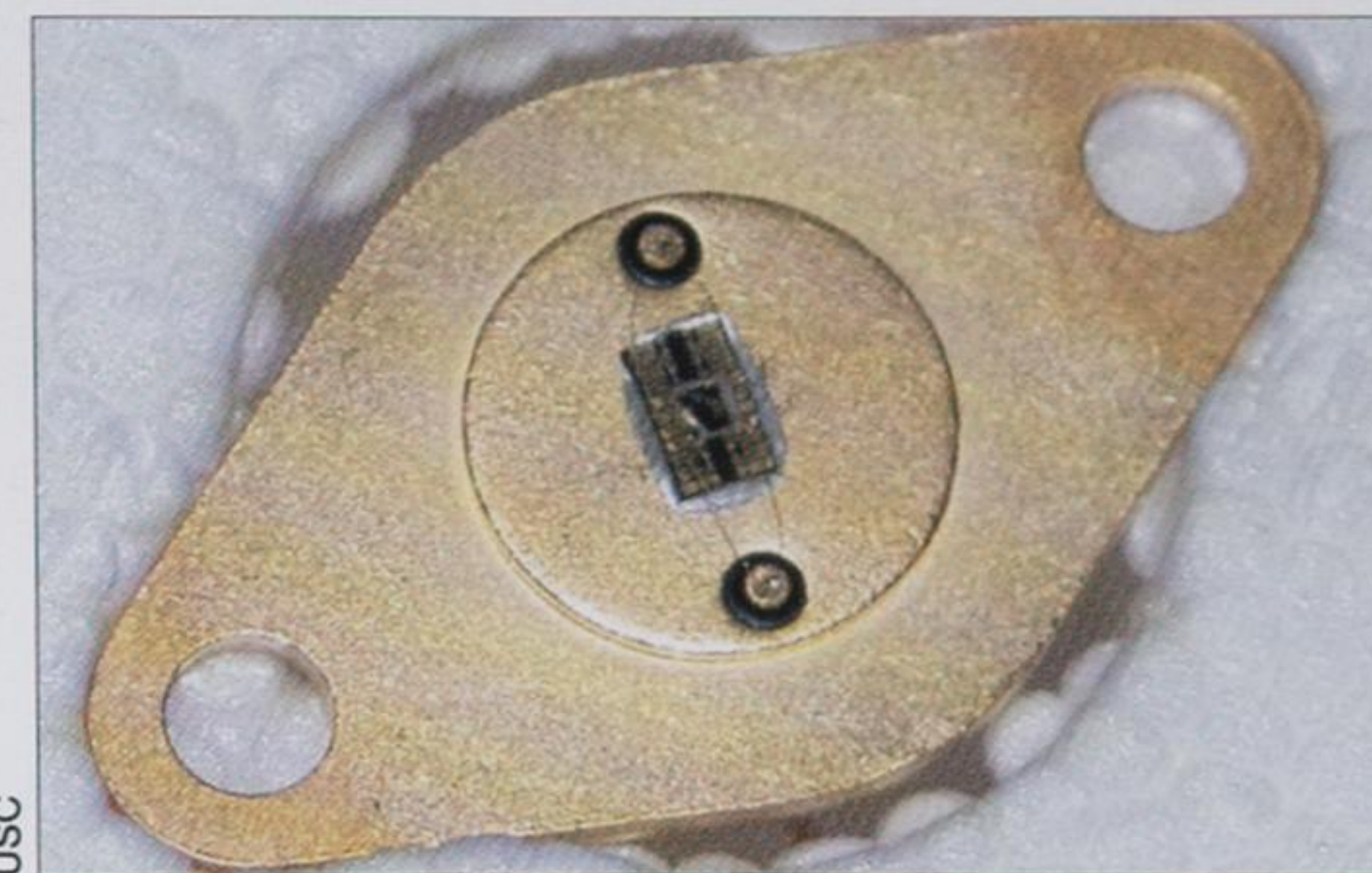
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US firm Lamina Ceramics has developed what it says is the brightest-ever LED array **p6**



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On the cover: 1700 SiC JFETs on a wafer fabricated by scientists at SiCED, a German company looking to exploit the wide-bandgap material in new applications. See page 27.

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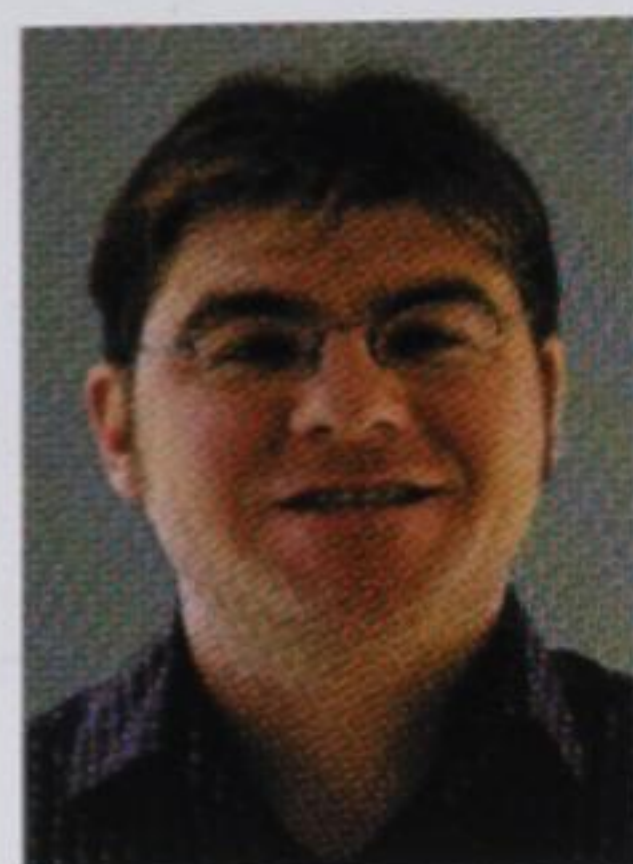
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Swings and roundabouts



So, do you want the good news or the bad news? OK, first the bad news. It appears – in the short term at least – that the industry's recent strong showing in MOCVD sales is on the wane. After spending the first half of 2004 ratcheting up epi capacity for LED manufacturing, companies in Asia appear to have slammed on the brakes and frozen spending. Veeco's MOCVD orders have slumped 70% in the process (see p6).

Michael Yang, who has been working in the Taiwanese epi industry for the past five years and recently resigned as chief executive at Visual Photonics Epitaxy, says that there has been something akin to an arms race in MOCVD capacity in Taiwan over the past year. He believes that the excess capacity purchased in the first half of this year will satisfy Taiwan's LED industry for some time unless there is a sharp upturn in demand in 2005.

And now for the good news. It's 10 years since the fabrication of the first GaN-based blue/violet diode laser, courtesy of Shuji Nakamura and colleagues at Nichia. Now, the consumer electronics world is finally putting such devices into mass production. Nichia's licensing partner Sony will start sampling optical recording heads as of next month as the Blu-ray Disc and HD DVD industry camps step up their rivalry.

The DVD-consuming public will be the ultimate arbiters of which format gains greater industry acceptance, so there is a lot of effort currently devoted to signing up movie studios to provide content. While Sony's recent acquisition of Metro Goldwyn Mayer (MGM) may not appear to have much relevance to the III-V community on the face of it, it will certainly have a bearing on which becomes the winning format, and therefore on the companies that manufacture the laser chips.

Although it is not the great studio of old, MGM's library does include the James Bond franchise and the Pink Panther film series. It's an improbable link, but Nakamura, agent 007 and Inspector Clouseau could be regarded as three chief architects of the GaN revolution.

Michael Hatcher

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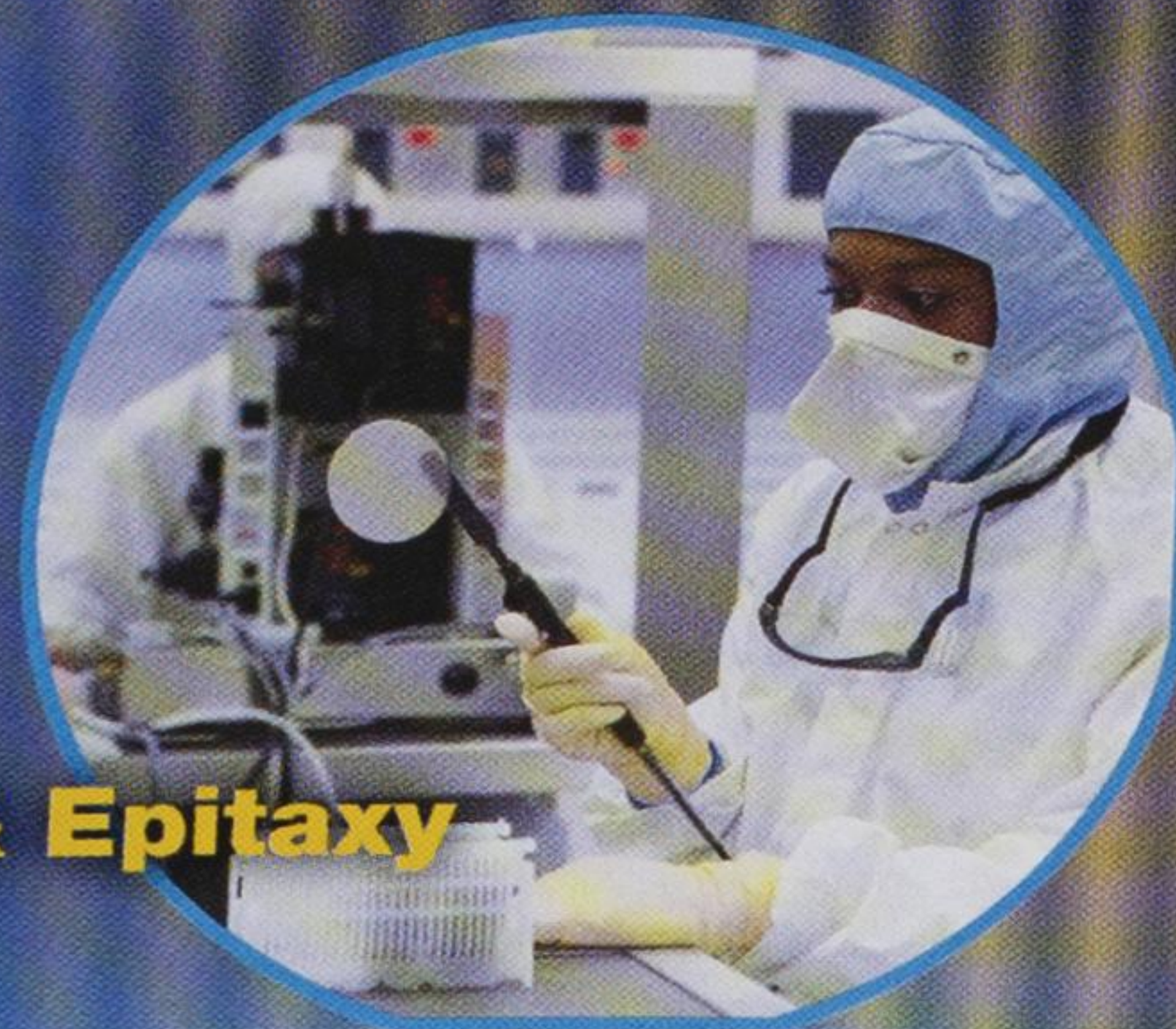
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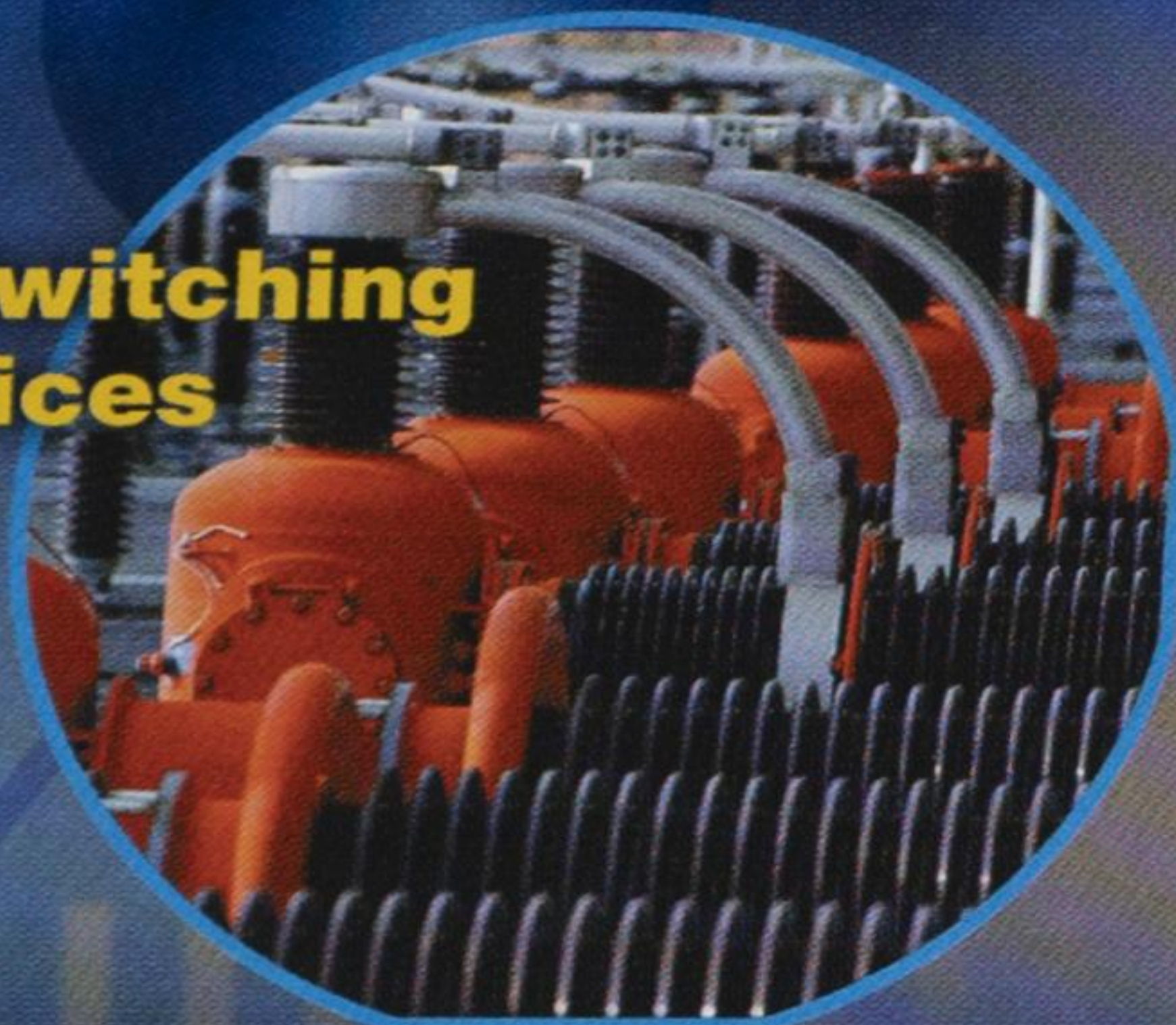


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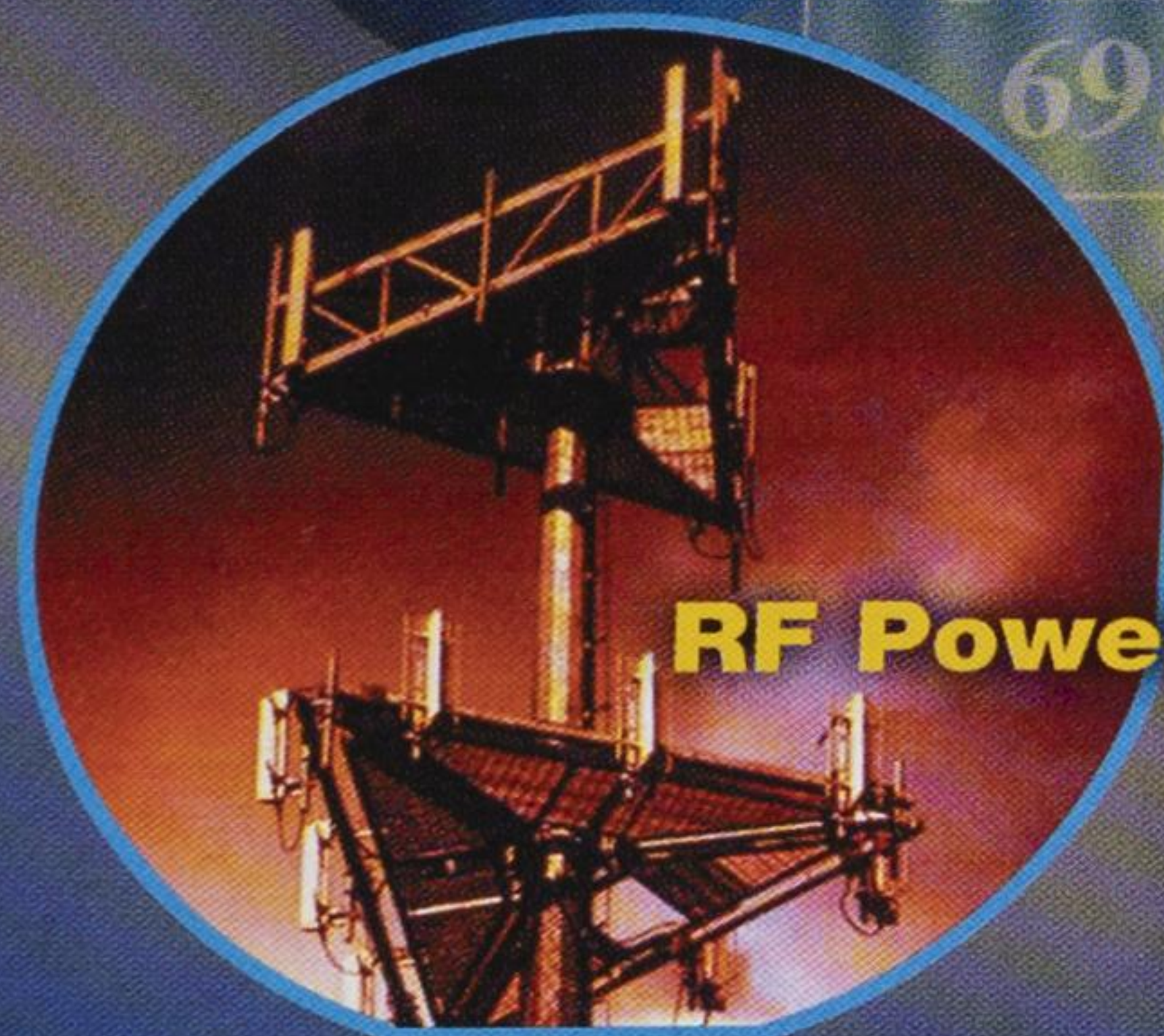


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Next-generation DVD war takes shape

By Michael Hatcher

Next year is set to become a crucial one for GaN-based blue/violet laser diode manufacturers, as the rival makers of next-generation DVD equipment launch their products.

The past month has seen a raft of announcements from both the newly formed Blu-ray Disc Association (BDA) and high-definition (HD) DVD industry camps, including the official launch of the BDA in early October. Whichever format wins, as the battle to dominate the next-generation DVD market accelerates, the makers of laser chips and the materials and equipment that are crucial to their manufacture are all set to benefit.

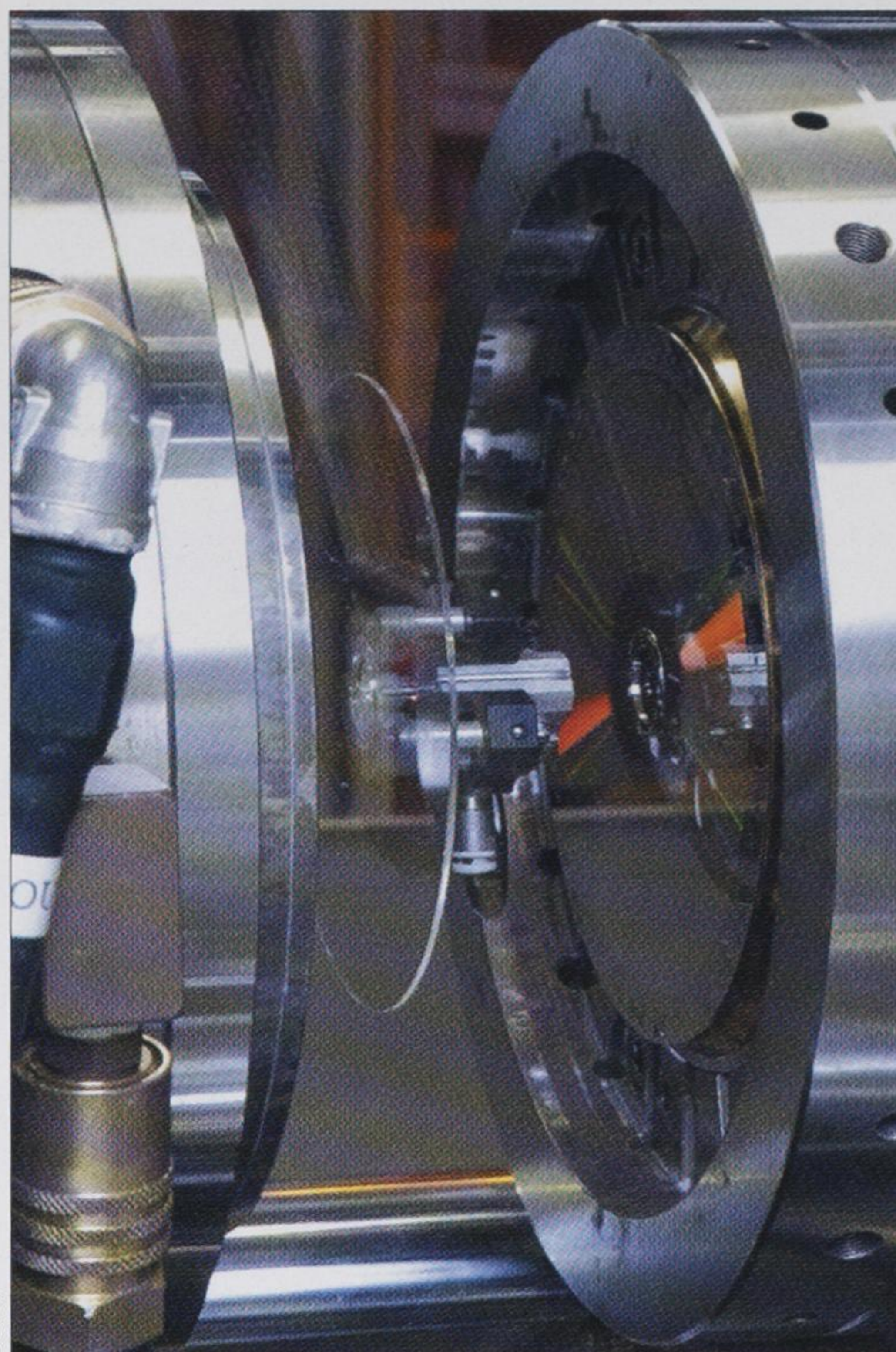
Sony starts sampling

BDA founder member and laser chip manufacturer Sony will begin sample sales of key Blu-ray disc components, including the recordable optical pick-up heads that are built around the laser chip, in early December. Sony is not the only laser chip manufacturer in the BDA, however, and multiple sources of the laser diodes will be used when volume production begins. Matsushita Electric, Samsung and Sharp are all BDA members and potential chip suppliers. Meanwhile, Nichia is believed to be investing around ¥5 billion (\$45 million) on its GaN laser chip manufacturing facilities in a bid to capitalize on the launch of the technology.

HD DVD-founding company Toshiba is believed to be planning an assault on the US market, which is the biggest in the world in terms of DVD sales, late next year. According to reports in the Japanese press, Toshiba plans to begin selling an HD DVD player in the US for under \$1000 in the final calendar quarter of 2005. Then, in 2006, Toshiba hopes to sell more than one million players in the US as it introduces sub-\$500 models to the market, says the report.

HP is one of the founders of Blu-ray and the firm features on the BDA's board of directors. Josh Peterson, who is director of strategic alliances for HP's optical storage solutions business, told *Compound Semiconductor* that all the specifications for the various Blu-ray formats should be finalized by the end of the year. Volume Blu-ray products should then begin appearing by early 2006 at the latest.

Content ownership will be a key factor in deciding which of the two rival blue-laser formats ends up dominating the consumer



Blu-ray discs in mass production at Sony: shown here is the beginning of the disc-replication process, where the BD-ROM master is placed inside an injection machine. Sony is planning to begin sampling optical pick-ups featuring blue-laser chips next month.

market, and a couple of recent developments suggest that Blu-ray may be winning this battle. First, Sony acquired the legendary movie studio Metro-Goldwyn Mayer in a multibillion-dollar deal.

Then the BDA was further bolstered with backing from 20th Century Fox, although the Hollywood studio has made it clear that this does not mean it is committed to publish on the Blu-ray format. Peterson says that the studios and the consumer market will ultimately decide which format goes on to dominate the industry, and he believes that the studios will decide on their position within six months. "It's clear that they don't want to deliver content on two formats," said Peterson.

The HD DVD camp has claimed that its format will result in cheaper disc manufacturing because it is compatible with existing production technology. Peterson dismissed this notion, saying that there will soon be a need to replace much of the existing DVD-manufacturing equipment, which has become

outdated and cannot match the tighter tolerances required for the new formats.

Blu-ray could have a significant advantage up its sleeve in that Sony researchers have shown the format to be capable of supporting an eight-layer structure. This would extend recording capacity to 200 GB from the current 25 GB single-layer form. Peterson contends that this extendibility will be much harder to implement on the HD DVD format because of the disc's construction.

Winning industry acceptance

Toshiba and its colleagues in the HD DVD camp have Disney and Warner Video numbered among its content providers. Japanese disc manufacturer Memory-Tech has installed HD DVD equipment on its mass-production line, and its Tsukuba plant has a capacity of 720,000 discs per month. Pony Canyon, which is Japan's leading distributor of DVD films, has announced its support for the HD DVD format and plans to launch titles in 2005.

"We are confident that we will see a number of major studios and software companies launching titles to coincide with our release of HD DVD products in 2005," said Toshiba's Yoshihide Fujii.

Peterson says that the recent BDA "kick-off" meeting, in which around 70 companies were involved, shows that the momentum is now behind the Blu-ray format, with the key studio Columbia also on board. Another firm to join the BDA recently was JVC, which has developed a new lens for optical pick-ups based on Blu-ray technology. According to JVC, the lens is smaller than current devices, while it can also be manufactured more cheaply. The lens and the laser chip are seen as two of the major contributors to the high cost of Blu-ray technology.

Maureen Weber is both the BDA's chief spokesperson and the general manager of HP's optical storage solutions business. She predicts that the JVC decision will mark the onset of a flood of companies flocking to pledge their support for the BDA cause. "We expect many more companies representing all segments of the consumer electronics, PC and optical-media industries to join as members," she said. "The BDA's growth from 13 to 73 companies over the past three months reflects the sheer depth of industry acceptance and support for Blu-ray as the next-generation optical disc format."

High-risk projects receive \$7.2 million

High-risk projects involving SiC power modules for automobiles, high-brightness LEDs for solid-state lighting and AlN substrates have won \$7.2 million in funding from the US Commerce Department. The department's Advanced Technology Program (ATP), which is managed by the National Institute of Standards and Technology in Boulder, CO, funded 32 new projects in the latest round of awards.

The ventures will run for three years, and all involve high-risk efforts that a single company would be unlikely to take on without additional backing from the state. However, the potential benefits of any successful projects on the US economy could be huge.

Three of the newly funded initiatives directly involve compound semiconductors. The biggest of these is focused on white LED

lamps for solid-state lighting. It includes chip-maker Cree and nanomaterials specialist Nanocrystal Lighting. With ATP backing of \$3.4 million, the total fund for this project amounts to almost \$7 million.

The aim is to demonstrate an LED-based lamp with an integrated-chip approach that would more than quadruple the brightness and double the efficiency of existing LED systems. If successful, such a development may reduce the cost per lumen of LED lamps to a point where their introduction for general solid-state lighting could be accelerated by three years. Cree and Nanocrystal plan to combine high-efficiency blue LEDs with phosphor nanomaterials that convert the emission into broadband white light.

Meanwhile, an intriguing project that could drastically reduce reliance on gasoline in auto-

mobiles has been sponsored by Mississippi State University spin-out and SiC-chip specialist SemiSouth Laboratories. With ATP funding of \$1.8 million, SemiSouth plans to develop an integrated SiC smart power chip that promises to halve the volume and weight of hybrid electric-vehicle power modules.

SemiSouth has lined up car manufacturer Nissan, as well as General Electric and Lockheed Martin, as potential partners in the project. A prototype module is expected to take five to seven years to produce.

The third initiative, which has received \$2 million from the ATP, involves the development of AlN native substrates by Crystal IS of Watervliet, NY. Armed with this extra cash, the company plans to accelerate the development of 2 inch-diameter boules for both electronic and optoelectronic applications.

Veeco faces fall in MOCVD sales

US-based equipment manufacturer Veeco Instruments has warned that its orders for the quarter ending 30 September 2004 will be \$40-45 million down on its earlier guidance of \$80 million.

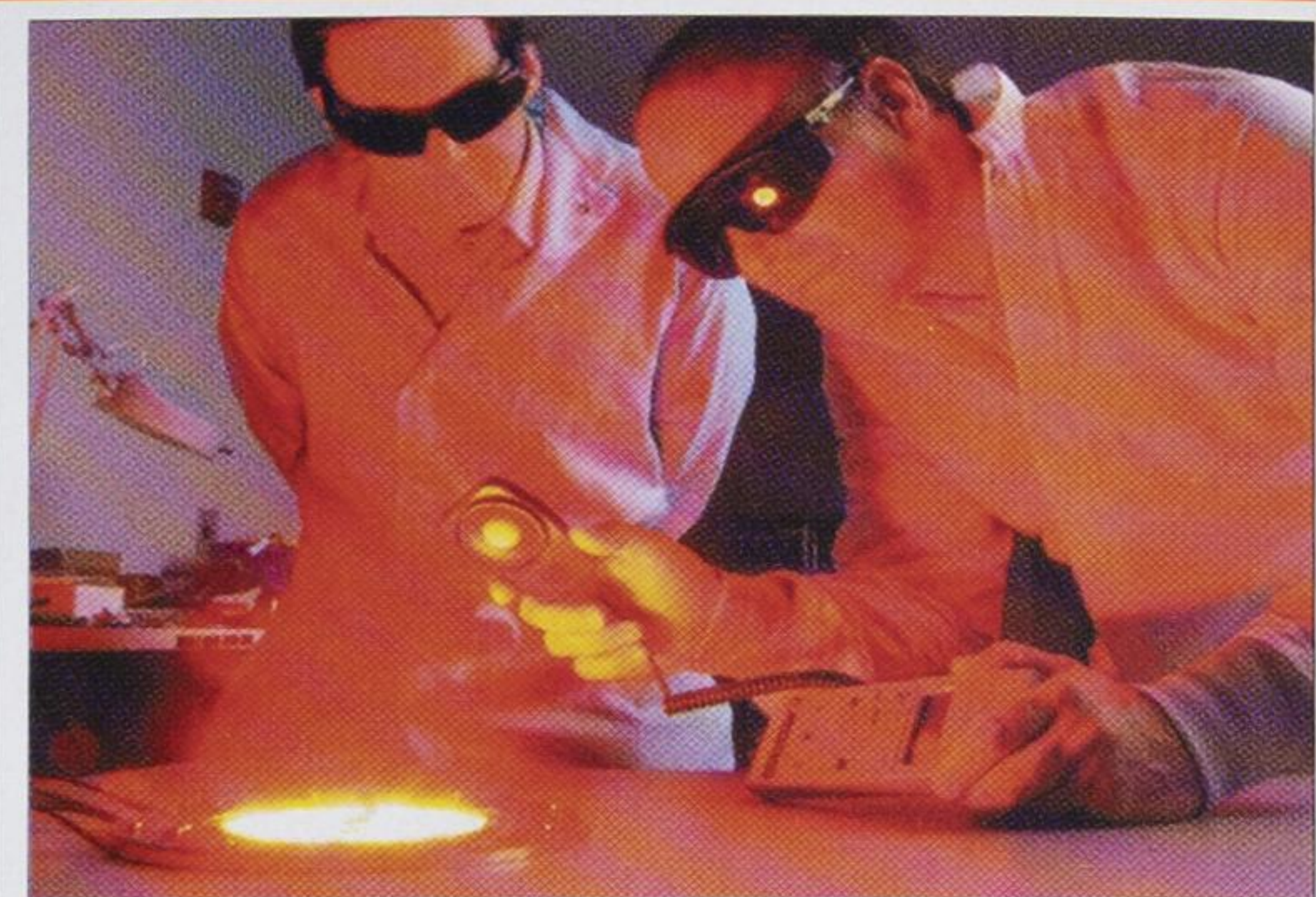
The problem is largely due to a 70% decrease in orders for MOCVD equipment placed by LED manufacturers. The company attributes this to Asian customers freezing their spending after significant outlays on Veeco's equipment in the first half of 2004.

Michael Yang, who recently resigned as president and CEO at Taiwan-based epiwafer foundry Visual Photonics Epitaxy to take up a post at National Taiwan University, said that the problem began in late 2003: "When one of the leading LED companies in Taiwan was looking for additional epi capacity outside the company, it had difficulty finding a reliable source. It decided to purchase MOCVD reactors itself," explained Yang.

To keep pace with that expansion, rival companies in Taiwan decided to follow suit in the first half of this year, leading to concerns surrounding potential overcapacity. "The market-demand growth has not been as fast as the capacity growth," said Yang. "Unless demand turns up steeply next year, the reactor suppliers can only expect the majority of orders to come from newly formed companies."

Yang also pointed out that some Taiwanese companies have started to increase wafer sizes from the 2 inch standard, and this may further slow MOCVD reactor sales in Taiwan.

Veeco is expecting the situation to improve next year. "In the near term, we expect our customers' current capital-spending reluctance to continue, but believe it will be outweighed by a need to fund their 2005 new-product roadmaps and to invest in the expected growth of next-generation consumer electronics," said Edward Braun, Veeco's CEO.



Thanks to improvements in thermal management, super-bright LED-array maker Lamina Ceramics claims to have smashed the world brightness record for solid-state light sources. Its red-green-blue LED array is said to emit 13,300 lm at 860 W, and is 10 times as bright as anything previously demonstrated. The three color channels are independently controlled, with the red source pictured above providing 4600 lm at 210 W. The achievement puts the brightness of LED luminaires on a level with incandescent sources.

InP-based antenna nears completion

Northrop Grumman's InP-based antenna for the Advanced Extremely High Frequency (EHF) payload, a military satellite communication system, hits the final stages of development after successful electrical testing.

The phased-array antenna, which receives

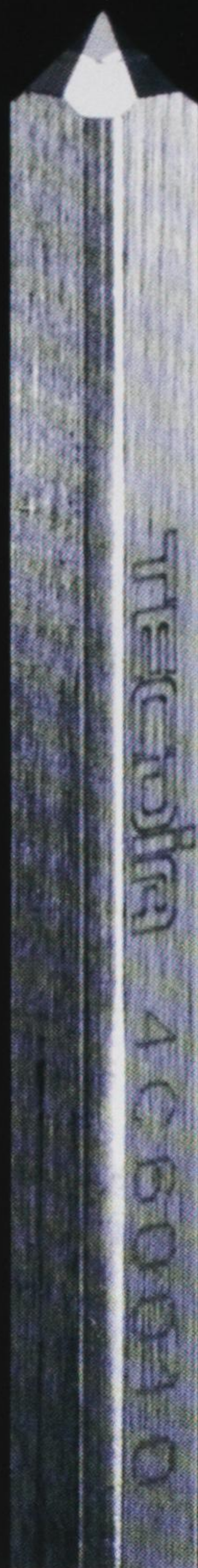
signals from ground terminals, directs RF beams electronically instead of using mechanical reflectors. This means that one array can replace many reflectors, and provide faster military satellite communications and low noise levels. The higher data rate of the InP antenna system will allow transmission of information such as real-time video, battlefield maps and target data.

The array contains more than 10,000

InP-based MMICs and operates at 44 GHz. Using highly directional signals from the antenna, the chances of jamming or interception by the enemy are reduced, allowing secure, reliable communication between command and control units and the satellite.

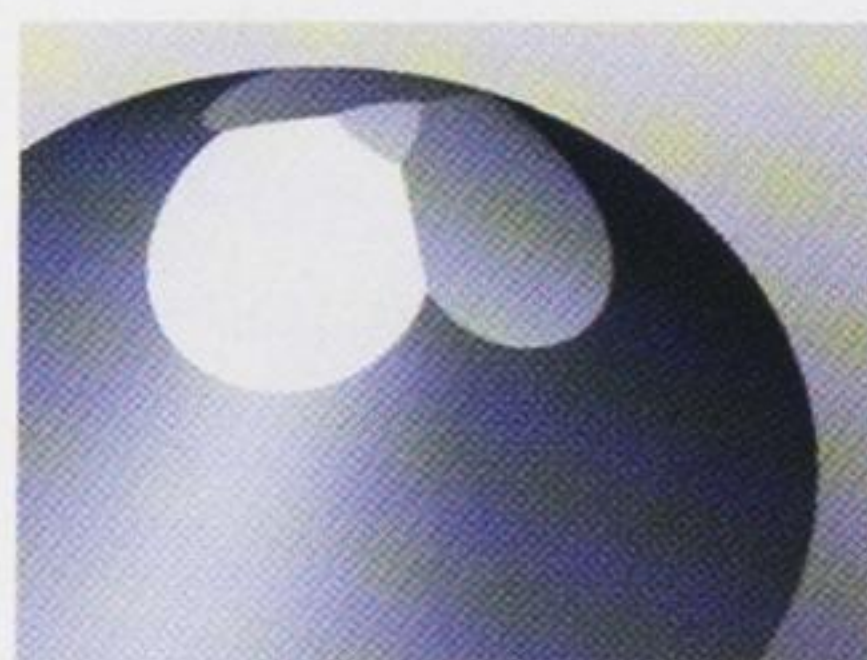
"The tests demonstrate that we are on track to deliver the first flight payload in April 2006," said Clayton Kau, manager of the Advanced EHF payload program.

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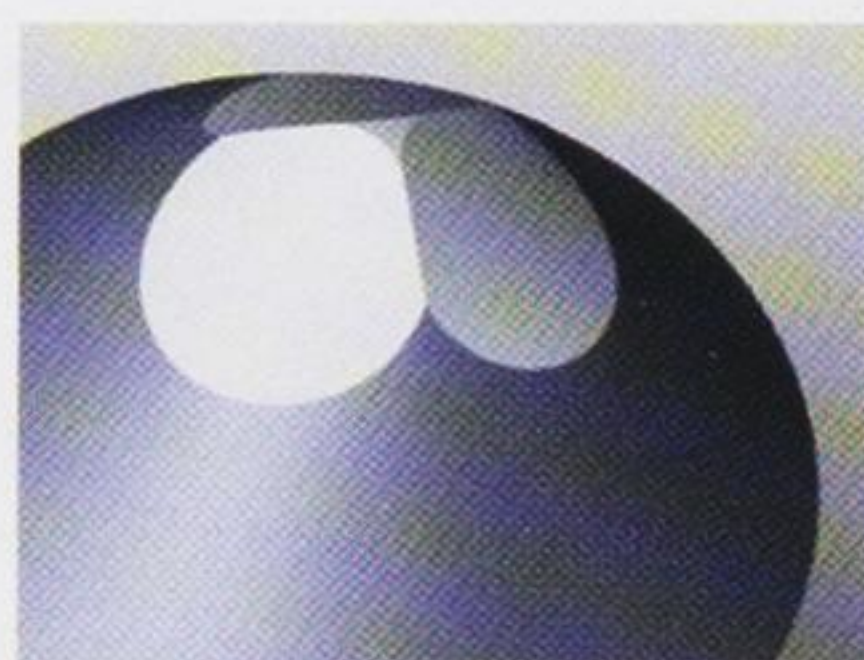
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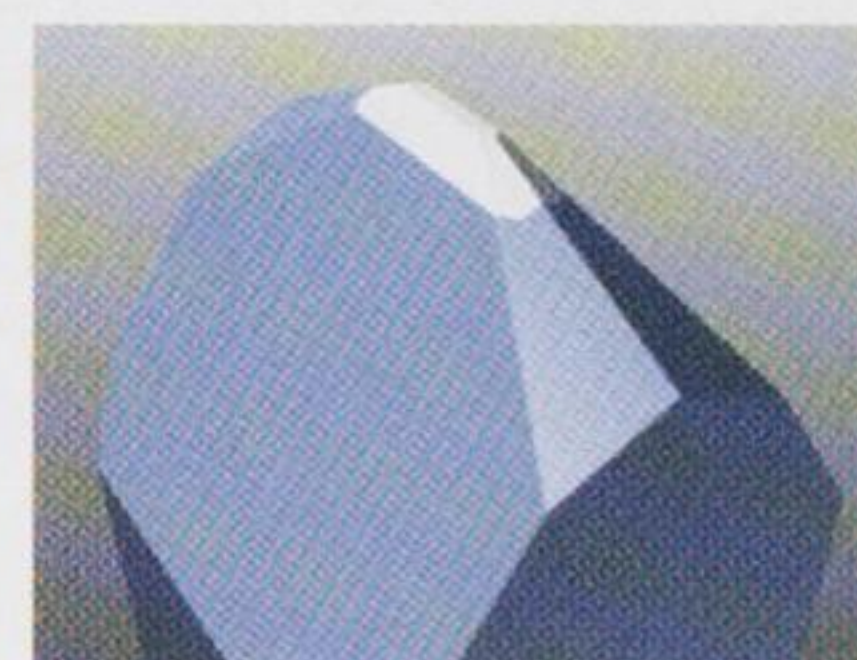
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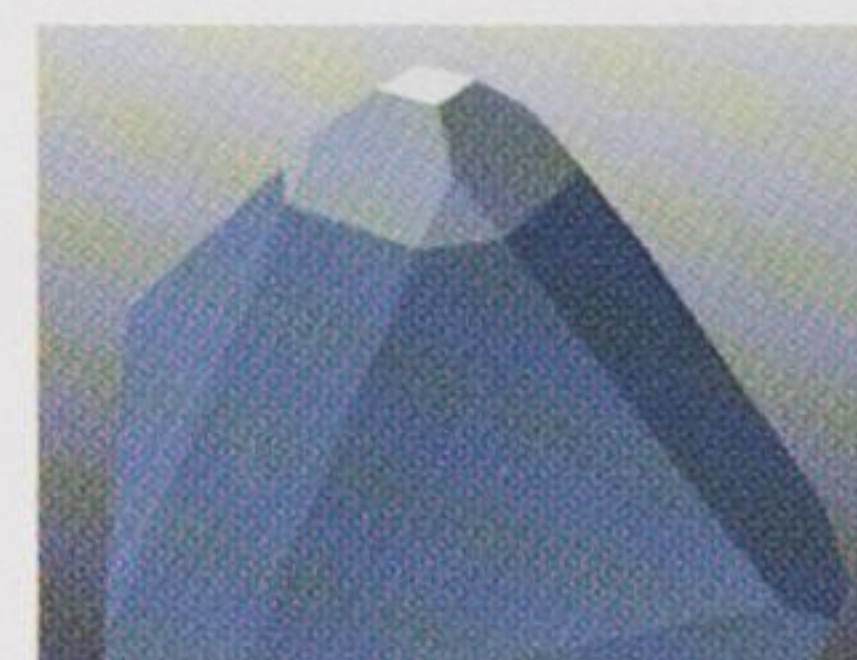
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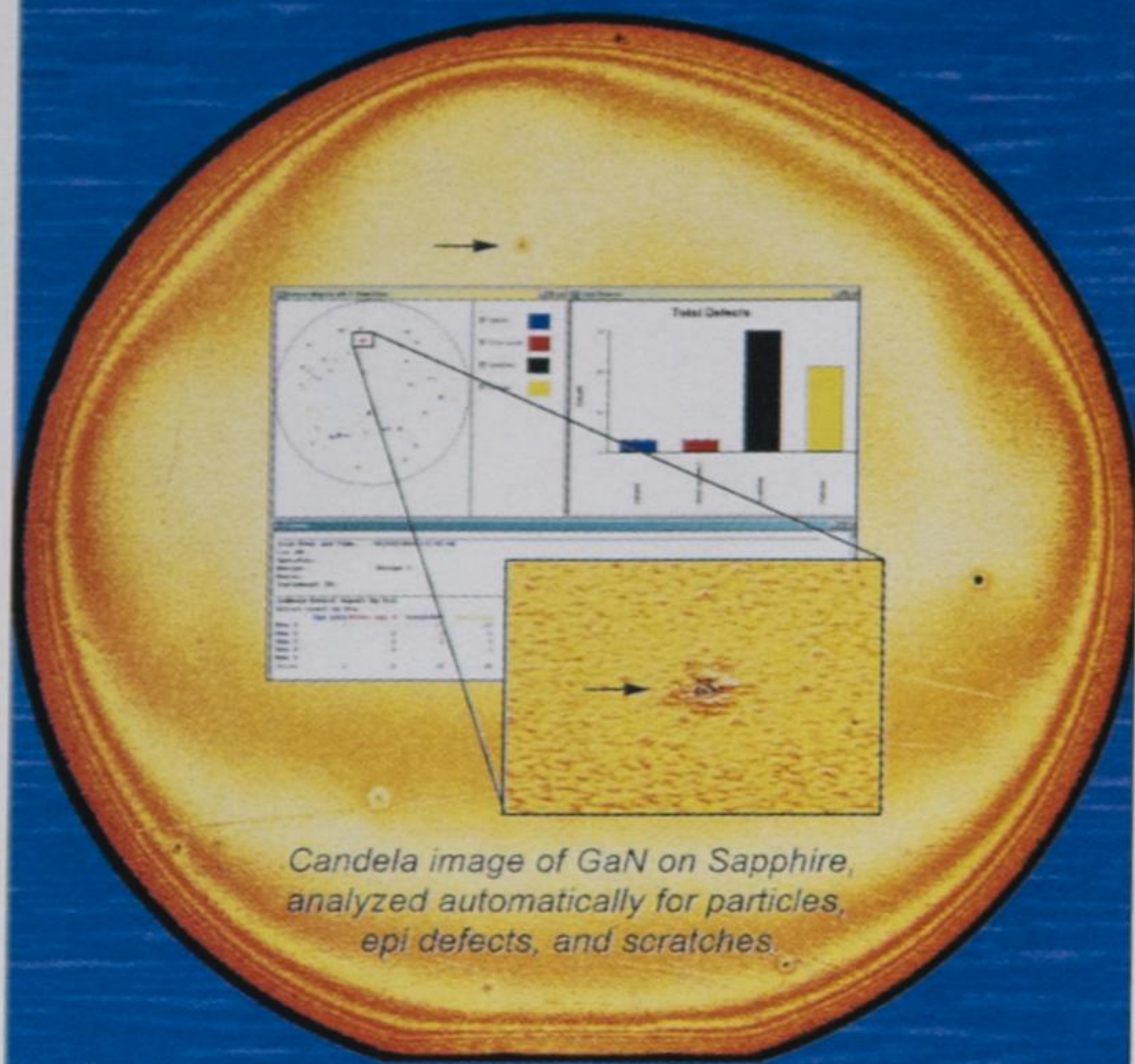
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GAAs & WIRELESS NEWS

RFMD does business with Nintendo and Motorola

RFIC maker RF Micro Devices (RFMD) has begun production shipments of its GaAs HBT-based 802.11 wireless local-area-network (WLAN) transceiver for use in the new Nintendo DS gaming platform, which is being launched in the US this month.

The Greensboro, NC, company has also begun shipping its Polaris Total Radio transceiver in volume to key cell-phone handset maker Motorola. The transceiver features alongside PowerStar power-amplifier modules in Motorola's new MPx220 handsets.

RFMD's WLAN transceiver provides a wireless link to other Nintendo DS units within range. Additionally, with its chat software and wireless capabilities, Nintendo DS gamers will be able to transmit text messages, and even drawings to one another.

"RFMD's energy-efficient wireless device enables Nintendo to include wireless technology in the handheld Nintendo DS at low cost," said Satoru Okada, general manager, research and engineering at Nintendo. "The embedded wireless functionality will enable developers to create rich game designs that were not considered possible in the past."

Kris Rausch, product line director of wireless LAN products at RFMD, said: "We are

extremely excited to be working with Nintendo, the world's leading name in the gaming industry. Additionally, we are pleased to build upon the success of our WLAN transceiver products, which offer distinct advantages in bill-of-materials cost, size, performance and power consumption."

Frank Morese, corporate vice-president of the wireless connectivity business unit at RFMD, added: "Nintendo provides RFMD a valuable growth opportunity as we expand into the explosive video-gaming market."

The video-gaming market had estimated shipments in 2003 of 56 million units and is expected to grow to 80 million units by 2007.

● RFMD was expecting lower revenue than previously forecast for its fiscal 2005 second quarter, which ended on September 30. Citing short-term problems with inventory, primarily in the Asian handset market, sales were estimated to come in at between \$146 million and \$152.5 million, well down on the \$166 million previously predicted. That equates to a 10% drop on the prior quarter. However, the company added that it anticipates growth to return to all three of its business sectors – handsets, wireless connectivity and networks – in the December quarter.

Peregrine Semiconductor throws down RF-switch gauntlet to PHEMT manufacturers

What is being billed as the first CMOS-based switch to connect directly to the antenna of GSM handsets could pose a threat to the GaAs PHEMT RF switch market.

Peregrine Semiconductor, the San Diego-based company that has developed the CMOS switch, says that it has been validated in some early phone designs, with production currently ramping up.

"For the first time ever, a CMOS-based integrated circuit [IC] can be directly connected to the antenna of a GSM handset," said a company spokesperson in a statement.

Offering 41 dBm power and 65 dBm (IP3) linearity, the company believes that the CMOS-based switch gives "superior performance, lower insertion loss, a smaller footprint and higher integration" compared with GaAs PHEMT alternatives.

The device is fabricated using Peregrine's own patented variation of silicon-on-insulator technology. Unlike the bulk silicon substrates conventionally used in the CMOS process, this "ultraCMOS" variant uses sapphire substrates, which Peregrine claims gives high yields and low costs. A thin layer of silicon is deposited onto the insulating sapphire substrate to improve device performance.

"[Handset] designers have long been constrained by the limitations of exotic IC technologies such as PHEMT used in high-power, high-throw switch ICs," said Peregrine's CEO Jim Cable. "This device delivers a simple and profoundly different approach to solving the toughest [switch] challenges."

GaAs PHEMT switch manufacturers include Skyworks Solutions and M/A-COM, both of which are based in the US.

Nokia sees an improving picture for phones and infrastructure

In anticipation of a bumper holiday season for cell phones, Nokia has increased its estimate of 2004 global handset sales to 630 million.

The Finland-based company, which is the world's biggest handset maker with a 33% market share in mobile devices overall, had previously indicated that it expected the sales figure to be around 600 million units.

"We expect continued strong growth in global mobile-device market volumes in the fourth quarter, even [after] the remarkable final quarter in 2003," said the firm.

Nokia sold 51.4 million mobile handsets in its most recent quarter, although the lower selling prices that the company introduced earlier in the year following a drop in its market share were, in part, responsible for a 13%

decrease in its handset revenue.

Although Nokia says that it has gained market share in Europe and maintained its lead in China, the company admitted that it has lost ground in the key US market.

On the network side of the business, Nokia is winning plenty of business as 3G W-CDMA gains commercial momentum. It has signed recent deals to build infrastructure in Bahrain, Taiwan and Libya, and is rolling out 31 W-CDMA networks in 19 different countries.

With customers in developing countries including Ethiopia, India, Pakistan and the Ukraine also signing up for GSM/EDGE networks, Nokia said: "The overall mobile infrastructure market is developing slightly better than previously expected."

Skyworks ramps up Helios production for Korean handsets

Leading GaAs IC maker Skyworks Solutions of Woburn, MA, has received the first high-volume order for its Helios radio system.

The order comes from a Korean handset maker, which is expected to incorporate Helios into its new EDGE products in early 2005.

Helios is an RF subsystem that incorporates a power amplifier (PA) module, a PA con-

troller and a direct conversion transceiver.

The subsystem supports the GSM850 and GSM900 bands, as well as PCS1900 and DCS1800, with two separate HBT PA blocks fabricated onto a single GaAs die. One HBT PA block supports the two GSM bands, while the other supports DCS and PCS.

Skyworks claims that Helios saves space on a handset and can enhance PA efficiency in EDGE mode by up to 10% compared with conventional architectures.

According to one recent market survey, the chipset market for EDGE handset components could reach \$2 billion by 2009.

Mimix HBT MMIC targets satellites

Mimix Broadband of Houston, TX, has introduced a GaAs-based HBT MMIC voltage-controlled feedback oscillator (VCO).

The device uses an on-chip filter to give optimum oscillation conditions. The circuit comprises a linear Lange-coupled phase-shifter, a Lange-coupled quadrature generator, a differential amplifier, a four-quadrant I/Q modulator and an output buffer differential amplifier.

Identified as 9OSC0315, the VCO is said to be suitable for wireless communications applications such as millimeter-wave point-to-point radio, local multipoint distribution services, and satellite communications.

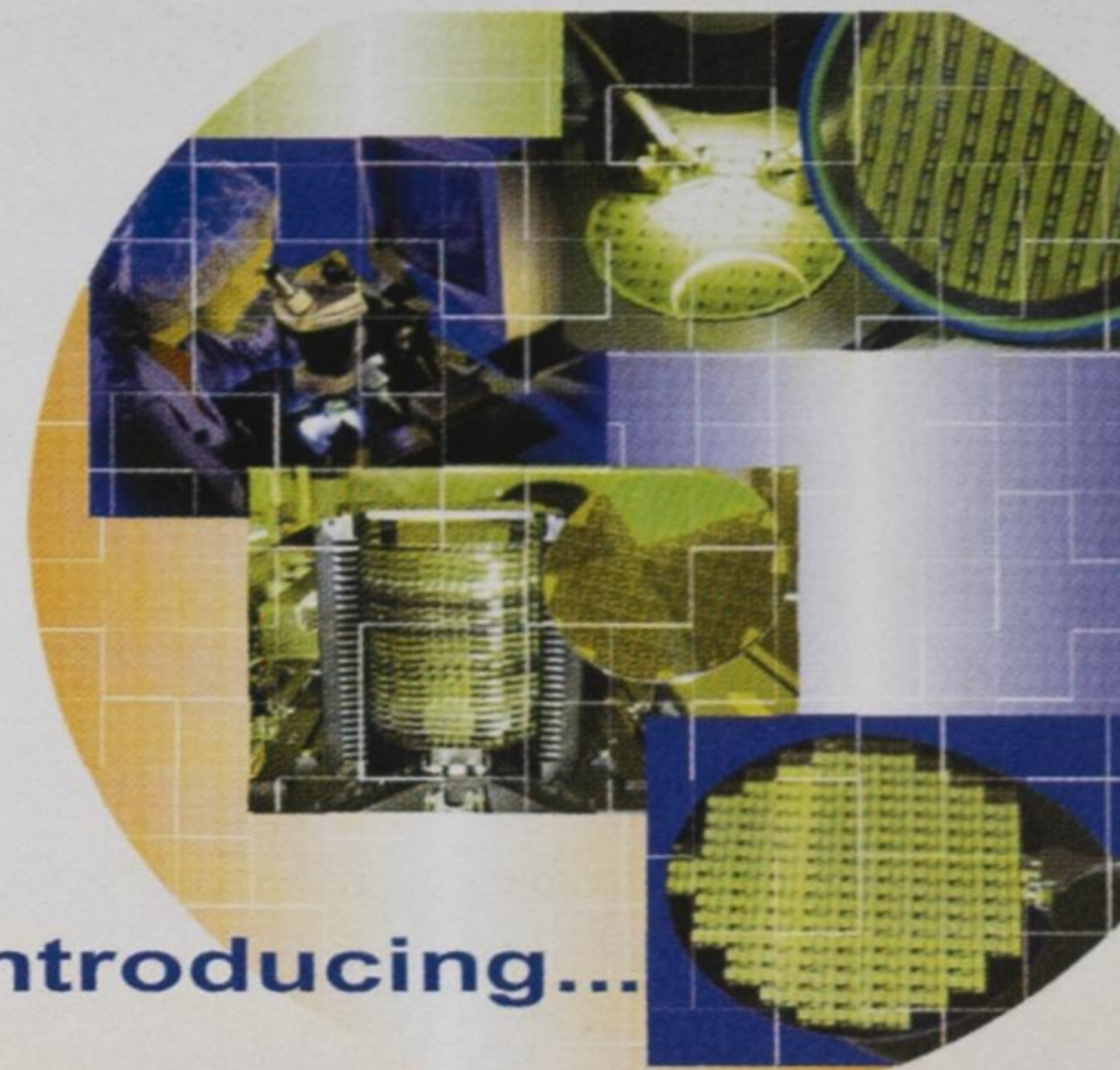
"Although feedback oscillators are well known in the literature, our innovation of

adding a vector modulator to the feedback path – thereby allowing arbitrary phase to be obtained – adds significant functionality," said Jim Harvey, CTO of Mimix.

"Instead of the single section filter used in previous feedback oscillators, we can use a two or three section filter, thus obtaining increased phase slope and better phase noise for a given level of on-chip 'Q' factor.

"We can tune the frequency of oscillation over the pass-band of the multisection filter and obtain wider tuning ranges than other varactor-tuned on-chip resonator-based oscillators. A companion circuit with the filter wired externally allows a variety of tuning ranges from 6 to 12 GHz to be obtained by the user."

The chip also has surface passivation to give a rugged part with backside via holes and gold metallization to allow either a conductive epoxy or eutectic solder die attach process.



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Second LED distributor yields to Osram pressure

According to LED manufacturer Osram Opto Semiconductors, a second US distributor has decided not to import or market products that are alleged to infringe the German company's intellectual property. Osram says that the declaration from American Microsemiconductor, which is based in Madison, WI, relates in particular to products supplied by the Malaysian company Dominant Semiconductors.

In June this year, Osram filed a lawsuit with the International Trade Commission over Dominant's alleged infringement of patent rights concerning two aspects of LED manufacturing. Two months later, Dominant replied with a counterclaim of its own.

Dominant's alleged infringement concerns the conversion of blue light from an InGaN LED into white light through the use of a phosphor. These one-chip white LEDs are widely used to backlight displays in cell-phone handsets and automotive dashboards. The second

area of contention concerns the design of electrical connections for high-power LEDs used mainly in automotive applications. American Microsemiconductor is the second US distributor, after American Opto Plus, to bow to Osram's pressure on intellectual property.

Osram has licensed its technology to a number of major LED manufacturers, including Nichia and Rohm in Japan, Vishay in the US, and Everlight and Lite-On in Taiwan. Osram Opto's managing director, Rüdiger Müller, added that another Taiwan-based firm has also given recent reassurance that it would only use Osram's licensed products and would not risk infringement by manufacturing.

"The agreements between Osram and the two US distributors, and in particular between Osram and the Taiwanese companies, show that infringement of property rights is no longer seen throughout the world as a trivial offense," said Müller.

Global electronics firm Vishay has made its presence felt in the high-brightness LED market with the launch of six different ultrabright LEDs. The surface-mount AlInGaP- and GaN-based devices are said to have the smallest form factor on the market. They measure just 1.6×0.8 mm and are 0.6 mm high. Available in "super" red (633 nm), orange (606 nm), yellow (587 nm), green (570 nm), "pure" green (558 nm) and blue (466 nm), the LEDs provide up to 80 mcd of luminous intensity. Vishay's blue LED has a luminous intensity of 13 mcd. The devices are encapsulated in epoxy resin and packaged on a lead frame base.



Cree smashes its quarterly profit record

US-based LED, RF device and substrate manufacturer Cree has again reported record quarterly profit and revenue figures. In the company's first fiscal quarter of 2005, revenue was \$95.9 million – up \$5.1 million sequentially, and a massive 45% higher than for the equivalent quarter last year.

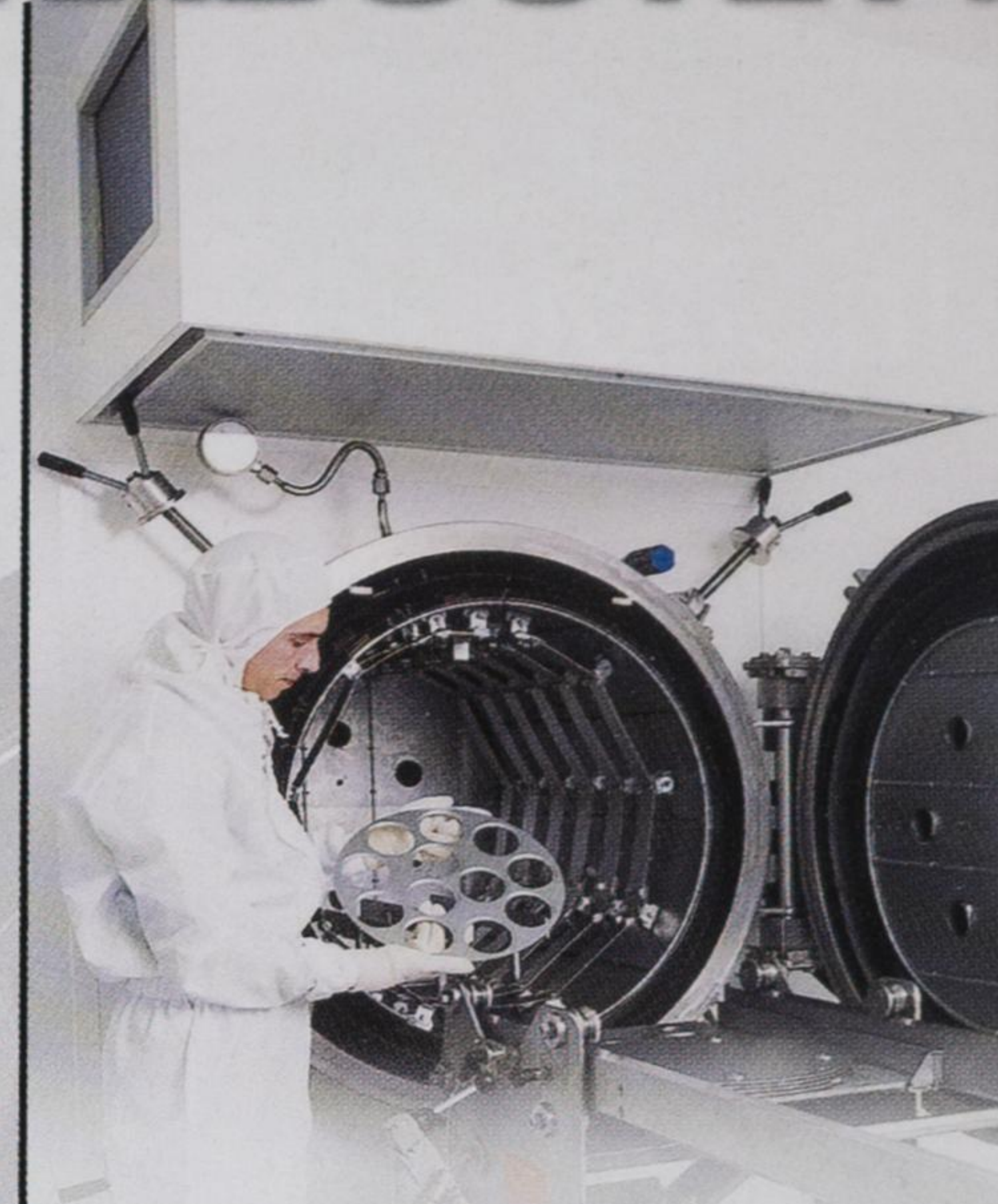
First quarter profit was \$24.4 million – higher than the \$20.9 million recorded in the previous quarter, and nearly three times as great as that posted just 12 months ago. LED products again dominated the recent sales break-

down, accounting for 82% of the revenue.

"Although we have started the 3 inch conversion for LEDs, we haven't seen the benefit yet. We expect the 3 inch migration to be a more important cost driver over the next several quarters, which should enable us to continue to aggressively pursue new business," said Chuck Swoboda, Cree's president and chief executive officer.

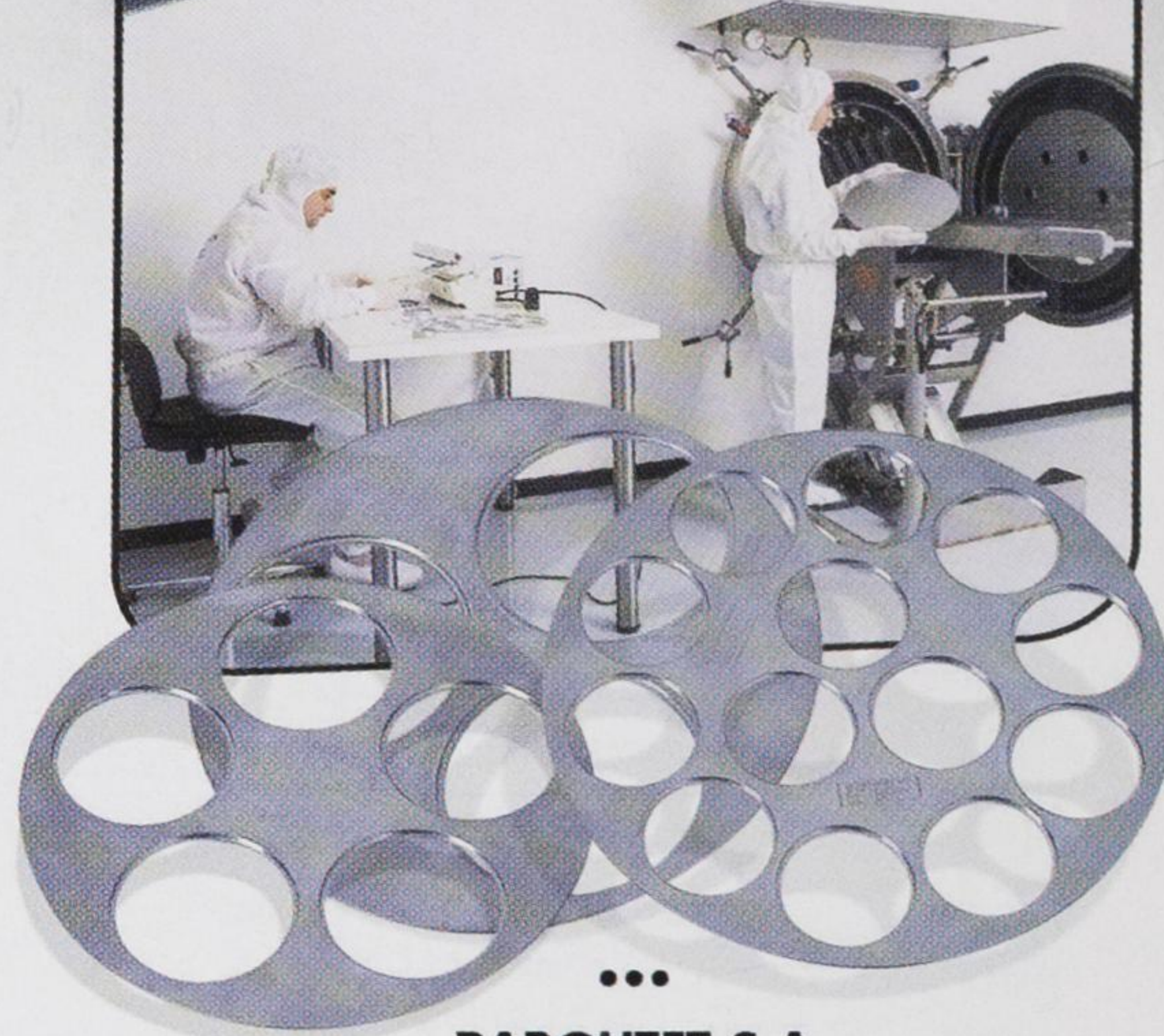
Cree's guidance figures for its next quarter indicate a slight rise in revenue to between \$98 million and \$100 million, and flat profits.

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Infrared emitter delivers improved security vision

Osram Opto Semiconductors says that it has produced an infrared emitter that delivers 50 mW using a "normal" chip size.

The 0.3×0.3 mm device, which emits at 850 nm, has been designed with the automotive and security sectors in mind, for use in applications such as night-vision systems. This is because the emission wavelength is ideally suited to illuminating CMOS and CCD light detectors, says Osram.

The infrared LED exploits Osram's thin-film chip technology, which allows the majority of the light that it generates to escape through the top of the device and reduces light loss from the side of the chip.

This means that the light output increases in direct proportion to the surface area of the chip. Osram says that it has made a prototype device that is nine times the "normal" size and produces 400 mW at 1 A drive current. In the future, the company plans to offer 1 mm² chips



Osram's LEDs assist with car-park security.

emitting 400 mW in its "Dragon" package.

Osram also believes that LED light emission can be improved considerably in future device generations. In two years, it says, output will be increased to 70 mW using standard chip dimensions. Even at the current output level, Osram claims that the LED produces a record radiant intensity of 700 mW/sr in a 5 mm radial package.

Lumileds boosts LED brightness for a better camera-phone flash

Camera-enabled cell phones that are used to take photographs in dark surroundings are set to benefit from two new LEDs from Lumileds.

The California-based LED manufacturer has just released Luxeon devices that have been specifically designed for the flash function of such phones. Lumileds says that its LEDs will offer 12 times the brightness of a typical flash on a camera phone.

The surface-mounted Luxeon Flash LXCL-PWF1 LED has an output of 40 lm at 1 A drive current, while the LXCL-PWF2

delivers double this luminous flux.

Camera phones featuring the Lumileds technology ought to come in particularly useful for taking pictures in the dark at a range of 1–2 m. The latest camera phones on the market feature high-resolution light detectors with many more pixels than previous designs. These require a higher light intensity than previous generations of phones to produce a good image, and consequently a brighter flash.

This is the third major application for LEDs in cell phones, after screen and keypad lights.

In brief

● **Toyoda Gosei** says that it has recently started shipping its TG White II, a 1000 mcd LED used in backlighting cell-phone handset screens.

The firm aims to start mass producing the devices, which contain a blue LED and a yellow phosphor, within a year. It is also developing a 1300 mcd product, which it plans to debut in March 2005.

● **Cree** has added two new high-brightness LEDs to its product portfolio. The XT-24 and XT-27, which emit 24 and 27 mW of white light respectively, have been released with LCD backlighting applications in mind. As well as finding traditional uses in backlighting LCD screens in mobile appliances, Cree believes that the devices could be incorporated into large-area LCDs.

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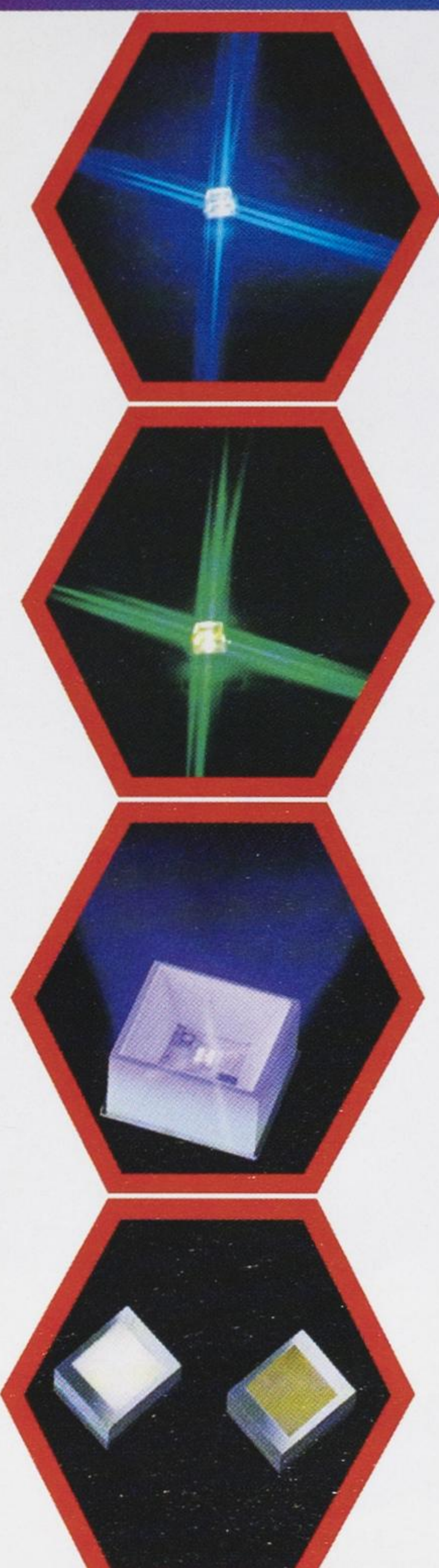
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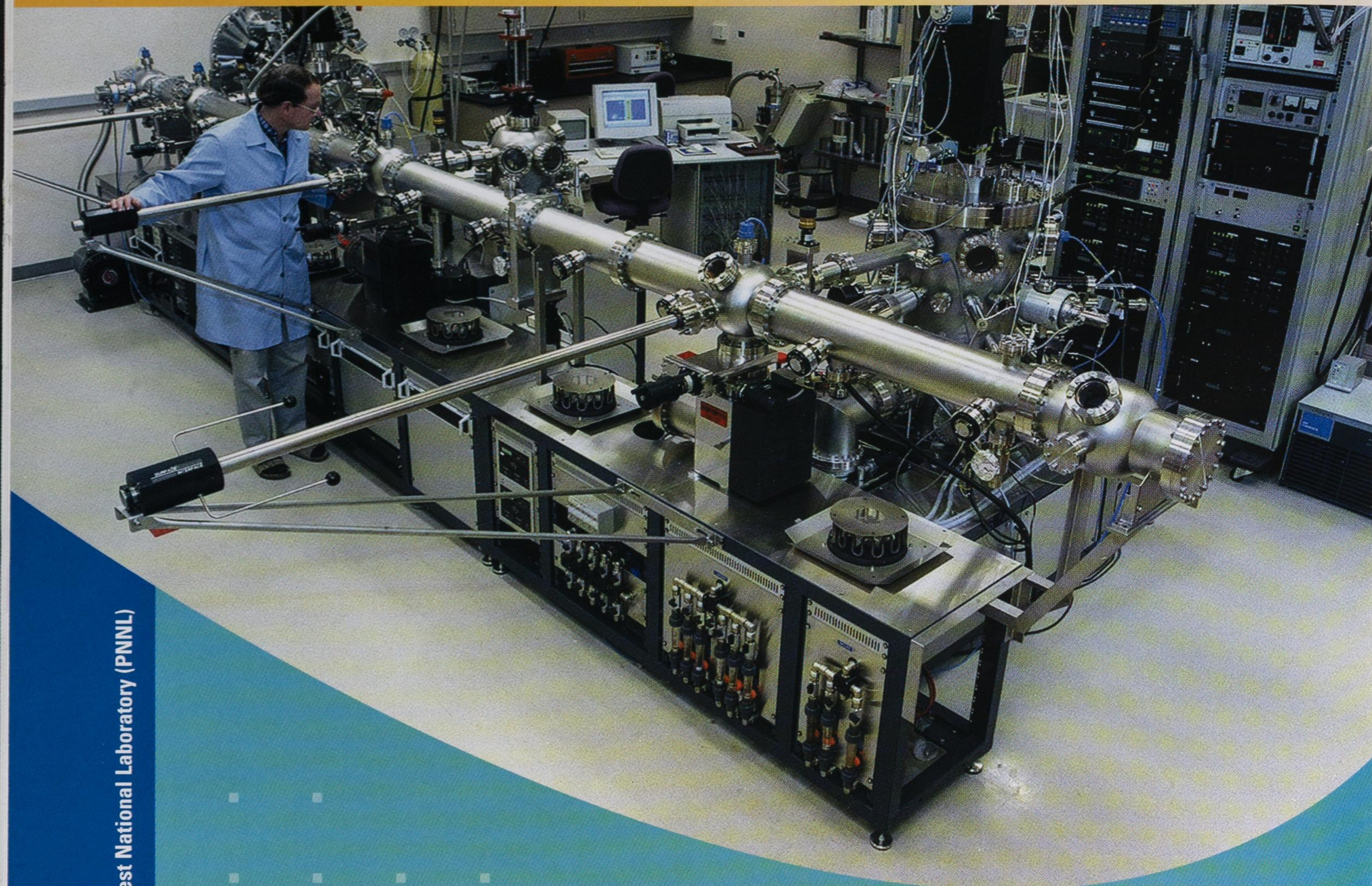


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Deep-UV LED is set for commercial use

Sensor Electronic Technology (SET) says that it has demonstrated deep-UV LEDs with both a high output power and a low drive current. The US-based start-up company has made the devices emit 1 mW in continuous-wave (CW) output at 280 nm with a drive current of 25 mA. In pulsed mode, the same devices yield 9 mW when driven at 200 mA.

SET has only recently been able to reduce the required drive current to a level that is suitable for commercial use. Previously, 280 nm-emitting LEDs had been made to emit

1.53 mW in CW mode, but only at a drive current of 450 mA.

The company has been working on developing the novel light sources – suitable for biological agent detection, spectroscopy and water purification – under a DARPA Small Business Innovation Research contract.

“This is a major development in our efforts to commercialize semiconductor-based deep ultraviolet sources,” said SET’s CEO, Remis Gaska. “Our technology can provide ultraviolet LEDs emitting in any part of the spec-

trum currently covered by mercury lamps, and deliver power levels that are acceptable for a variety of commercial applications.”

The company currently manufactures the deep-UV sources using its proprietary migration-enhanced MOCVD technology. According to SET, epiwafers that are grown using this technique have a better material quality and improved doping characteristics, particularly when it comes to depositing layers with a high aluminum content, such as AlGaIn-based 280 nm LEDs.

InSb-based camera improves performance of brakes on trains



The use of InSb-based infrared cameras to analyze braking could lead to safer trains.

Researchers from the Ecole Universitaire d’Ingénieurs de Lille (EUDIL) are using InSb-based infrared cameras to optimize the braking performance of France’s Train à Grande Vitesse (TGV) express trains. Working in partnership with both infrared camera specialist CEDIP, and brake-pad manufacturer Flertex, the team aims to improve management of the heat load on brake discs.

Infrared cameras allow the identification of “hot spots”, a dangerous phenomenon in frictional parts that can cause either damage and early brake failure, or unacceptable levels of braking performance such as brake fade or low-frequency vibrations.

Results of the study have already allowed EUDIL to improve the shape and the type of material used in the brake cladding.

Sensors Unlimited unveils its Visible-InGaAs camera



Sensors Unlimited’s compact camera is used by the US Department of Defense.

InGaAs short-wave infrared (SWIR) sensor manufacturer, Sensors Unlimited, has introduced Visible-InGaAs, which it claims is the world’s smallest camera to simultaneously image in the visible and SWIR spectra.

The Visible-InGaAs SU320Mvis 1.7RT MiniCamera, currently used by US military, is built around Sensors Unlimited’s proprietary InGaAs focal plane arrays. The camera features a 320 × 240 pixel array with a 40 µm pitch. According to Sensors Unlimited, the device requires no cooling and has no moving parts, and with the factory-set non-uniformity corrections and the built-in anti-blooming, it never needs field adjustments.

The dual sensor’s quantum efficiency is said to be greater than 70% at 1000–1600 nm, greater than 50% at 800 nm, and greater than 10% at 400 nm. Applications include industrial machine vision, hyperspectral imaging and laser-beam profiling.

AOI is awarded four US patents

Applied Optoelectronics Inc (AOI) has been issued with four new US patents covering tunable-laser technology. These latest awards bring the total number of patents that AOI owns in the tunable-laser field to 10.

“The patents are a significant part of a broad portfolio of technologies developed to address the shortcomings of existing diode-laser technology,” said Wen-Yen Hwang, the company’s vice-president of engineering.

Wen-Yen Hwang went on to say that AOI expects to start offering commercial products that are based on the extensive intellectual property that it now owns sometime over the next few quarters. This Texas-based firm,

which manufactures components at its headquarters near Houston, has previously worked on a number of exotic devices, including quantum cascade lasers.

Three of the recently awarded US patents are focused on multiple-reflectivity band reflector (MRBR) technology. For example, patent number 6,788,466 details an MRBR consisting of a stack of dielectric layers. These layers are arranged to create a reflectivity profile in one of the laser’s mirrors. Two wavelength bands are set to have a reflectivity above the lasing threshold, while a third wavelength range (between the other two) has a reflectivity below the lasing threshold.

Crystal IS ploughs \$5 m funding into expansion

Native AlN substrate manufacturer Crystal IS has raised \$5 million in its Series A venture-funding round. Founded back in 1997 and based at the Rensselaer Polytechnic Institute Incubator Center in Watervliet, NY, the company now plans to use the money to expand production capacity, improve substrate quality and drive device development.

Glen Slack is chief scientist at Crystal IS and a co-founder of the company. He said: "It is great to see this technology develop to the point where we are poised to make a significant impact on commercial markets."

A Crystal IS spokesperson also told *Compound Semiconductor* that it will continue to expand its business within the current facility for the time being, but explained that it has aggressive growth plans. Future projects and continued expansion mean that it is likely to relocate within the next two years.

The \$5 million venture funding will be spent partly on more manufacturing equipment, as well as improvements in yield and collaborative device development.

The native AlN substrates developed by Crystal IS offer significant advantages over foreign substrates such as SiC and sapphire, which are currently used in GaN-based LEDs, blue lasers and wide-bandgap electronic devices. Foreign substrates inevitably introduce higher defect levels into devices; manufacturing with native substrates leads to lower defect levels and improved device performance and reliability.

These native materials are typically much more expensive and cannot be grown to such large wafer diameters as their foreign counterparts, but Crystal IS believes that AlN will eventually offer both high-quality and large-diameter substrates.

Intrinsic buys AMDS

Wide-bandgap materials supplier Intrinsic Semiconductor has entered the SiC device market. The small US firm, which acquired Bandgap Technologies in August, has continued its expansion with a buy-out of Swedish company Advanced Micro Device Solutions (AMDS) in a part-cash, part-stock deal.

AMDS has a portfolio of SiC MESFET devices, and is sampling to customers at the design-in stage. The firm will now operate under the name Intrinsic Semiconductor AB.

"The acquisition allows Intrinsic to have an organic presence in Europe – a key market for the future growth of our business," said Intrinsic CEO Cengiz Balkas.

Intrinsic's move guarantees the device-making operation an internal supply of SiC substrates and epitaxy services. The company also has access to a qualified SiC foundry and is said to have a significant patent portfolio.

The Swedish operation has MESFET power amplifiers and other SiC devices in development, including sensors for commercial and military applications.

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Finisar pays less for Infineon fiber unit

Finisar will pay less than originally expected for Infineon Technologies' fiber-optic business unit. The two companies agreed a deal in April this year under which Finisar would acquire the German chip manufacturer's subsidiary for 135 million Finisar shares.

However, following a disappointing six months of operating results at the Infineon unit, in a still-deflated fiber-optic sector, Finisar will now only part with 110 million shares for the acquisition. This will give Infineon a 33% equity in Finisar, less than the 38% originally expected if the deal is approved.

Although the transaction remains subject to approval by Finisar shareholders, the company said that CEO Jerry Rawls and CTO Frank Levinson, who own 16% of Finisar between them, would vote in favor of the deal. The transaction is now worth \$141 million, compared with \$263 million six months ago.

Infineon will also provide financial assistance to cover the costs of "restructuring" the operations of the fiber-optic unit.

InP chipmaker gets \$10 million boost

CyOptics, the US-based optical module maker with an InP fabrication facility in Israel, has raised \$10 million in its fourth funding round.

Led by Jerusalem Venture Partners (JVP), both existing partners and one new investor took part in the latest round, the proceeds from which will be used for product development and for sales and marketing activities.

"CyOptics has weathered the downturn and emerged a stronger, more focused and innovative company," said Glen Schwaber of JVP, who is also on the CyOptics board.

Initially set up to focus on the development of 10 and 40 Gb/s optical components, CyOptics completed its 7000 ft² InP wafer-fabrication facility in Yokneam Illit, Israel, back in early 2002 following an investment of more than \$10 million. The fab features two MOCVD reactors. The company also boasts a 30,000 ft² component packaging and test facility located in Allentown, PA.

Rather than concentrating solely on speed, CyOptics now says that its primary focus will be to shrink modules to one-fifth of the size of the current industry standard, while also reducing their power consumption.

Optillion's pluggable transceiver demonstrates low-cost potential

By Michael Hatcher

Laser chip manufacturer Optillion says that a recent field trial of one of its transceivers has shown that different fiber-optic systems can be mixed and matched to reduce the high investment costs associated with the technology.

In collaboration with pan-Nordic telecommunications operator Song Networks, the Sweden-based company demonstrated that Ethernet switches with a populated XENPAK slot can deliver 10 Gb Ethernet traffic across existing long-haul networks.

The trial showed that interoperability issues between the different systems can be overcome. Optillion combined its transceiver with Nortel dense-wavelength division multiplexing (DWDM) transmission equipment and a switch from Extreme Networks to carry 10 Gb Ethernet traffic over more than 600 km.

"Using Optillion transceivers, Song Networks has shown that DWDM systems can

use 10 Gb Ethernet switch equipment from different vendors. We believe this solution is optimized for the cost-sensitive needs of carriers," said Optillion CTO Patrik Evaldsson.

Evaldsson explained that the Optillion transceiver used in the trial, which is designed as a 10 km reach product, enables an Ethernet switch to interface directly with an installed SONET/DWDM long-haul link. This means that the cost of the interface is significantly lower than that of a normal router.

Optillion uses directly modulated 1310 nm lasers and externally modulated 1550 nm lasers in its extensive range of XENPAK transceivers, which are designed and manufactured at its in-house facility.

Evaldsson believes that pluggable transceivers such as XENPAK are a growth area, because applications such as voice-on-demand require long-distance links with DWDM capability.

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Substrates and epitaxial growth

Eliminating micropipes in SiC substrates, altering growth conditions in real time to reduce the overall strain in GaN-on-silicon heterostructures, and fabricating cubic SiC on silicon substrates all featured at this year's ECSCRM. **Richard Stevenson** reports.

The city of Bologna, Italy, played host to the 5th European Conference on Silicon Carbide and Related Materials (ECSCRM), and during the five-day meeting delegates were treated to a broad coverage of the field. However, the recurring themes were crystal growth and epitaxy, with the developments that drew the most attention including the growth of ultrahigh-quality single crystals of SiC, increased growth rates of SiC through the addition of HCl, and the growth of GaN-on-silicon LEDs.

The key talk of the conference was given by Daisuke Nakamura, from the Toyota Central R&D labs in Japan, who outlined research that he claimed could "open the world to SiC device technology". Nakamura explained that he and colleagues at Toyota and DENSO Corporation have rendered SiC substrates that are "almost dislocation free". "It will be possible in the near future to eliminate dislocations perfectly, and to enlarge the [substrate] diameter to several inches," he said.

Until now, SiC wafers have been plagued with high concentrations of defects. These limit commercial applications of the material to just a few devices, such as Schottky diodes. Bipolar SiC devices have tended to suffer from a degradation of the material's electrical properties, which seems to originate from in-plane dislocations.

Nakamura's team made the breakthrough by employing "repeated *a*-face growth" (RAF). The team started with a single SiC crystal grown on an *a*-face, which consequently had a high dislocation density, and took a section of this crystal along its *a*-axis (see figure 1). The researchers then allowed the crystal to develop on its other *a*-face, before continuing with conventional *c*-face growth. Repeating the *a*-face step appears to eliminate stacking faults and suppress dislocations.

In a 20 mm-diameter substrate grown with RAF, the average etch-pit density (EPD) was 75 cm^{-1} , which is one-thousandth that of conventional SiC substrates. The result for

micropipes was even better, because these were completely eliminated in the RAF-grown wafers. The team also made some *pin* devices using the technique. According to Nakamura, these devices were much more reliable than is normally the case.

Nakamura explained that to make the technology suitable for commercial use the team tried to increase the crystal size, and fabricated a 3 inch substrate with an average EPD that was about one-hundredth of that found in conventionally grown material.

Semi-insulating substrates

The availability of affordable, high-quality, large-diameter substrates was discussed by Ilya Zwieback, from US-based II-VI. Zwieback focused on semi-insulating substrates for GaN-based RF and microwave devices. He explained that if devices are to be reliable at elevated temperatures then semi-insulating substrates with resistivities as high as $10^{11} \Omega\text{cm}$ are required.

To manufacture crystals, II-VI uses an advanced physical vapor transport process (VPT) that is "principally the synthesis of SiC from separate sources of silicon and carbon". The company produces semi-insulating 6H-SiC substrates in 2 inch, 3 inch and 100 mm diameters, as well as 2 and 3 inch $n^+ 4\text{H-SiC}$ substrates, which are required for SiC-based power/switching devices.

Zwieback believes that to produce high-quality boules it is important to prevent crystal defects by controlling precisely the temperature gradient. II-VI uses growth temperatures of 2000–2300 °C and pressures of 5–50 mm Hg, backed up with computer-aided thermal simulation. The company's semi-insulating 6H substrates are fabricated through compensation – the addition of precisely controlled amounts of vanadium – and assessed by a room-temperature non-contact resistivity mapping system (see figure 2).

Zwieback explained that material with high background contamination, usually resulting

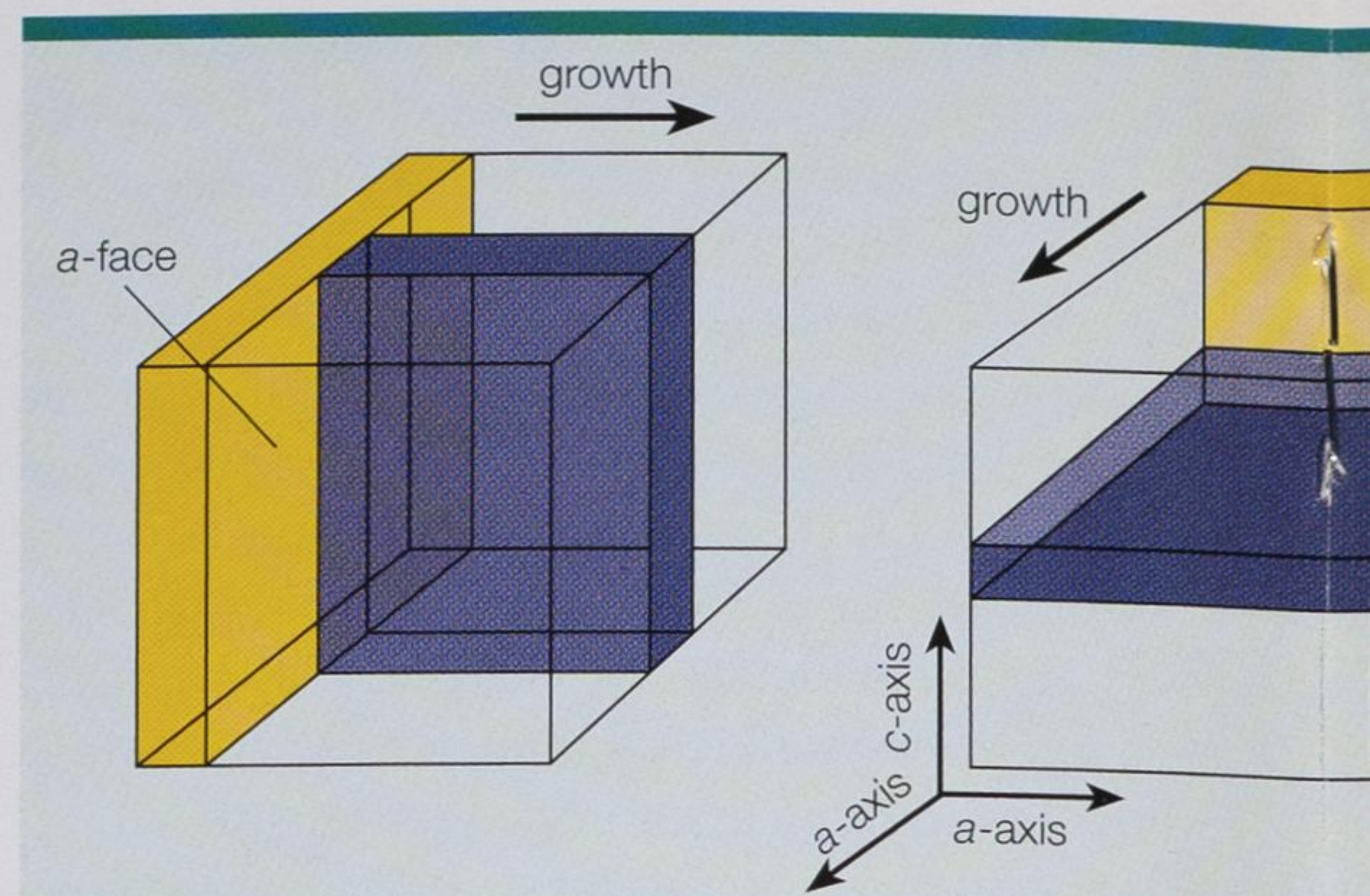


Fig. 1. The repeated *a*-face growth technique is the secret. The crystal is first grown on the *a*-face of a seed crystal, before a segment is grown on the *c*-face. A slice of this crystal is then used in the final growth stage.

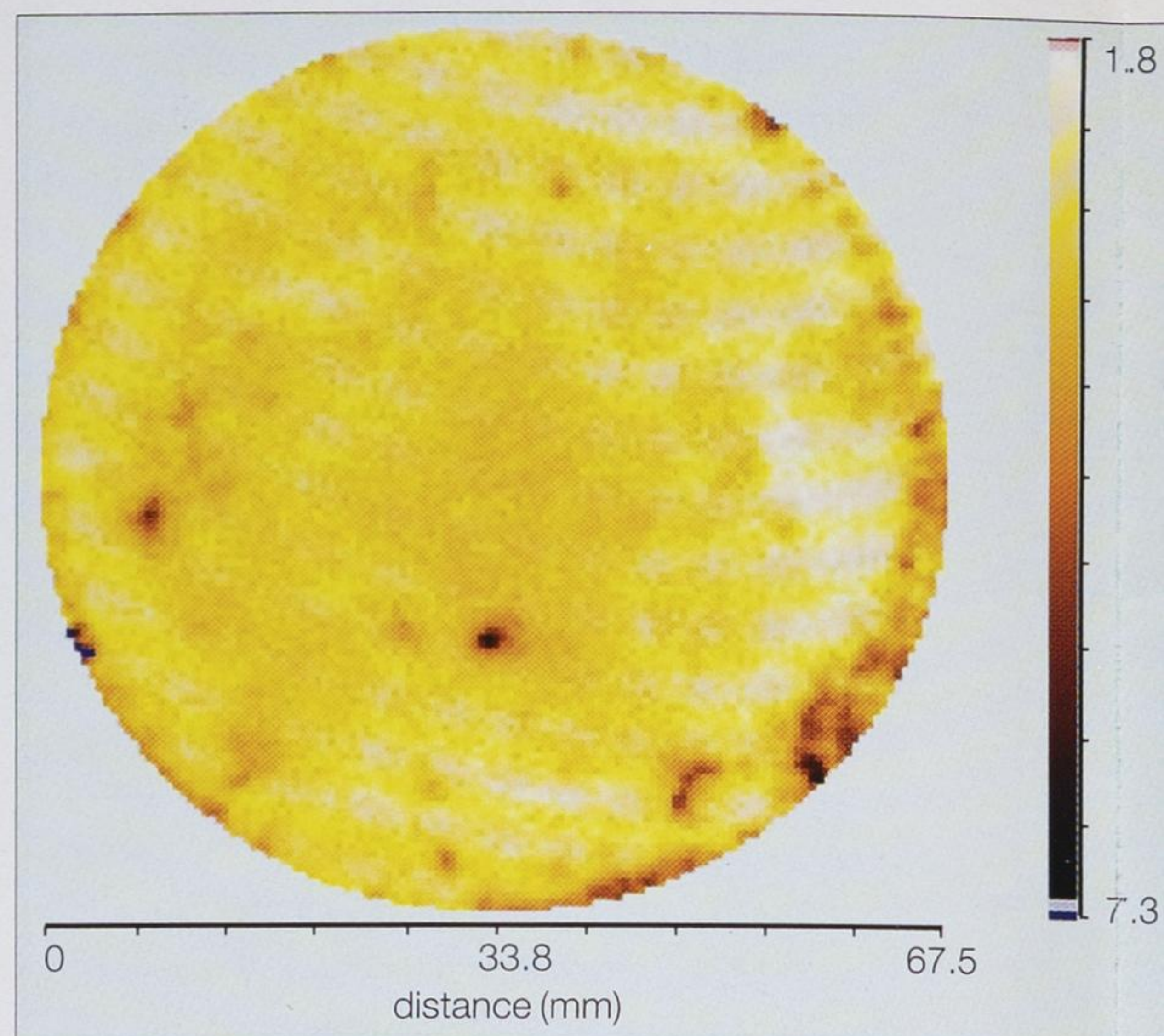
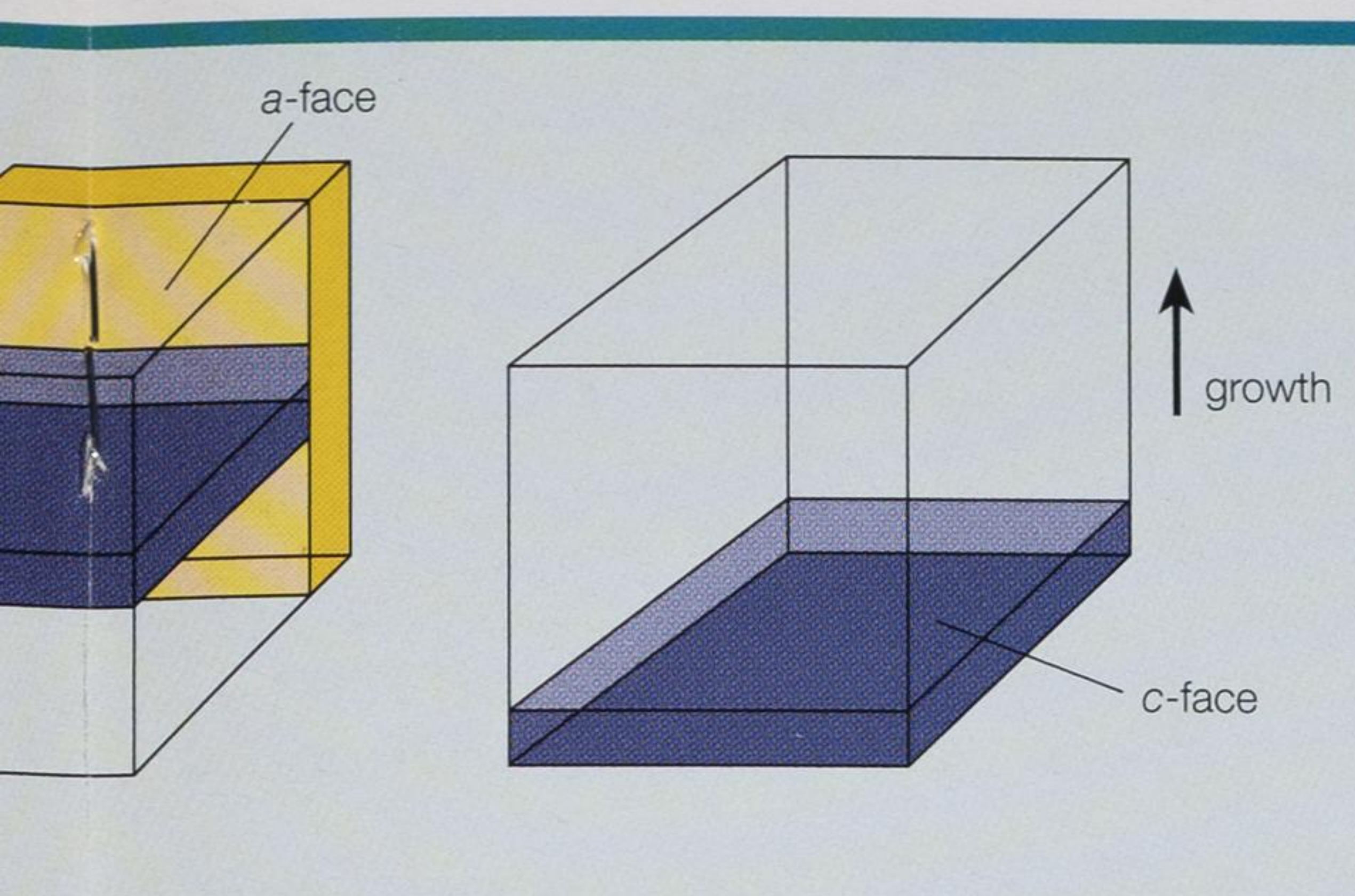


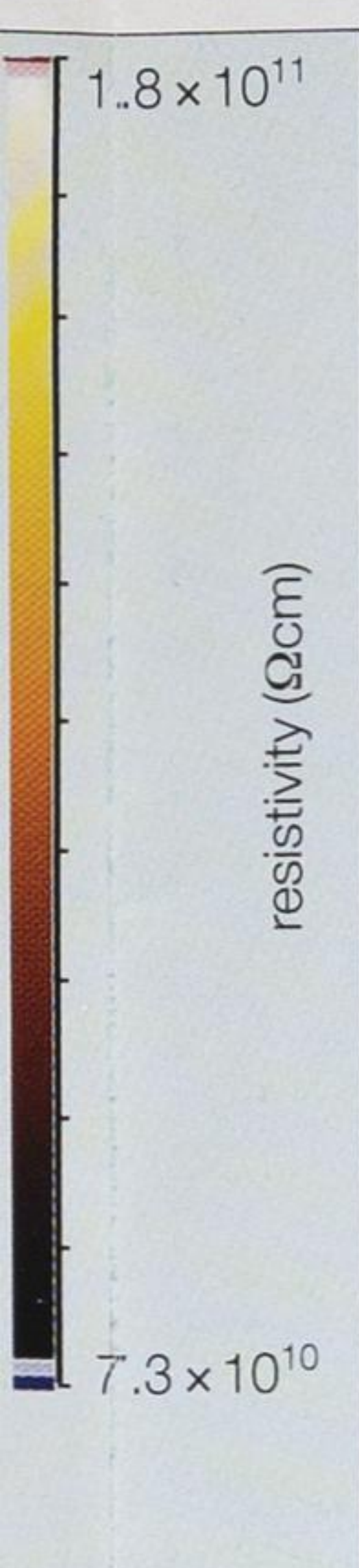
Fig. 2. A room-temperature resistivity map of one of II-VI's 3 inch vanadium-compensated semi-insulating 6H-SiC wafers.

from shallow impurities such as boron and nitrogen, requires a higher concentration of vanadium doping for full compensation, but this is not always desirable. II-VI's response was the recent introduction of a new process with reduced background contamination, and a small and precisely controlled vanadium flux. "We [now] produce crystals with incredibly high resistance, greater than we can measure," said Zwieback. The "low-vanadium-doped" substrates often exceed the upper measurement limit of $10^{12} \Omega\text{cm}$. II-VI is now working on its next goal, to grow undoped 2 and 3 inch 6H substrates. Resistivities as high as $10^{10} \Omega\text{cm}$ have already been reported.

h dominate ECSCRM discussions



secret behind the Toyota team's revolutionary process. SiC a segment of this crystal is used for the a-face of the next final stage, but this time the crystal is grown on the c-face.



of II-VI's
-SiC wafers.

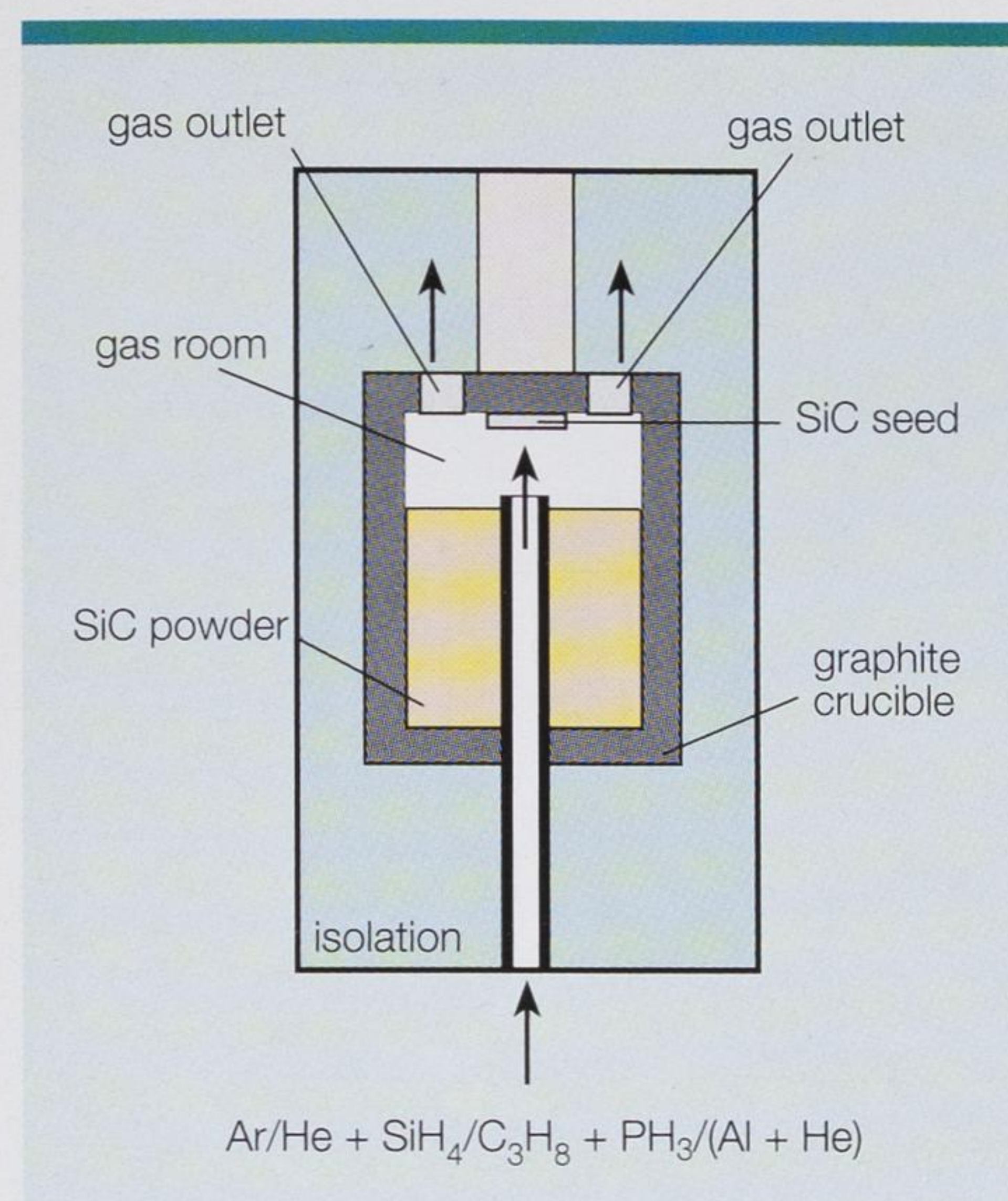


Fig. 3. The modified PVT process allows greater control of crystal growth by adding small amounts of gases for "fine tuning".

Gas flow regulation

Greater control of crystal growth through the addition of a pipe to the growth chamber was described by Peter Wellman from the University of Erlangen, Germany. Wellman explained that SiC crystals are traditionally grown by PVT in a closed graphite crucible at temperatures above 2000 °C. This approach prevents adjustments of gas flows, such as the carbon:silicon ratio and dopant concentration, and is susceptible to changes in the temperature distribution of the crucible, which can lead to growth instability.

A process called modified PVT (MPVT),

in which a pipe is introduced to the standard set-up to enable a small amount of gas to be added, offers several advantages. These include controlling polytypism (the crystalline form of SiC), and reducing defect density through a silicon-rich gas phase by adjusting the carbon:silicon ratio (see figure 3).

Wellman's co-worker, Ralf Müller, described how MPVT is used to produce highly aluminum-doped SiC substrates for high-power bipolar device applications. Aluminum is rarely the first choice of dopant for SiC – when added as a powder it initially causes high defect generation before depleting and causing a large variation in the doping concentration across the boule. Boron, today's preferred choice, provides greater doping uniformity, but the penalty is a deeper doping level and consequently lower device efficiencies. With MPVT, the depletion of aluminum is avoided. This allows aluminum-doped wafers with resistivities of 0.09 Ωcm for 6H-SiC and 0.2 Ωcm for 4H-SiC. Both of these values, which are suitable for high-power device applications, are far lower than the best published value of 0.45 Ωcm, said Müller.

Changing direction

Exploiting different crystal orientations to improve boule quality by PVT was discussed by Christoph Seitz, from the University of Erlangen-Nürnberg, Germany. He told the audience that growth in the conventional direction, [0001], is straightforward, but disadvantages include polytype switching and micropipe formation. After outlining the benefits and pitfalls of other directions, such as the [10-10] direction, he posed the question: "What about the in-between directions? Do we add up the positive aspects, or the negative ones?"

Seitz and co-workers used the PVT process to fabricate two 6H-SiC crystals in the [01-15] direction. The cap, which measured 2 mm thick and 30 mm in diameter, had an extended facet and a flat growth surface, but the boule, 15 mm thick and 70 mm in diameter, exhibited several additional facets and a considerably curved growth surface. Further analysis with high-energy triple-axis X-ray diffraction revealed two issues of concern: pronounced curvature of the lattice planes; and a micro domain structure, which can also be found

in crystals grown in the [0001] direction. Seitz said that research will continue, and his team is now investigating stacking fault densities, dislocation densities and polytype impurities.

Other orientations

Improving SiC growth by using different crystalline directions was a theme continued by Hiroaki Saitoh, from Kyoto University, Japan. "The quality of [today's] SiC epitaxial layers is insufficient," he announced, and went on to describe a study of epitaxial layers grown on 4H-SiC substrates, off-orientated at 1, 2, 4, 8, 15, 30 and 45° from (0001) toward the <11-20> direction. Growth was carried out in a horizontal hot-wall CVD reactor SiH₄-C₃H₈-H₂-Ar system, using conditions of 80 torr and 1550 °C. Flow rates for SiH₄, H₂, and Ar were fixed, and the carbon:silicon ratio was varied by adjusting the C₃H₈ flow.

A low carbon:silicon ratio of 0.75 gave good morphology for all substrate orientations, but at higher ratios of 1.5 and above, the substrate angle became significant, with substrate off-orientation of 4° or less producing "specular morphology". However, using a low carbon:silicon ratio is not always the answer because it results in a high donor concentration that prevents the growth of high-quality epilayers with low background doping. Instead, using highly miscut substrates and high carbon:silicon ratios can be successful: Saitoh and co-workers grew epilayers with donor concentrations as low as $3 \times 10^{13} \text{ cm}^{-3}$ while maintaining high-quality surfaces (with surface roughness RMS values of 0.1 nm) using 15° off-axis substrates and a carbon:silicon ratio of 1.5. The team suggests that for low background doping – achieved by minimizing nitrogen incorporation – 8 to 15° off-axis (0001) substrates should be used.

Speeding up the process

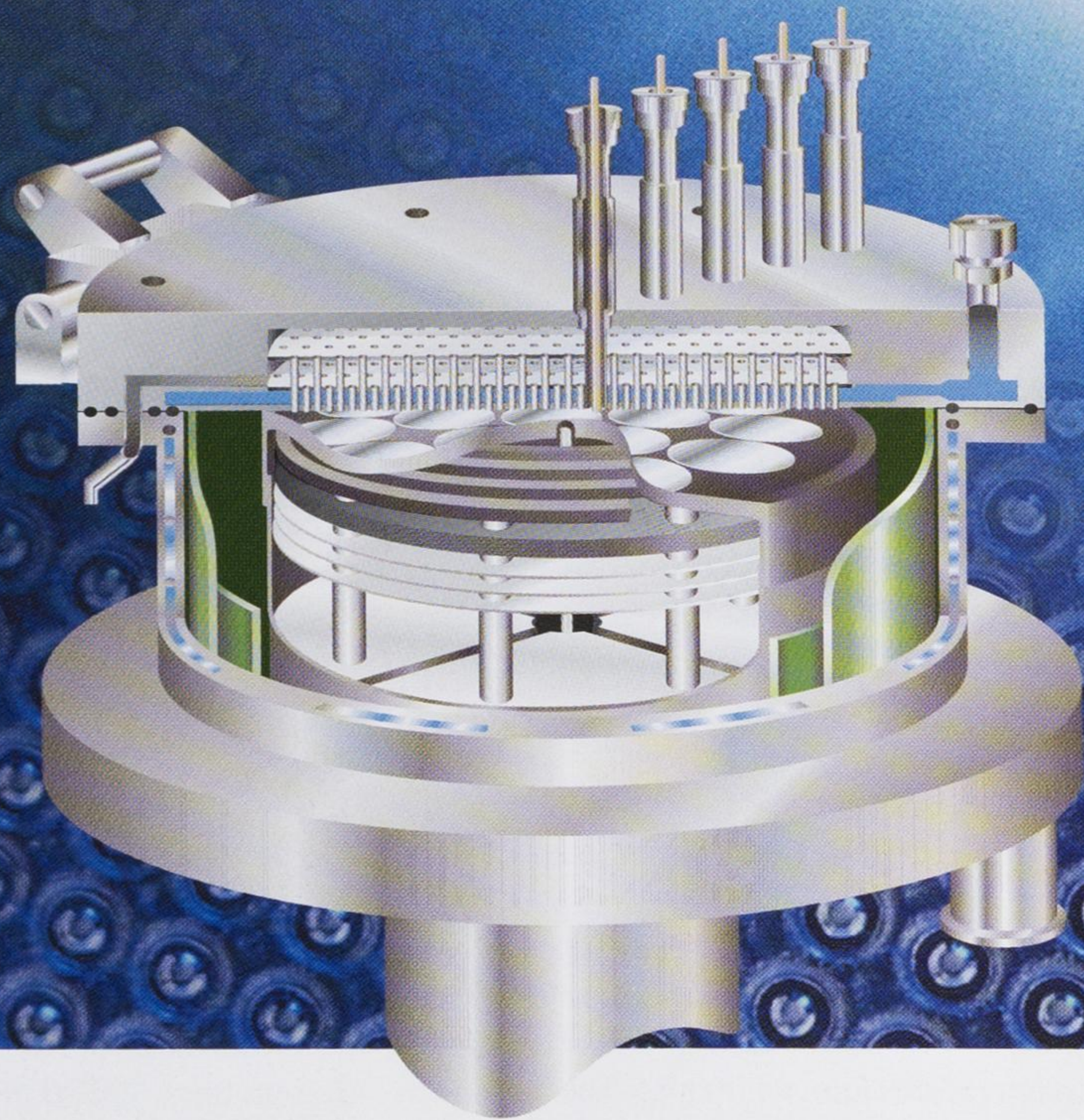
Another factor that is limiting SiC growth technology is the low growth rate associated with standard process chemistries, according to Rachel Myers from the University of South Florida. She described the more than three-fold increase in the SiC growth rate that has been achieved by adding HCl. This has led to growth rates of up to 55 μm/h.

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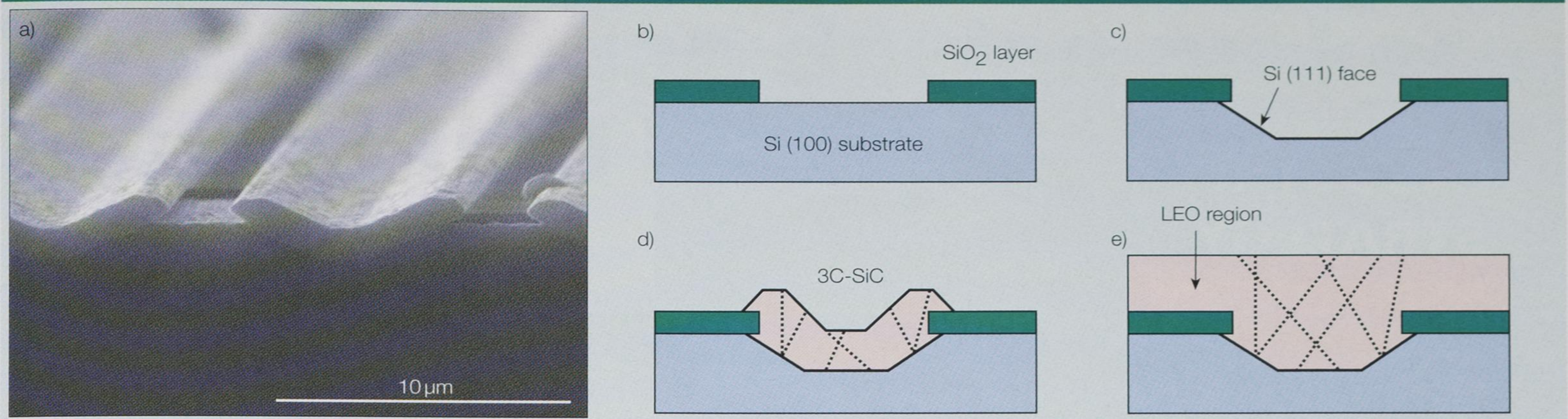


Fig. 4. (a) Lateral epitaxial overgrowth (LEO) of cubic SiC on a silicon substrate with a SiO₂ mask using a horizontal hot-wall CVD reactor. (b) to (e) These images outline the LEO process, with dotted lines representing a high-defect area. (b) Depositing the SiO₂ mask. (c) Etching the silicon surface with HCl. (d) 3C-SiC starting to grow laterally on SiO₂. (e) Formation of a low-defect 3C-SiC layer on the SiO₂ mask.

is to increase the flow of silane, but when silane cracks, silicon clusters form, causing poor morphology and 3D island growth. HCl suppresses silicon clusters, enabling high-growth-rate, high-quality films. Myers and co-workers used a low-pressure, hot-wall CVD reactor with silane and propane precursors to produce films several microns thick. A growth rate of 28 $\mu\text{m}/\text{h}$ produced a “specular and flat” epilayer, but the higher growth rate of 55 $\mu\text{m}/\text{h}$ resulted in a polycrystalline film. “We are still working on this,” said Myers. The team’s goal is to achieve rates of 100 $\mu\text{m}/\text{h}$ or greater.

Reducing defects with LEO

HCl gas also features in the work outlined by Seiji Sugishita, from the Kyoto Institute of Technology, Japan. This involves growing epilayers of 3C-SiC on silicon substrates using a CVD lateral epitaxial overgrowth (LEO) technique (see figure 4). A simpler approach, growing 3C-SiC films directly on silicon, is not possible due to the dislocations, twins and stacking faults at the 3C-SiC/silicon interface caused by the large lattice mismatch of 20%.

LEO has been used previously to decrease the defect density of 3C-SiC-on-silicon epilayers. Then, 3C-SiC films were grown on a silicon substrate with micron-sized SiO₂ features. The extra step taken by Sugishita and co-workers is to add an HCl etch in the growth chamber. This establishes V-shaped grooves, which reduce defect formation (see figure 4c).

One outcome of the research is the need to use SiO₂ patterns with dimensions below 2 μm . For widths greater than 2 μm , reaction atoms that adhere to the SiO₂ surface cannot reach the silicon surface and instead nucleate on the SiO₂ surface, causing defects to form.

Sugishita also offered the following advice: “Too fast a growth rate, of [for example] 6 $\mu\text{m}/\text{h}$, is not good for making single crystals.” Al Burk and co-workers from US-based firm Cree discussed SiC epilayer uniformity in a multiwafer reactor – a key issue for high-volume manufacturing. The team used a 7 × 3 inch capacity warm-wall planetary SiC-VPE reactor to produce multilayer devices on 4 and 8° off-axis substrates. The devices included MESFETs, JFETs and bipolar junction transistors. Within a run, the total average intrawafer thickness and doping were about $\pm 1\%$ and $\pm 5\%$ respectively, said the team.

Not standing still, Cree has also investigated the growth uniformity on 4° off-axis 4H-SiC wafers in a 6 × 100 mm and a 9 × 3 inch configuration. The 6 × 100 mm set-up produced thickness and doping uniformities of 3 and 9%, respectively.

Alois Krost from the Otto-von-Guericke University, Magdeburg, Germany, discussed the benefits of using silicon as a substrate for GaN. Acknowledging the lack of GaN sub-

strates, he said that silicon offers a “mature, real alternative” to sapphire and SiC. He cited low cost, good thermal conductivity, large wafer area, and the possibility of chemical etching as some of the advantages.

GaN-on-silicon

Krost believes that cracking is a significant issue that is hampering the development of GaN-on-silicon epitaxy. Cracking results from the large difference in thermal expansion coefficients between GaN and silicon, and the resulting tensile strain. Krost and co-workers have monitored this strain *in situ*, using a home-made optical sensor adapted together with an EpiTT system from LayTec to measure curvature and temperature.

These real-time measurements of the strain allow instantaneous changes to the growth process. The contribution to the overall strain from various epilayers and interfaces can be balanced, enabling crack-free, flat-layer growth of structures up to 4 μm thick. The measurements also reveal the variation in tensile stress caused by different p-type dopants: a magnesium concentration of $5 \times 10^{19} \text{ cm}^{-3}$ induces the same amount of stress as a silicon concentration of $5 \times 10^{17} \text{ cm}^{-3}$.

Krost’s team has fabricated a transistor and an LED by GaN-on-silicon heteroepitaxy. The 3.7 μm -thick LED structure, containing a five-fold InGa_{0.5}N/GaN multi-quantum-well active region, produced a 0.89 mW output at 477 nm under 20 mA drive current (see figure 5). “GaN-on-silicon is promising for LEDs,” concluded Krost. A 2 μm -thick GaN/AlGa_{0.3}N transistor structure, which had two growth interruptions to add stress-reducing AlN layers, had output powers of 2.2 and 2 W/mm at 2 and 5 GHz, respectively.

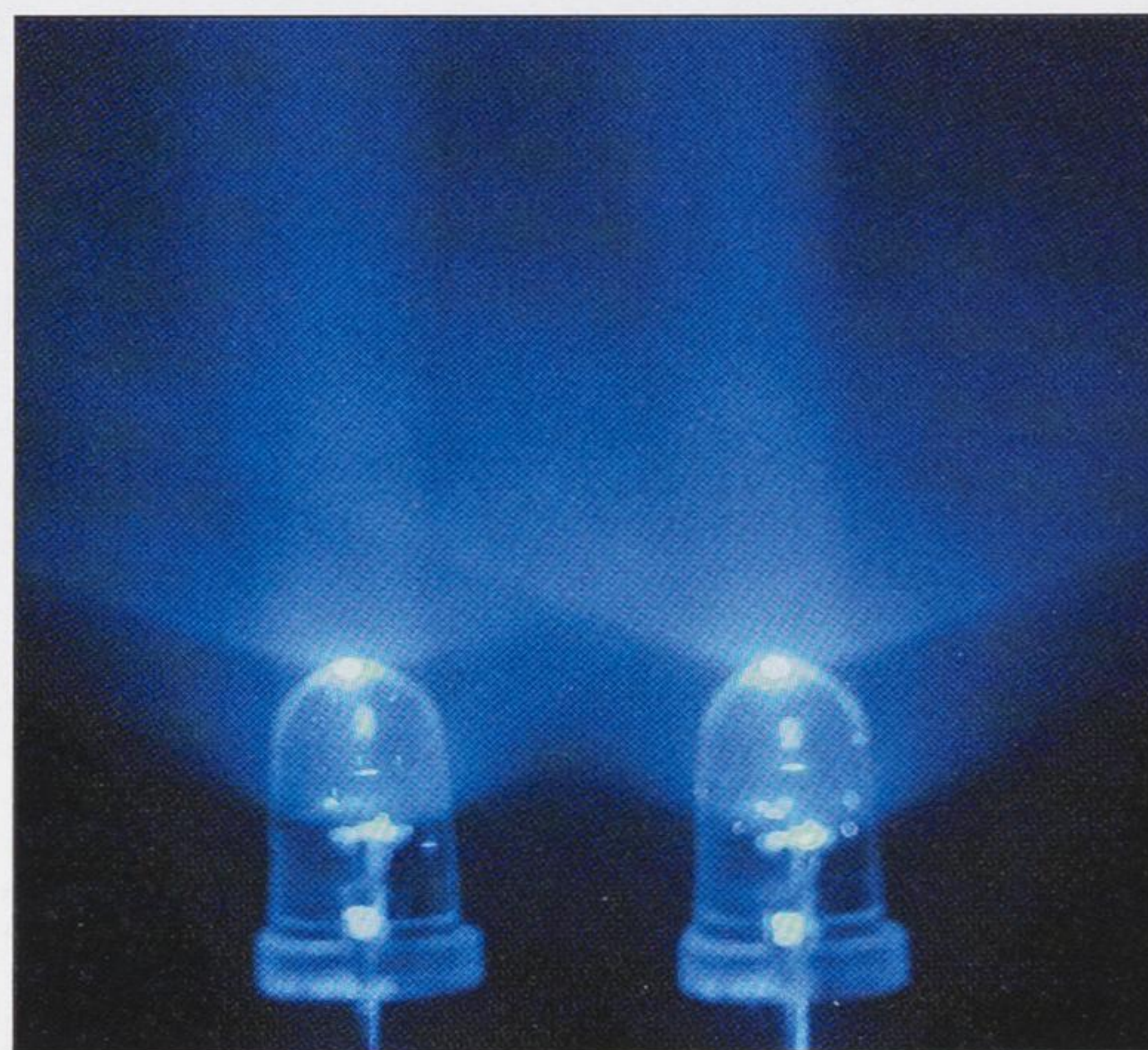


Fig. 5. Emission from GaN-on-silicon LEDs.

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APPLICATION MARKETS

Wide-bandgap device makers need to find high-volume uses

Despite the realization of 3G wireless networks and defense applications of wide-bandgap devices, makers of transistors based on SiC and GaN must find other, higher-volume applications of the technology to sustain future production. **Michael Hatcher** searches for opportunities.

There are many reasons for future GaN and SiC device manufacturers to be cheerful. Nokia expects close to 100 wideband-code division multiple-access networks to be operational by 2005. Defense contractors require advanced radar solutions and devices offering X-band and S-band emission, while the satellite communications industry needs power amplifiers operating in the K_u and K_a bands for uplinks and downlinks.

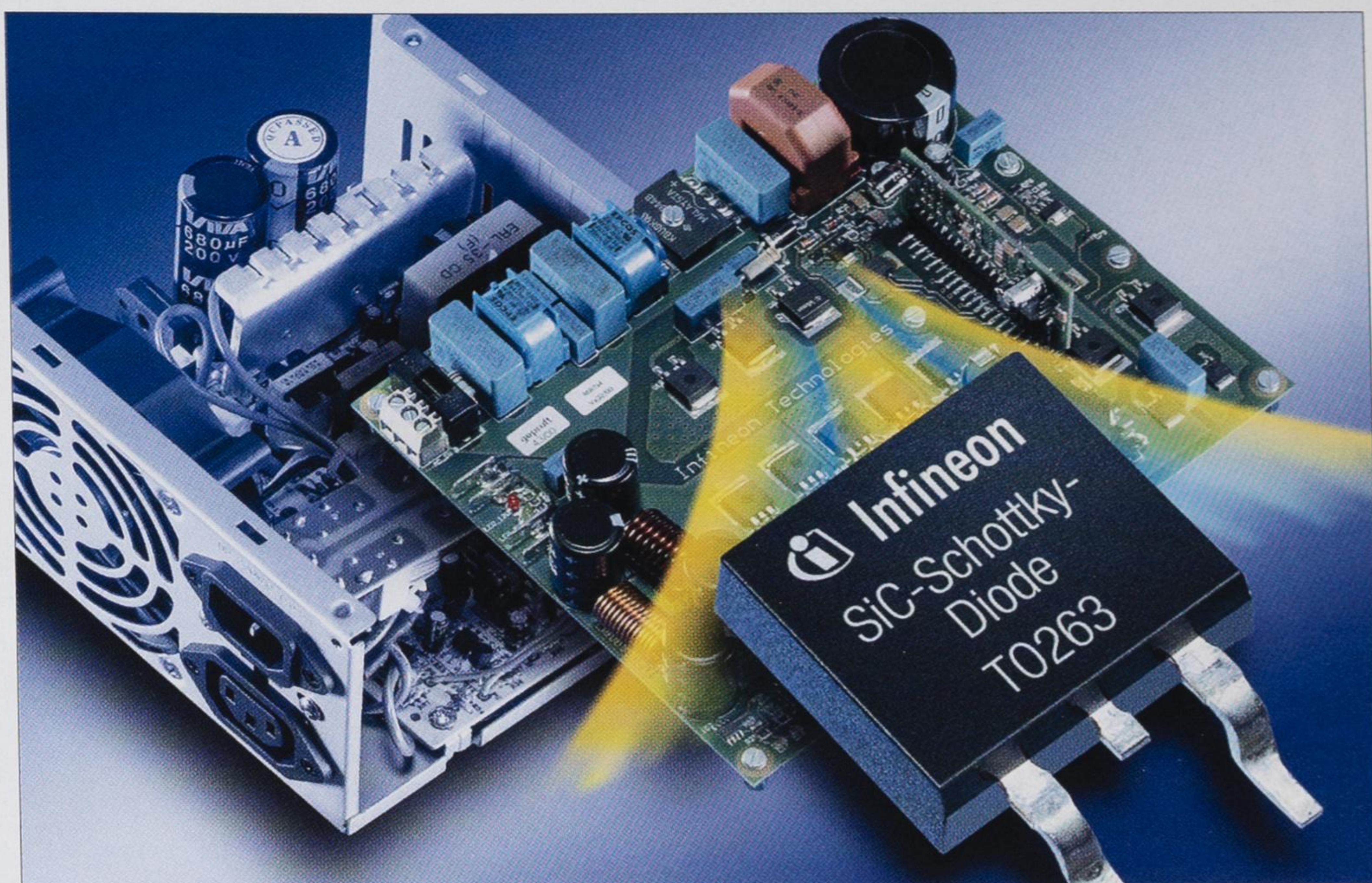
There's just one problem. Together, all of these applications still do not represent a large market. According to Yole Developpement, the French analyst company that specializes in wide-bandgap device markets (and which is currently putting together detailed reports on SiC and GaN technology for its clients), the prospective device-makers need to focus on other applications of the technology that will require much higher volumes.

SiC and GaN tend to be talked about as a single group when the future uptake of RF transistors is discussed. However, this no longer makes sense. According to Yole's Philippe Roussel, the distinction between SiC and GaN device applications has now become clear: "We think that the market will split between RF applications using mainly GaN, and high-power electronic applications using SiC," he told *Compound Semiconductor*.

Application divide

Important recent developments that have driven the two technologies apart include Infineon Technologies, Germany, extending its range of SiC Schottky diodes and Japan-based Eudyna Devices' progress with GaN HEMT RF devices. The latter is a clear indication that GaN has left SiC behind technologically as far as RF applications are concerned.

"Regarding RF and microwave applications, the latest work shows that GaN reliability, lifetime and linearity are more advanced than [that of] SiC components," said Roussel,



Infineon Technologies first entered the SiC-Schottky-diode market in early 2001, but it ramped up its product offering in mid-2004 with a portfolio of 300 and 600 V devices that operate at between 2 and 12 A. The devices are currently used in high-end PC and server power supplies, but with a relatively small drop in price and improved manufacturing yield they could penetrate the high-volume, low-end PC market.

who believes that this is principally due to the greater funding enjoyed by developers of nitride technology in recent times.

So, where does that leave SiC? Schottky diodes are the only SiC devices on the open market, and Infineon's chips are used in a single application: power supplies for high-end PCs and servers, such as those used by telecom companies. The diodes are being supplied to at least two Taiwanese power-supply manufacturers. According to Roussel, the size of the SiC chip required presents the main obstacle to its deployment in low-end supplies: "The main issue is that you have to completely redesign the architecture," he explained. "It's not a chip-to-chip swap. That's why only the high-end market has been targeted."

Roussel is optimistic about the SiC devices, whose excellent heat properties mean that the need for expensive, heavy cooling fans and heatsinks in power supplies is much reduced. He believes that the mid- and low-end markets also present an opportunity. "We don't think that it will stay this way – it's just a question of price," the analyst said. Last year, Roussel estimated, the SiC-Schottky-device price was around \$0.70 per amp. This year, the figure has dropped to \$0.50 per amp. At \$0.20 per amp, the low-end market could open up to SiC.

A number of developments will be required to drive prices down to this level. One key aspect that is starting to be addressed is the manufacturing switch from 2 to 3 inch wafers. Cree has announced its intention to do this

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and, as the US company is also Infineon's substrate supplier, the move will directly impact Schottky-diode selling prices. Roussel says that improvements in the speed and quality of epitaxial processes are also needed – he estimates the current device yield to be 70%.

Roussel predicts that SiC Schottky diodes will breach the crucial \$0.20 per amp figure in 2007, but admits that this could happen sooner if rival competitors to Infineon and Cree emerge before then.

Competition looks likely, however, with the Switzerland-headquartered semiconductor giant ST Microelectronics and International Rectifier of El Segundo, CA, expected to enter the fray (see p27).

Automotive potential

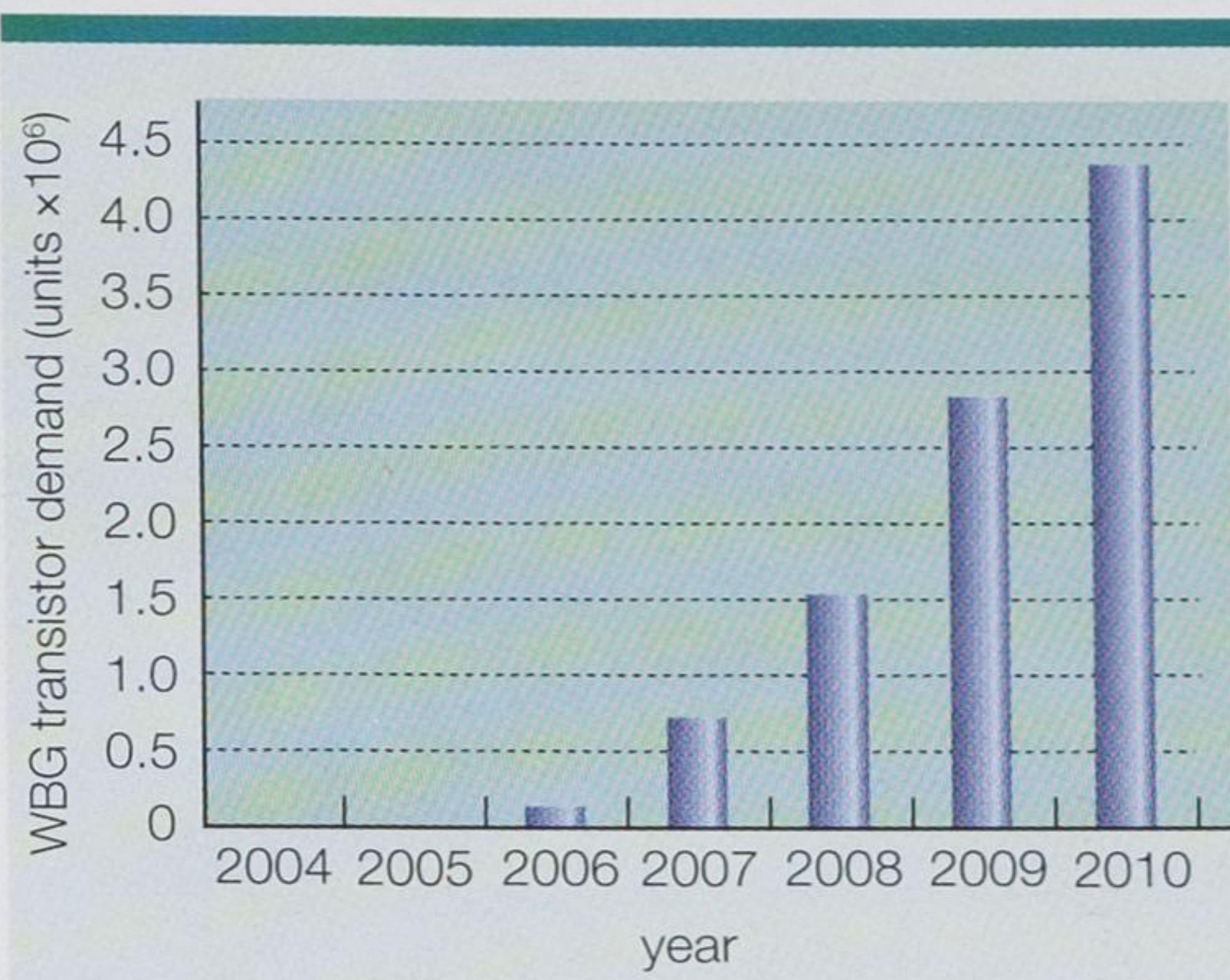
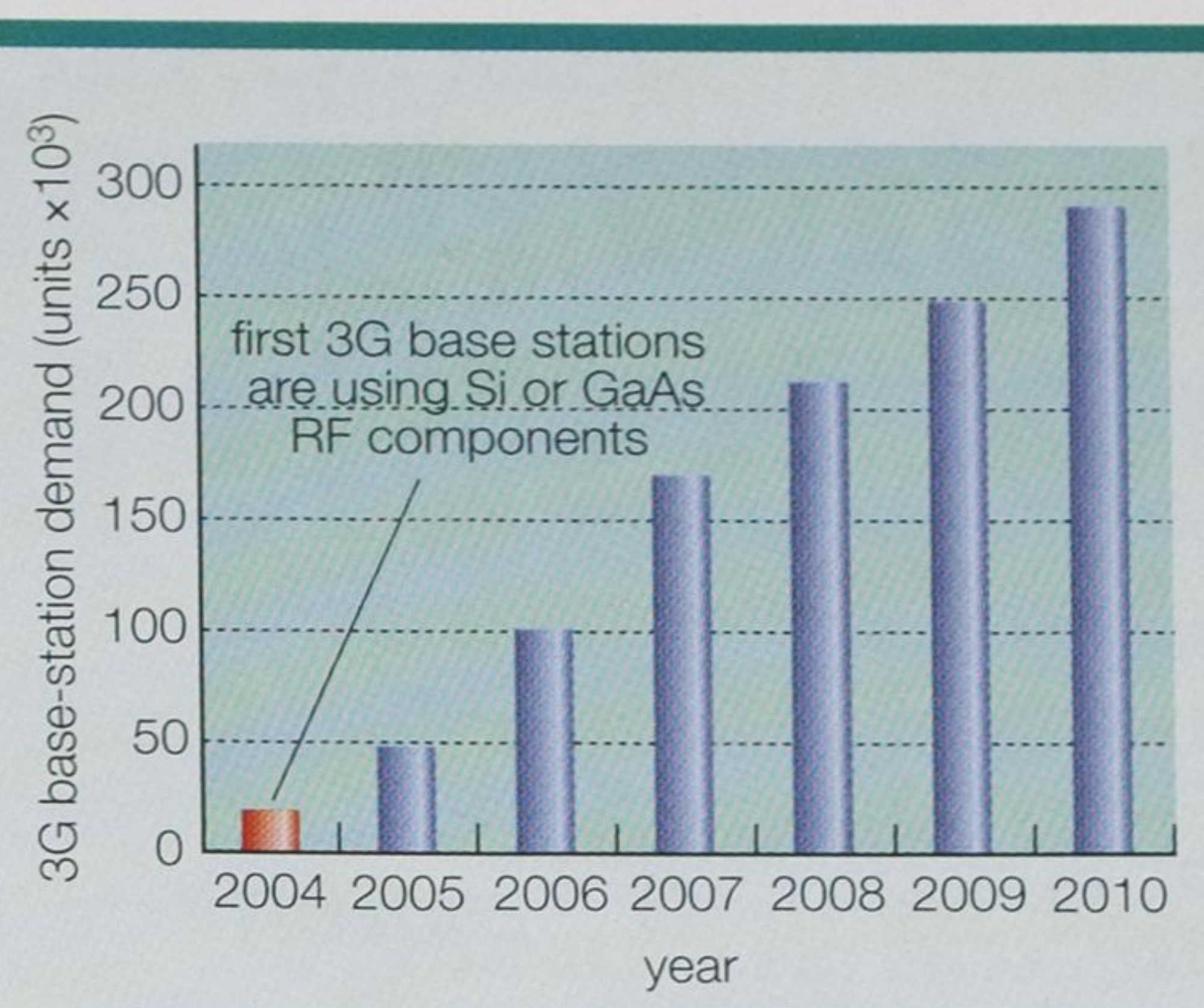
A pretty clear roadmap exists for SiC Schottky diodes, but there are some other high-volume applications that SiC can penetrate. "Everyone is waiting for [SiC] MOSFET and *pin* structures," said Roussel. Applications for such devices are likely in the transport market, for example, to replace some *pin* diodes currently used in high-speed trains that require a full silicon wafer to provide a single device.

The problem with SiC in this area is the thickness of the epitaxial layer that is required, which is around 100 μm . Difficulties with defects, such as micropipes, has also meant that the devices take up a large area, with Cree managing to fabricate only 16 *pin* diodes on a 2 inch wafer.

However, micropipe problems could become a thing of the past thanks to impressive recent research by Japanese company Toyota (see ECSCRM report, p18). Although not previously noted for its SiC work, the Toyota research team has developed SiC substrates with a virtual absence of micropipes, which promise to move forward the development of SiC MOSFETs.

So, why is a Japanese car manufacturer like Toyota getting involved in the development of SiC substrates? The answer could lie in the future design of car engines, thinks Roussel: "Companies like Toyota are looking at this alternative power technology for hybrid electric vehicles." Something of a hot topic in Japan, innovative engines of the future could use a combination of SiC MOSFETs and Schottky diodes for drive electronics.

Another Japanese car-maker, Nissan, is involved in a US project in conjunction with SemiSouth Laboratories, a spin-out from the Mississippi State University, that is aiming to develop a prototype multichip power module



3G base-station volumes and requirements for wide-bandgap transistors. With the first wave of 3G base stations using LDMOS or GaAs RF components, it will be 2006 before the market is penetrated by GaN devices. By 2008, 1.5 million GaN transistors will be required, says Yole Developpement's Philippe Roussel. But even so, this will only require 10,000 2 inch wafer equivalents, assuming a component size of 5 mm² and a production yield of 50% – a low enough volume for a solitary chip supplier to satisfy.

made entirely with SiC-based control electronics by around 2010. The \$2.5 million project recently received backing from the US Commerce Department through its Advanced Technology Program awards.

Low-volume demand

With GaN technology streaking ahead of SiC in terms of RF and microwave applications, the roadmap for this material ought to look pretty rosy. The problem is that wireless base stations, defense applications and satellite communication do not amount to much in terms of the volume of demand for wafers.

Although the base-station market was estimated at \$6 billion in 2003, this translated into roughly \$650 million for PA modules. And even though 70% of PA costs arise from the transistors used, the market is dominated by sil-

icon LDMOS, accounting for 85% of PAs in base stations today. Silicon-friendly Freescale, the US-based spin-off from Motorola, owns 60% of this chip market and appears unlikely to switch to any III-V solution.

Despite this, there is a clear opportunity for GaN transistors as they promise to reduce the cooling expense in base stations, which is one of the major costs encountered. Although current 3G base stations use LDMOS and GaAs technology to achieve the necessary 300 W output at 2–2.5 GHz, the required electronic architecture is highly complex, something that a GaN solution could capitalize on.

Japanese firms using the DoCoMo standard have been more willing to accept new technologies in the past and this, coupled with Eudyna's advanced technology development, means that Japan is the most likely place for GaN to enter the base-station market. Yole predicts that the wide-bandgap share of this transistor market will rise from zero today to 12% in 2008 and 25% in 2010 (see figures, left).

Even so, 3G base-station build-out isn't going to offer a substantial market for chip-makers. "Only one company will be required [to supply] the entire market," Roussel predicted. He believes that just 10,000 2 inch equivalent wafers will be sufficient to satisfy demand from this sector in 2008. "There are currently too many players. In the end, we think that the first to win will be the base-station market. We have a feeling this could be Eudyna." Roussel says that Eudyna could provide the breakthrough for GaN towards the end of next year.

Defense is another area touted as ripe for GaN infiltration, with applications for advanced radar and X-band communications. For example, the US company Nitronex, as well as developing base-station solutions, has always been closely aligned with US military bodies such as DARPA. But again, the defense market is not one requiring high volumes, even though it would still be lucrative given the relatively small supplies required.

Roussel reckons that 1000 processed wafers will be enough for the approximately 150,000 RF transistors likely to be needed in 2006, and it's a similar story for satellite communications. With 50–100 satellites launched each year, and each satcom unit (including almost 50 PAs) needing about four RF transistors, the total market would only amount to something in the region of 15,000 GaN RF transistors per year.

All of this begs the question: why build extensive GaN capacity for the RF transistor market? Another communications application

APPLICATION MARKETS

may be one reason to do so. So-called very small aperture terminal (VSAT) technology looks to be an attractive tool for building communications infrastructure in developing countries such as China and eastern Europe, where the immense cost of digging trenches makes copper wireline and fiber-optic deployment unfeasible.

High-volume answers?

Today's typical VSAT transceivers use two MMIC modules operating at 2–4 W power, and are currently based on GaAs HEMT technology. With 0.8 million units sold in 2003, and the sector's compound annual growth hitting around 13%, VSAT manufacturers believe that the annual market potential could run into several million units over the next five years. Roussel says that GaN technology could help to reduce the cost and size of VSAT, because of the reduction in the number of passive heat-controlling elements that it allows.

Roussel understands that French media and technology giant Thomson MultiMedia is targeting a price of \$300 for a low-cost VSAT module, meaning that the challenge for GaN

With an annual market currently exceeding 50 million units ready to be tapped into, microwave ovens may just turn out to be the star application for GaN-based RF transistors.

device-makers would be to produce a 5 W MMIC costing only \$50. This could be possible, he believes, through the use of GaN on-silicon technology that takes advantage of the low-cost substrate to enable 4 or even 6 inch wafer production.

In a more radical piece of thinking, Roussel says that the ideal application for GaN RF transistors, certainly in terms of high-volume production, could be sitting in the kitchen. Microwave ovens are very heavy, mainly because of the microwave-producing mag-

netrons required to cook the food. Replacing these magnetrons with GaN transistors is a serious possibility, insists Roussel – provided that there is a fall in the cost of transistors.

"It sounds funny, but we have heard Matsushita [Panasonic] suggesting that to bring down the cost of microwave ovens, you also need to reduce their weight," said Roussel. Replacing the magnetron with transistors would reduce weight and therefore transportation costs, and render the oven's rotating plate – which is often the cause of a breakdown – obsolete. The required operating frequency would be 2 GHz – the same as that of a base station – with a power requirement of 1 kW. Technologically, this is no problem; the issue will be to bring cost down. After all, magnetrons cost only \$10, so the price per GaN transistor would need to be a challenging \$3–5.

The rewards could be huge, however. With an annual market currently exceeding 50 million units ready to be tapped into, microwave ovens may just turn out to be the star application for GaN-based RF transistors.

• For more information on Yole Développement's SiC study, visit www.yole.fr.



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STMicroelectronics is set to drive SiC-device competition

Siemens spin-off SiCED and STMicroelectronics are sampling SiC Schottky diodes, MOSFETs and *pin* diodes. With commercialization soon to follow, **Richard Stevenson** investigates.

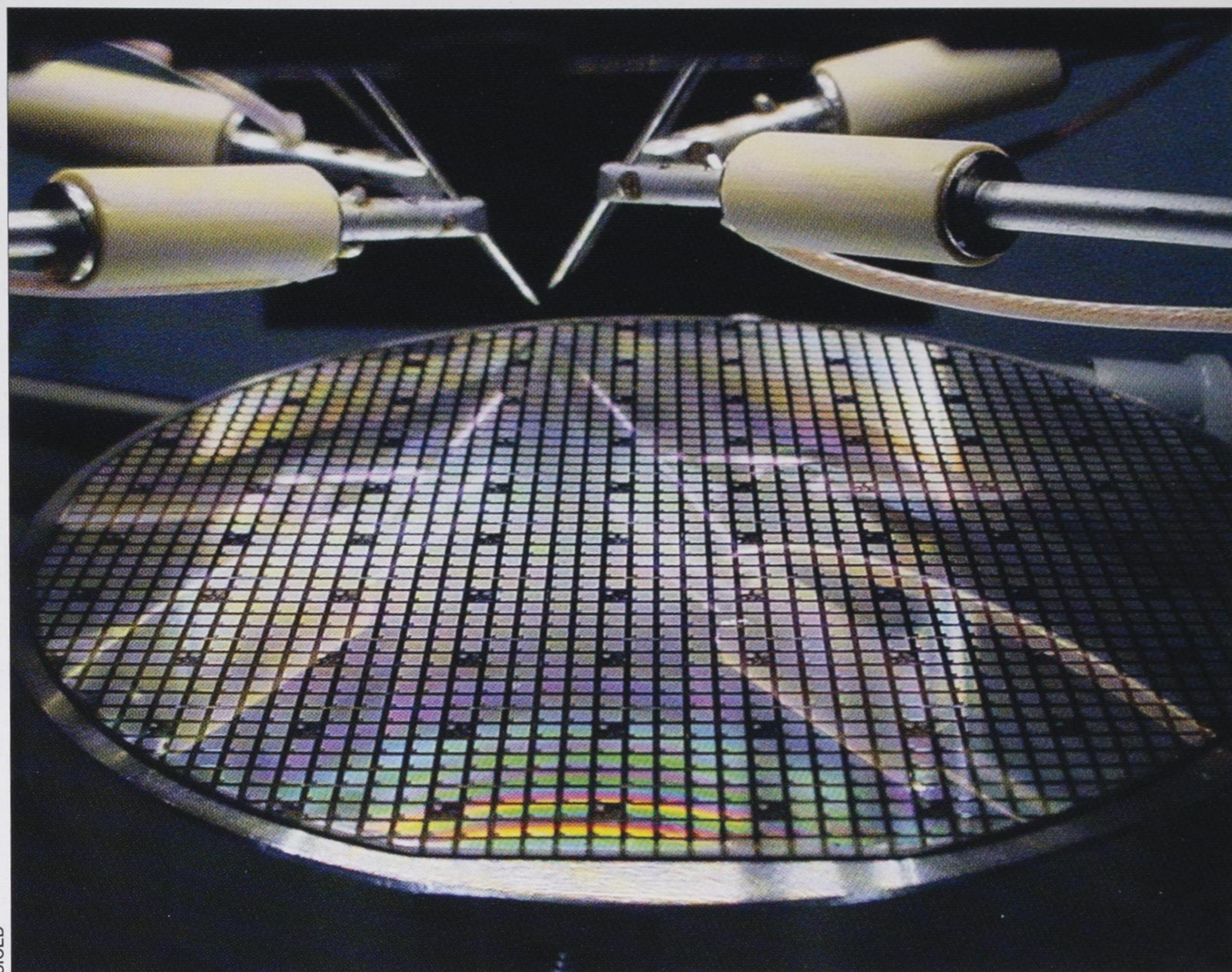
In 2001 Germany-based Infineon Technologies launched a range of SiC Schottky barrier diodes (SBDs), and this year it increased its portfolio with the release of more 300 and 600 V diodes, rated at up to 20 and 12 A respectively. Today, however, Infineon's SiC devices, which are grown on material from Cree, are competing against similar devices produced by a handful of manufacturers, including Cree itself and Japan-based Rohm. Even more competition is to come, with firms such as STMicroelectronics aiming to bring their SiC products to market.

"We feel that the time is right to start investing significantly in SiC," explained Salvo Coffa of STMicroelectronics. Coffa is research director of the SST (soft computing, silicon-optics and post-silicon technologies) group within the company's R&D division.

STMicroelectronics is the world's sixth-biggest semiconductor manufacturer, and in 2003 it had a global market share of 4%. The company, which has its headquarters in Geneva, Switzerland, already has an established portfolio of silicon-based power devices. Over the last few years it has investigated aspects of SiC technology, such as epitaxial growth, metallization, and junction formation. Its reason for doing this is straightforward – SiC can overcome the limitations associated with silicon (see "Comparison of silicon and SiC devices" on p29).

"What has changed, as was shown in the meeting in Bologna [the 5th European Conference on Silicon Carbide and Related Materials, which took place in September], is that there is an increase in the number of providers of substrates, epitaxial reactors, and so on. This is the only way to start having economies of scale in the manufacturing of these [SiC] devices," said Coffa. He explained that the company has made significant progress in its ability to process SiC, using mostly 3 inch substrates in its existing lines.

STMicroelectronics has yet to produce SiC



A SiCED 3 inch wafer containing 1700 JFETs that have an "on-resistance" of less than 1.2 Ω .

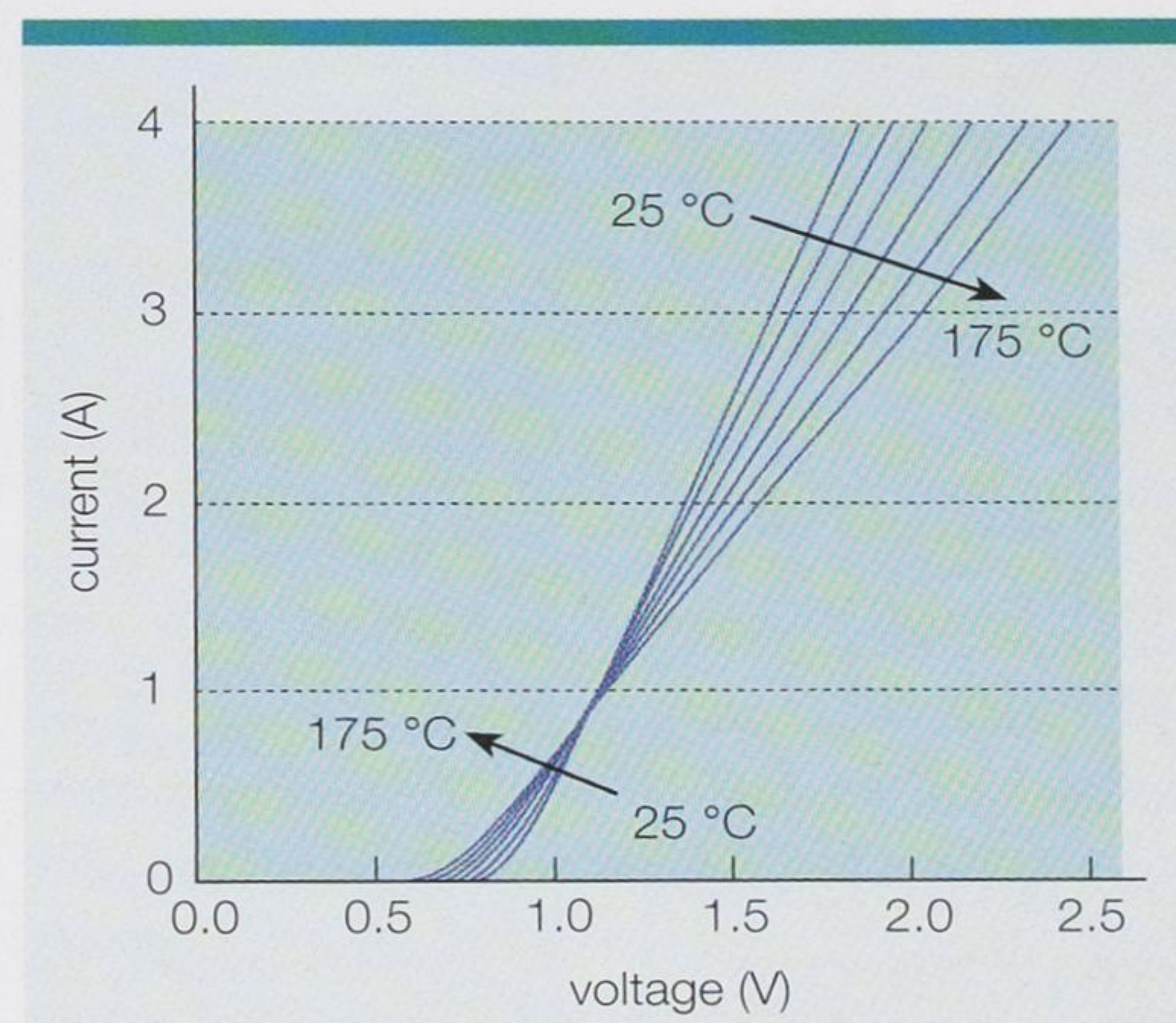


Fig.1. SiC Schottky diodes, which have small variations in their I-V characteristics, are ideally suited to high temperatures.

SBDs commercially, but it has sent samples to customers to be evaluated. Short-term goals include the production of 600 and 1200 V Schottky diodes, and the development of 600 V power MOSFETs.

The temperature dependence of the company's SiC SBDs, which Coffa claims could operate at temperatures of up to 300 °C, is shown in figure 1. These devices will compete directly with Infineon's thinQ! range, which includes 11 different SBDs that are claimed to operate at up to 600 V and at temperatures of -55 to 175 °C.

The temperature stability of SiC SBDs is superior to that of equivalent silicon-based devices, thanks to the wider bandgap. Coffa explained that Schottky devices that can per-

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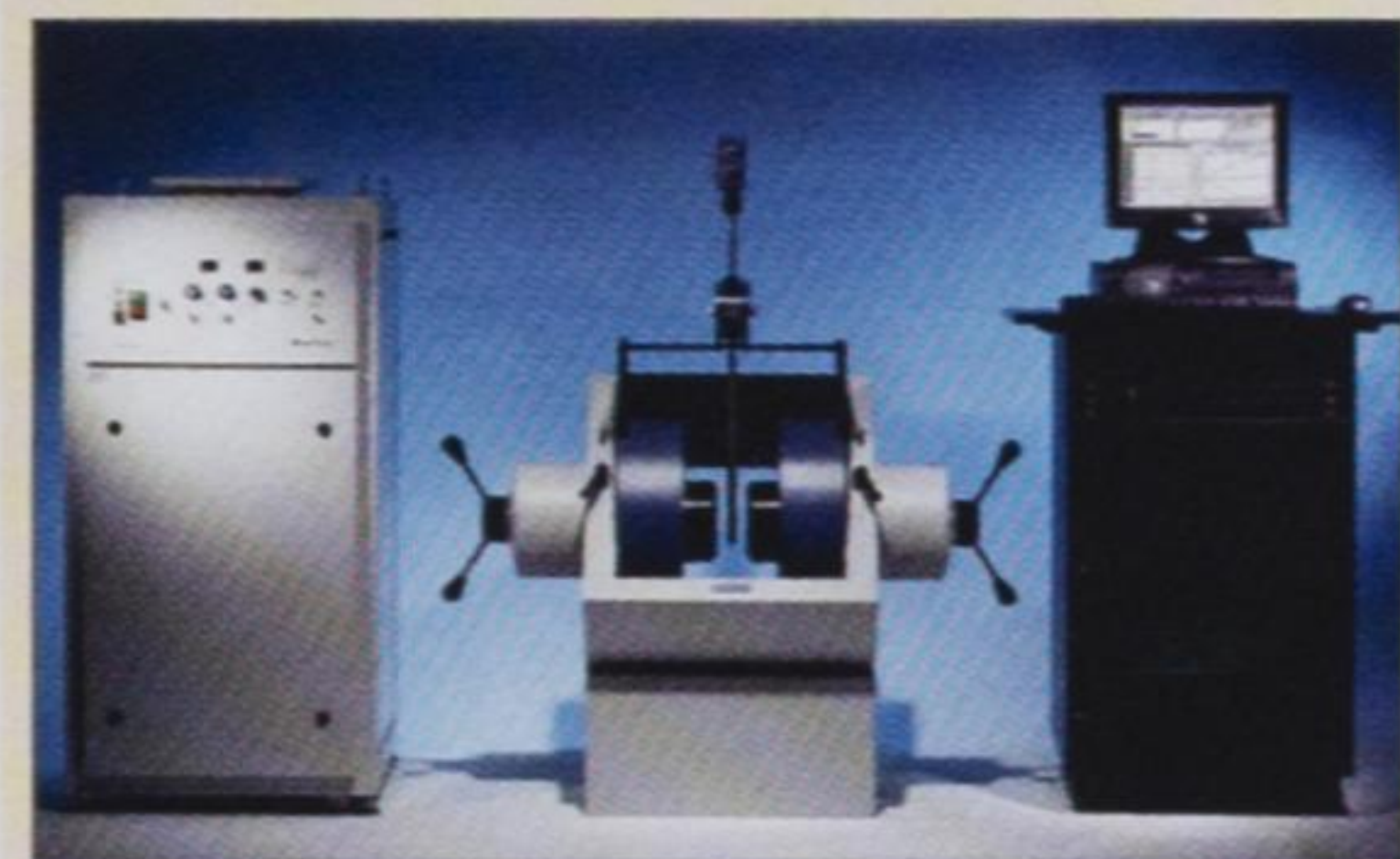


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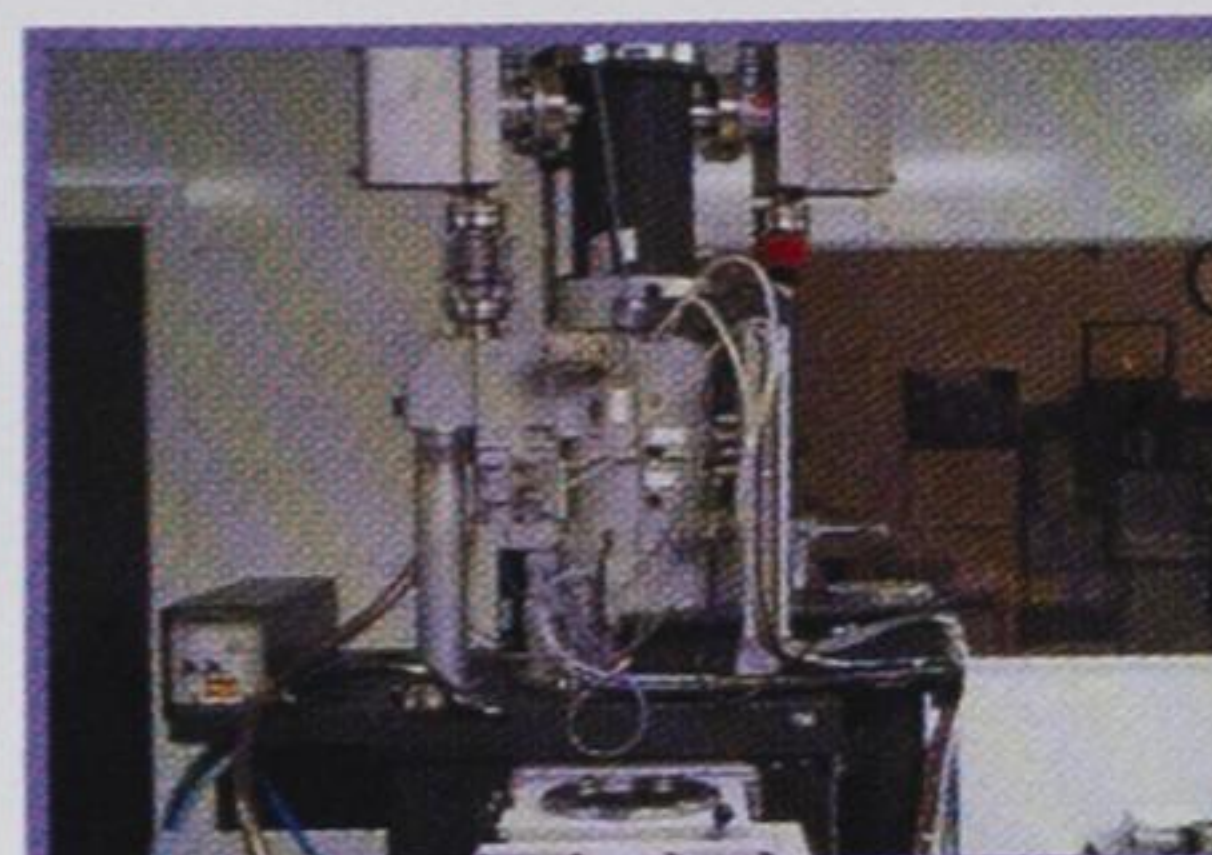
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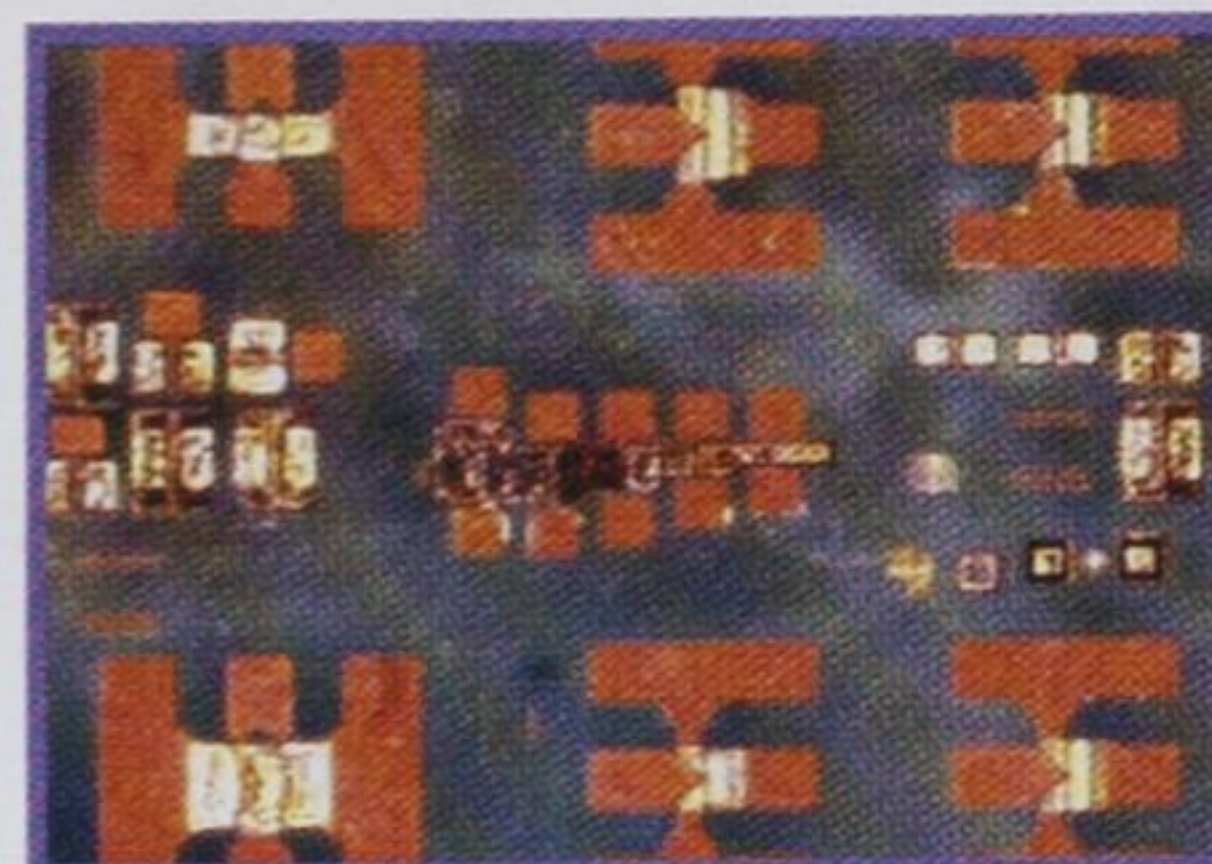
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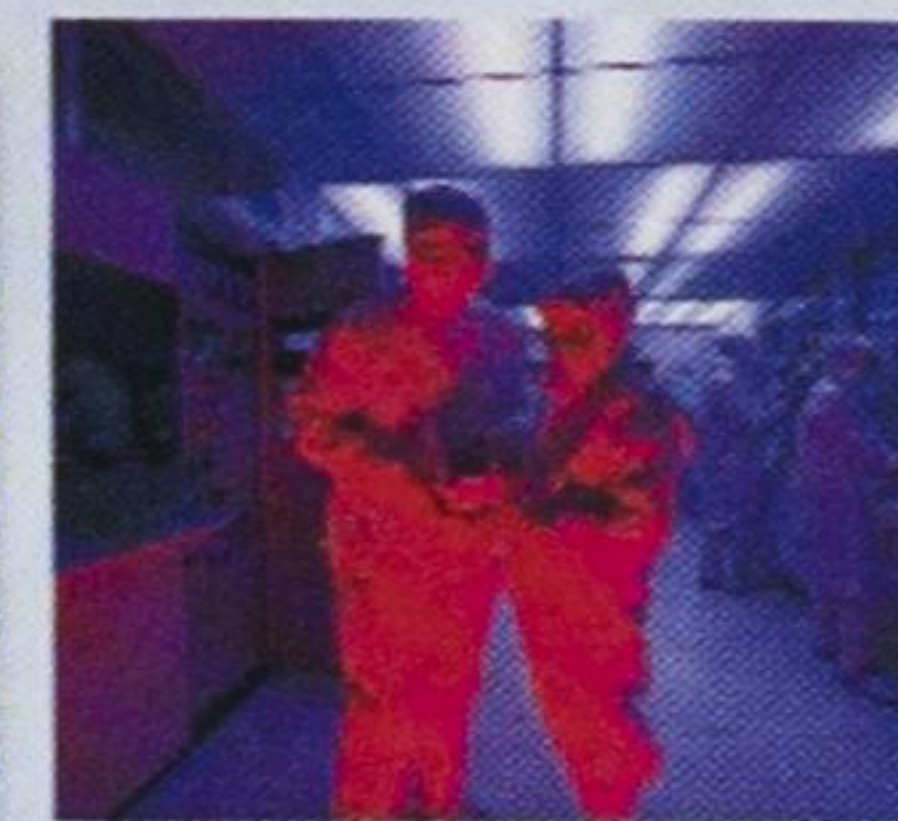
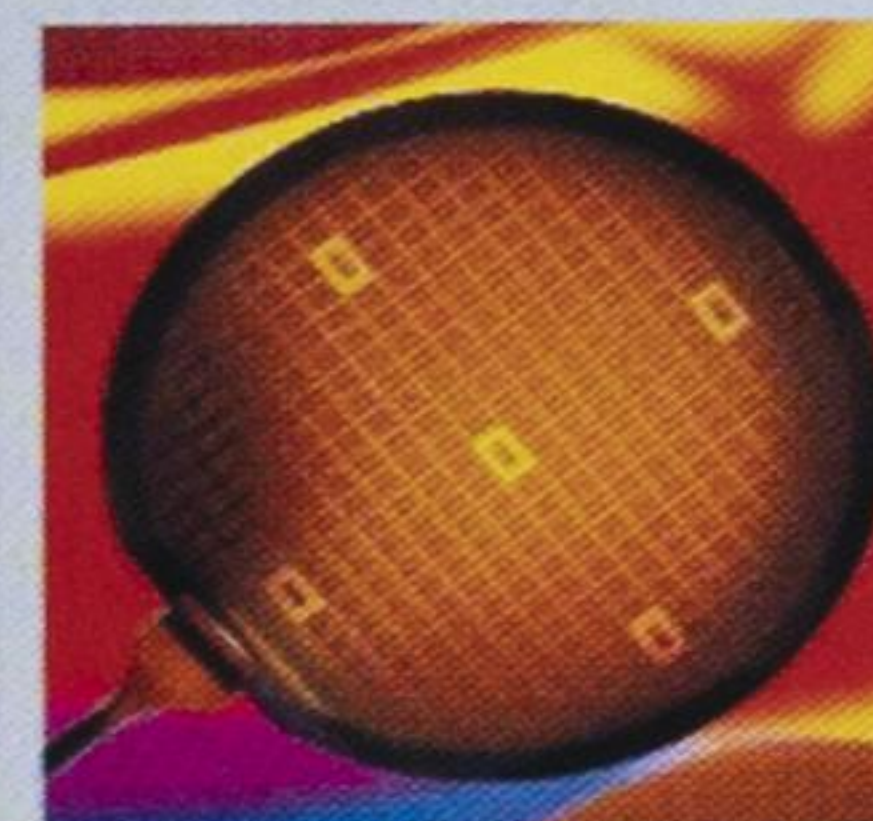
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form at high temperature are important in two applications. First, in devices that operate at high powers and are subject to self-heating; and second in devices that operate in harsh environments, such as the combustion chamber of an automobile engine.

STMicroelectronics has also investigated the dependence of the leakage current from its SiC SBDs on temperature and applied voltage. Coffa explained that it is difficult to give a definitive value for an acceptable leakage current because it depends so much on the intended application. The main problem associated with leakage currents is power dissipation in the “off state”, when the diode is under reverse bias. Coffa noted that Schottky diodes have higher leakage currents than bipolar devices, and that individuals would have to decide which device was appropriate.

The dynamic characteristics of SiC SBDs have been compared with silicon diodes, and found to be superior. Silicon bipolar devices, which have similar breakdown voltages, respond more slowly than SiC devices because they require the recombination of minority carriers.

SiC takes the pressure

In collaboration with an undisclosed car manufacturer, STMicroelectronics is investigating the use of SiC in pressure sensors in combustion engines. SiC is incorporated into a membrane, and changes in pressure lead to deformation and variations in the resistance of the material. To increase the sensitivity, four piezo resistors are configured in a Wheatstone bridge circuit, forming a package measuring $4\text{ mm} \times 4\text{ mm} \times 850\text{ }\mu\text{m}$. This device, which can withstand high temperatures and pressures, has already been tested in an engine and provided pressure readings with the engine running at speeds of 500, 1050, 1400 and 2000 rpm. Coffa believes that these sensors may be employed in cars in the next 5–10 years, depending on the price. He pointed out that one SiC device could replace several of the sensors that are used in cars today.

Despite these recent advances, Coffa warned against complacency: “Sometimes silicon surprises you. For example, for years people have considered silicon to be unsuitable for photonics, but my group has clearly shown that you can have some applications of silicon in the optical domain. You can have LEDs that are completely made with silicon processes. This doesn’t mean that you can cover all the applications of compound semiconductor devices, but in some cases you can

SiC takes voltages to the limit

The various benefits that SiC devices offer over silicon, such as operating at very high voltages and fast switching speeds, all arise from their superior physical properties. For example, the higher bandgap values lead to lower on-resistance values, because this parameter is inversely proportional to the cube of the electric critical field (which is directly related to the bandgap – see table).

The advantages of SiC can also be seen in figure 2, right, which reveals the higher blocking voltages obtainable with SiC. The ideal limit, calculated from the physical parameters of

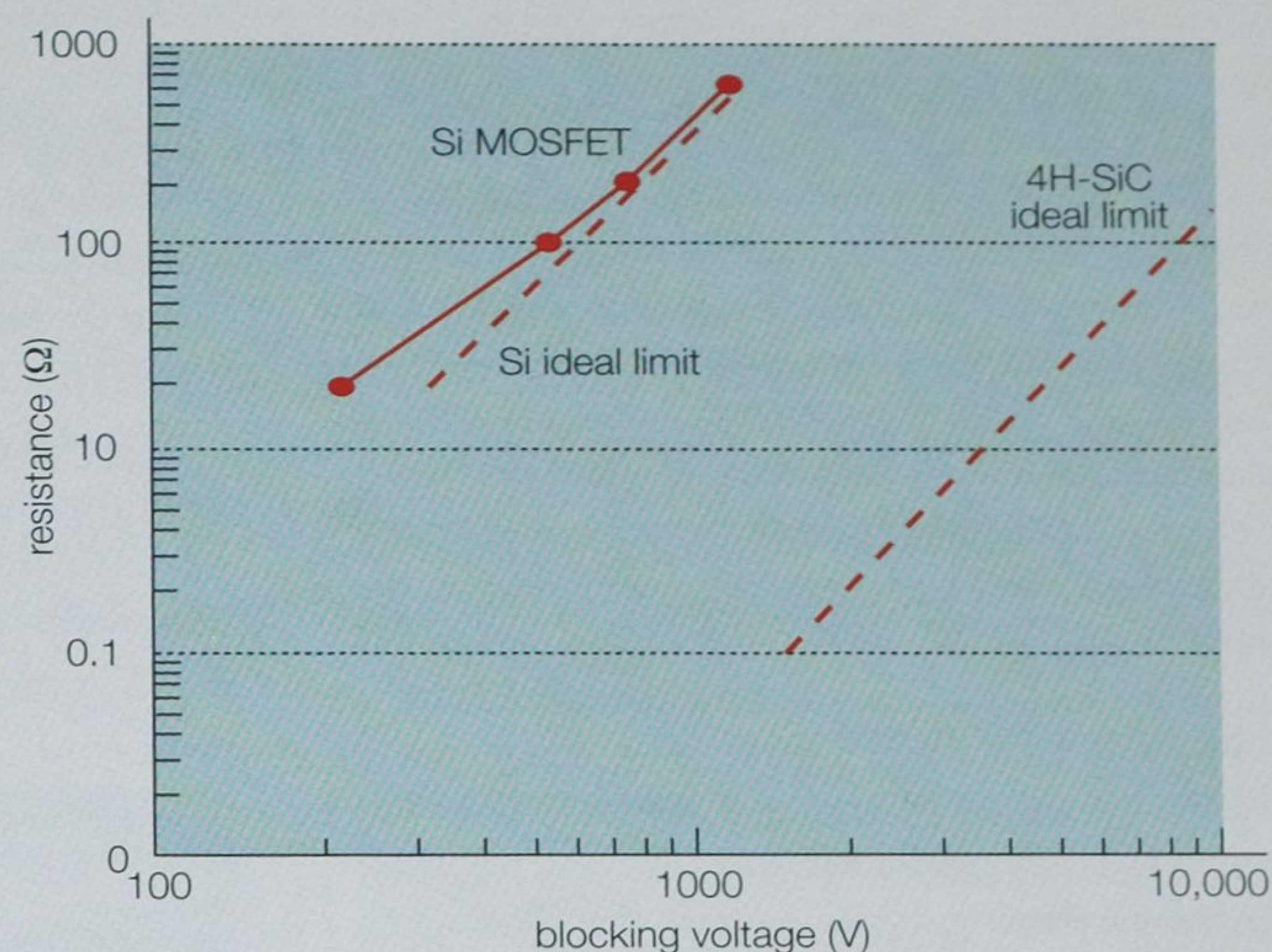


Fig.2. SiC excels where silicon lags behind in two primary areas: low “on-resistance” and blocking voltage.

the material, can be exceeded by using non-planar structures. However,

silicon-based devices will not reach the SiC limit even if this approach is used.

Comparison of silicon and SiC devices

Property	Si	3C-SiC	6H-SiC	4H-SiC
Bandgap, E_g (eV)	1.1	2.3	3	3.3
Electron saturation velocity (cm/s)	1×10^7	2.5×10^7	2×10^7	2×10^7
Electron mobility (cm^2/Vs)	1350	1000	380	947
Dielectric constant	11.8	9.7	9.7	9.7
Critical electric field, E_c (V/m)	2×10^5	3×10^6	4×10^6	3×10^6
Thermal conductivity, k (W/cmK)	1.5	4.9	5.0	5.0

SOURCE: STMICROELECTRONICS

use silicon, especially if you want to integrate the optical part with the electronics part.”

SiCED develops hybrid switch

Another company that manufactures SiC-based power electronics is SiCED. It was established in 2000 as a joint venture between Siemens and Infineon Technologies, and now acts as an R&D center for both of its parent companies. Dietrich Stephani, senior director of the Germany-based company, believes that the two major technological breakthroughs made in the SiC-based electronics industry occurred in 1993, when SBDs fabricated on 6H-SiC substrates showed blocking voltages of 1000 V, and 1 inch 4H substrates became available from Cree. However, these two achievements didn’t lead immediately to the commercialization of SiC-based devices, and Stephani believes that only the very optimistic

could have foreseen that they would have applications in industry.

Today that progress is evident, with SiC-based devices appearing in everyday appliances. For example, a 2000 W transformer containing Infineon’s 600 V SiC SBDs is half the size of its conventional 650 W counterpart; and SiC SBDs are also used in Siemens’ 2.3 kW solar-converter.

Stephani explained that today’s commercially available SiC SBDs operate with blocking voltages of 300–1200 V and currents of 2–10 A. He said that “today’s winning combination” is power factor correction in switched-mode power supplies, where a 600 V SiC SBD is twinned with a 600 V low-loss silicon MOSFET. Looking ahead, he expects higher-voltage SiC SBDs, with blocking voltages of 1200–1700 V, to penetrate the low-power inverter sector and

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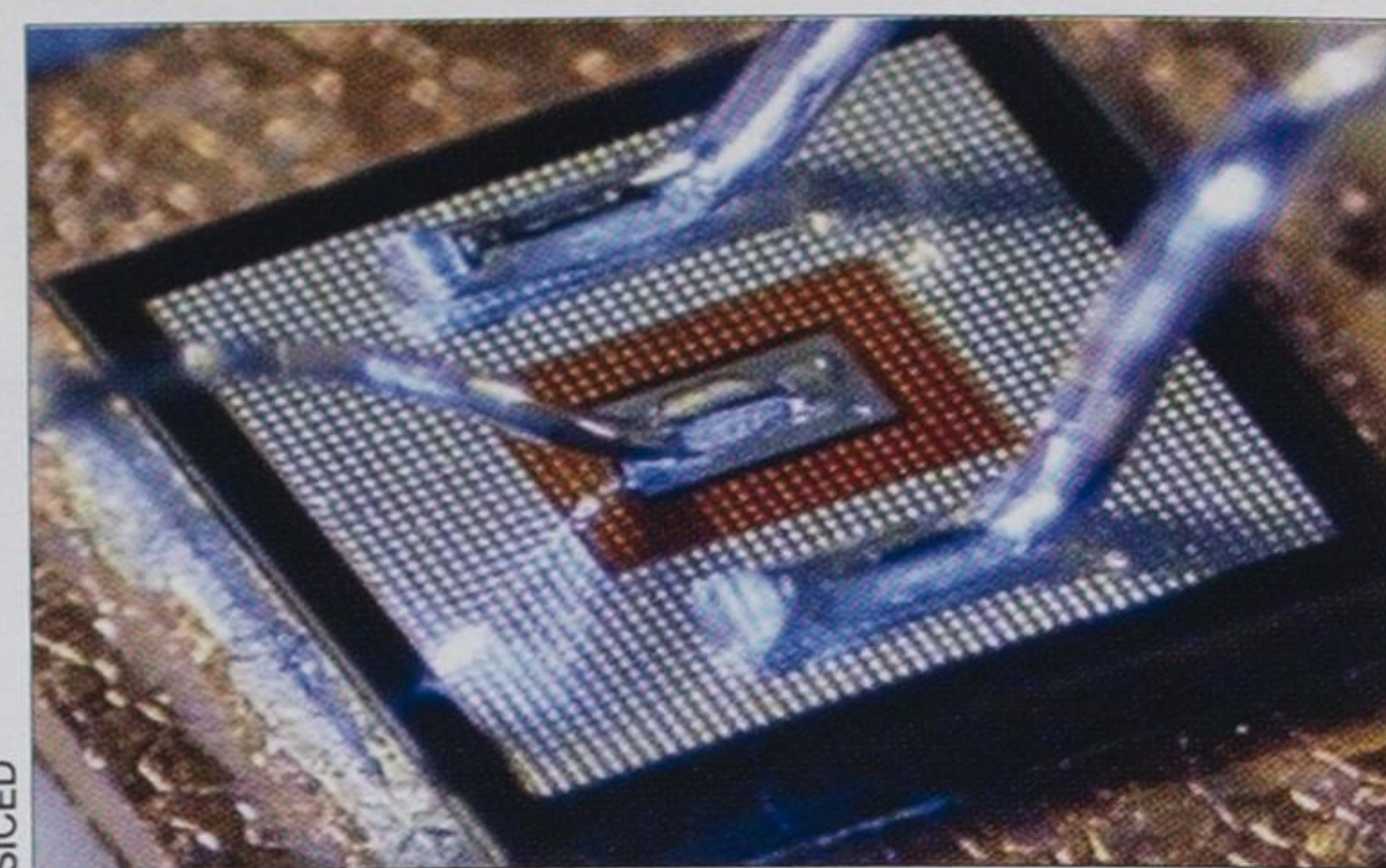
Stephani believes that over the next few years silicon-based power switches operating in the 1200–1700 V range will face increasing competition from SiC-based alternatives. Agreeing with Coffa, he pointed out that silicon-insulated gate bipolar transistors suffer from dynamic losses at high switching frequencies, and suggested that SiC junction field effect transistors (JFETs) might offer a high-frequency elevated-temperature solution, with an unparalleled on-resistance. SiCED is developing a hybrid switch by combining a vertical SiC JFET with a low-voltage silicon MOSFET, for use in resonant converters and auxiliary power supplies.

Low channel mobility and long-term stability of the gate oxide are cited as the two key issues hampering the development of SiC n-channel inversion MOSFETs. Stephani noted, however, that recent progress using N_2O in the thermal oxidation process had enabled the fabrication of 3 kV SiC MOSFETs with a room-temperature on-resistance of 3Ω , for a 2.1 mm^2 chip area. He believes that within the next three years these devices, which have an attractive cost:performance ratio, could impact the market, although their precise application is not yet clear.

Stephani's optimism does not extend to the commercialization of SiC *pin* diodes, though. Here SiC has to compete with its well established silicon-based counterparts, which have lower turn-on voltages thanks to their lower bandgap. One area where SiC devices can compete is in operations demanding very high blocking voltages, said Stephani. He thinks there is a need for 6.5 kV, 25 A single chips. High-voltage SiC *pin* diodes require high current-handling capabilities, and consequently large chip areas. Engineers at SiCED have demonstrated a SiC *pin* with an emitter area of 5.7 mm^2 and a blocking voltage of almost 5 kV, but Stephani explained that today the yield of large-area chips is low because of poor-quality SiC material. This causes high defect densities, which lead to an uncompetitive cost:performance ratio.

Bipolar SiC

Improved material quality and a reduced cost are also required before bipolar SiC power devices can impact the market. Stephani does not expect these devices to appear within the next three years, but he is optimistic about their long-term viability: "High dynamic performance combined with high-temperature operation and blocking 10 kV or more is the



Able to cope with high temperatures, JFETs are suitable for auxiliary power supplies.

"High dynamic performance combined with high-temperature operation is the ultimate challenge for electronic power switches. There is just one candidate today to solve this task – SiC."

DIETRICH STEPHANI, SiCED

ultimate challenge for electronic power switches. There is just one candidate today to solve this task – SiC."

Engineers at SiCED are already addressing the cost of SiC-based power devices by investigating the quality of epilayers grown on a multiwafer reactor. Bernd Thomas, also from SiCED, has set targets that are suitable for the production of 300, 600 and 1200 V SBDs: doping and thickness homogeneities better than 10 and 5% respectively; a doping range (the difference between the densities of donor and acceptor atoms, $N_D - N_A$) of $4 \times 10^{15} - 2 \times 10^{16} \text{ cm}^{-3}$; and drift layer thicknesses of 3–18 μm .

In trials, SiCED's engineers have used 4° off-axis (0001) 4H-SiC 3 inch wafers, which are more affordable than their 8° counterparts. They have also employed a multi-wafer hot-wall Epigress VP2000HW CVD system, which is capable of a 7×2 or a 5×3 inch configuration. Wafer-to-wafer uniformity has been evaluated by growing 18 μm -thick layers, with a doping of $4 \times 10^{15} \text{ cm}^{-3}$, suitable for blocking over 2.5 kV.

Intrawafer values of sigma/mean of 1.6 and 3.3% for the thickness and doping were calculated using an exclusion zone of 2 mm, which Thomas says "meet the requirements for production process management".

Start-up stakes its future on InP for cell-phone handsets

Just two months ago Xindium Technologies parted company with its research team, including the start-up's co-founder Milton Feng. CEO John Brewer says that after first establishing a foothold in the handset supply chain with GaAs-based products, Xindium's priority will be to produce InP-based cell-phone power amplifiers for the EDGE market. **Michael Hatcher** reports.

John Brewer was parachuted into the Xindium Technologies hot seat back in December 2002 with a brief to channel the company's technological expertise in InP towards applications in cell-phone handsets. Milton Feng and colleagues from the University of Chicago at Urbana-Champaign had originally set up the company to serve the optical communications market, but when they founded Xindium in 2001 the sector was already in free-fall after the telecom bubble burst.

Following Brewer's arrival, Xindium radically changed direction to develop InP for power amplifier (PA) applications. Then, two months ago, the company lost its entire research team along with co-founder Feng in acrimonious fashion after an apparent difference of opinion with Brewer over the commercialization of products.

Xindium is now focused squarely on PA solutions, and Brewer says that InP can make an impact in handsets sooner than might be expected. "There are products that [handset OEMs] can't ship today because the PA doesn't work properly," he said. "Every major compound semiconductor company has got InP-based PAs on the near-term road-map, and so does every handset manufacturer."

By short-term, Brewer means the next two to three years at most, but he believes that manufacturers will make their move in the next year. "This is one of those things that's been creeping along below the radar for quite a while, but our epitaxy vendors have got people demanding high-power, high-breakdown voltage InP constantly. Our processing partner has the same issues."

Brewer is not the sort of character to sit on his hands waiting for the InP PA market to materialize, however. Having got what he describes as "reasonably good development of an effective epitaxial process for an InP-based PA" out of his technical team before the



John Brewer believes that the uplink speed of today's EDGE handsets, such as the new Nokia model 7260, is no better than that achieved with GPRS. Power amplifiers based on InP could provide the solution.

company split, Xindium has just begun sampling InGaP/GaAs PAs to handset manufacturers in South-East Asia.

So what is a tiny start-up like Xindium doing taking on high-volume incumbents like RF Micro Devices, Skyworks and Renesas in the handset PA arena? According to Brewer the opportunity lies in the "cracks in the market", where certain GSM handset makers in Asia have found it difficult to get a reliable supply of PAs for their GPRS phones.

"Our market is InP for EDGE and W-CDMA. We will live or die on that."

JOHN BREWER, XINDIUM CEO.

"Last December the very strong demand was underforecast," explained Brewer, adding that the two components that proved particularly difficult to obtain at that time were color displays and PAs. The smaller handset ODMs saw their supply squeezed at the expense of larger customers, and good lead times and delivery were hard to come by, he added. This would allow a smaller company like Xindium to find its niche in the market.

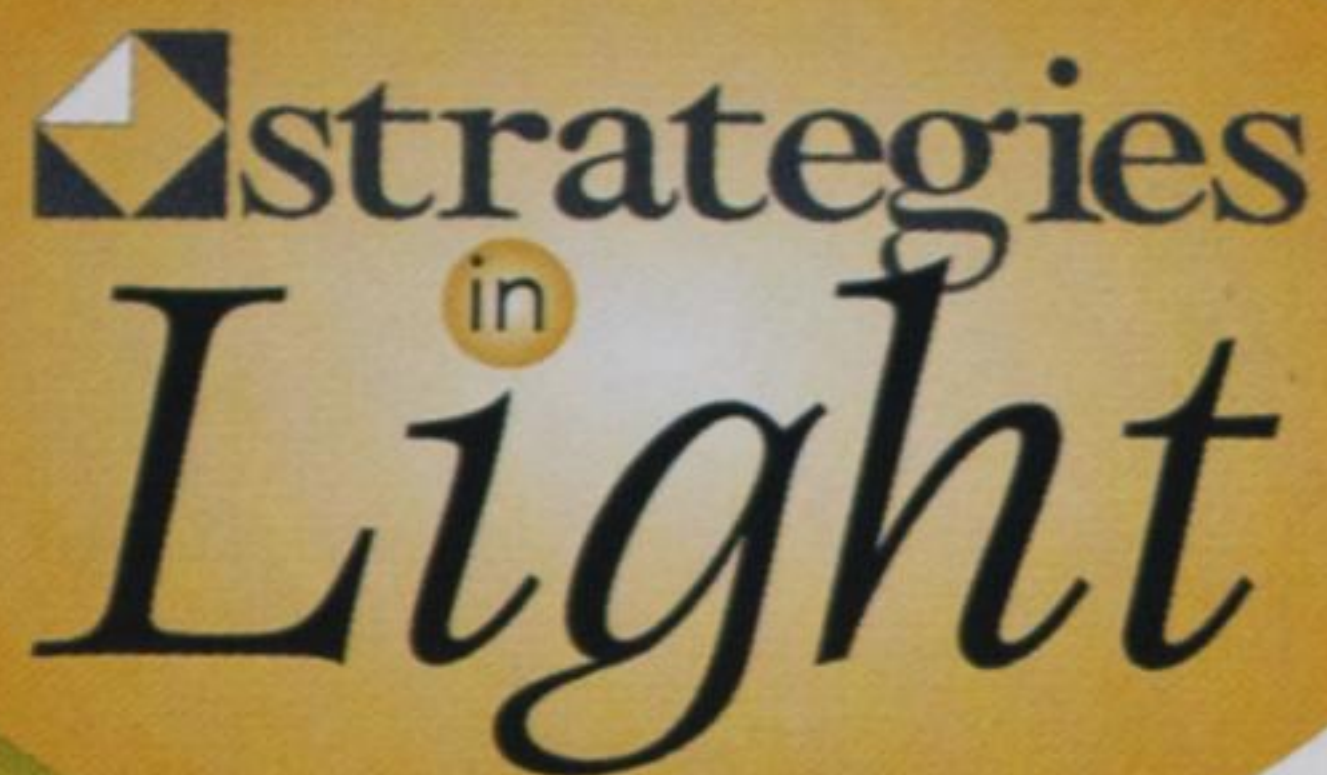
Xindium already has one GaAs-based quad-band PA product on the market, and Brewer says that this portfolio will be extended to three or four by early next year, with essentially the same product but in a different package. "We're selling die into module manufacturers in Asia. There's a whole group of companies that build all sorts of modules for things like Bluetooth, but they can't buy GSM die – so they're left out of the GSM market."

Future rests on InP

Brewer says that although it was not part of the company's original plan to commercialize GaAs-based RF devices, it has been an important factor in forcing the start-up into commercial mode, selling products, and getting its name in front of handset makers.

This may be crucial now, but however well Xindium performs in the GaAs PA market, its future products based on InP will ultimately determine whether or not the company is a success. "Our market is InP for EDGE and W-CDMA. We will live or die on that," Brewer told *Compound Semiconductor*.

Although EDGE phones are on the market and networks are being built to accommodate their higher data throughput, Brewer says that these handsets do not have "true" EDGE capability. "Nobody can build an EDGE PA right now that meets the output power and the multi-time-slot transmit requirements," he claimed. "EDGE phones are shipping, and they all do up to 100 kbit/s in the downlink,



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but in the uplink they're all limited to half the necessary transmit power and one time slot – essentially no faster than GPRS is today.”

And this is where InP-based PAs come in. One of the key physical advantages of InP compared to GaAs technology is its high thermal conductivity. “What's limiting transmit power and speed in EDGE is the PA heating up,” explained Brewer. “InP is a 50–60% better heat conductor than GaAs, and it also has significantly better speed and bandwidth. So you can make smaller transistors that generate less heat but the right amount of power.”

Brewer appears to be under no illusions regarding the technical challenge of developing InP-based PAs for commercial EDGE applications. “An EDGE PA is probably the hardest thing ever done in a MMIC at these power ranges, in terms of linearity and efficiency,” he said.

High-end opportunity

Cost is another issue with InP, but Brewer believes that InP PAs can make an impact in high-end handsets: “There will always be room [in the US market] for a \$500 handset that has the latest, whizziest bits in it. And in that segment there's enough room on the bill of materials for PAs to go in at the high \$3 range. In 2005 this will not be an issue for InP.”

What could be more of a problem is ensuring that the cost of an InP PA can follow the sharply downward trend of its GaAs counterparts as suppliers drive manufacturing efficiencies. “The trick is to reduce component cost by 15–20% each year until you're in the sub-\$2 range,” said Brewer.

That will mean extending the brittle, awkward-to-handle InP substrates from 4 inches to 6 inches in diameter, a technical feat that seems unlikely when the substrate has to be thinned to just 100 μm . Brewer thinks that an answer may lie in epitaxial techniques, where a thin film of InP is deposited onto a GaAs substrate. “The epitaxial challenge in 2005–6 is to work on 4 inch diameter wafers, but to have a 6 inch solution. I think that GaAs substrates are probably the solution.”

While Xindium concentrates on its material solution to the heat problem, other PA makers are trying to solve it through advances in packaging technology. “We're now seeing flip-chip PAs, when a few years ago this would have been viewed as heresy,” said Brewer. “But we know of two vendors that have produced flip-chip prototypes to improve heat conduction in GaAs PAs.”

Although Xindium is without its Urbana-

InP in handset PAs? Reasons for and against

There is no question that InP has physical properties that make it seem the ideal material with which to build power amplifiers (PAs) for cell-phone handsets. In particular, it has higher thermal conductivity than GaAs, which means lower operating temperatures at high RF output powers (see figure 1).

This is important, because the higher data transport rates demanded from EDGE handsets mean that the PA is “on” and generating RF power for more of the time than in GPRS phones. This higher duty cycle leads to more heat building up in the collector of the final-stage PA transistor, which affects the output power and linearity of the PA. The result can be interference with other frequency channels, or even dropped calls.

Its higher thermal conductivity means that using InP in the PA stage ought to reduce these effects. InP's higher breakdown voltage also means that it can support smaller ICs for the PA stage, with more efficient power conversion and less build-up of heat.

Coupled with a lower

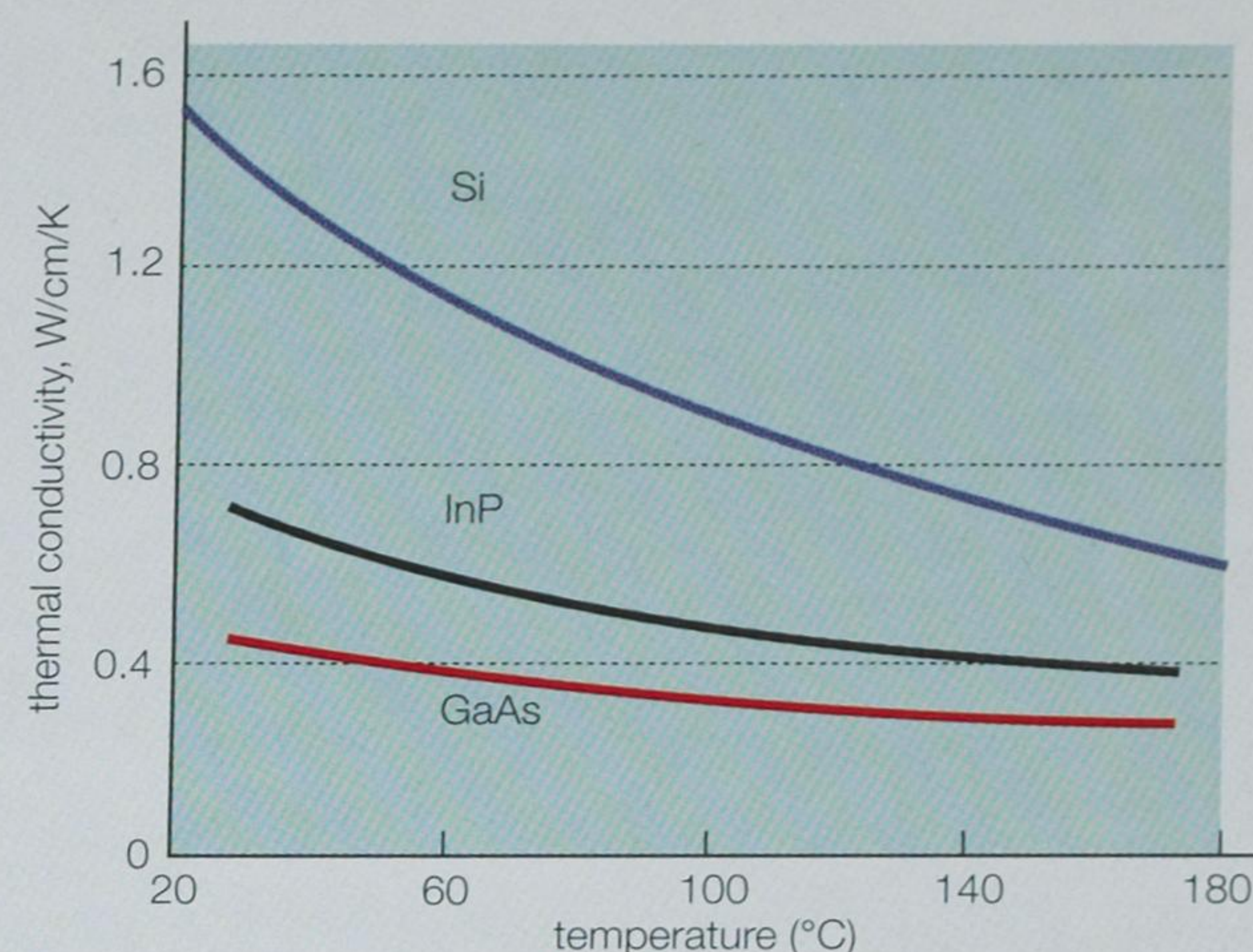


Fig. 1. The relative thermal conductivity of Si, GaAs and InP.

turn-on voltage and higher electron mobility, the technological argument in favor of InP is pretty clear. The problem lies in the manufacturability of InP-based devices. Whereas GaAs HBTs can be made cheaply and in huge volumes on 6 inch wafers, the same cannot yet be said of InP. Restricted to 4 inch wafers at the most, and more often than not 3 inch, the substrate poses the manufacturing problem.

The brittleness of the material presents its own difficulties, especially when wafers are thinned. There are also problems in scaling up to 6 inch wafer production – something that

is critical to bringing down the cost of InP-based PAs at a rate of 15–20% per year, as handset makers would inevitably demand.

Switching to a different material technology for PAs would require a huge leap of faith by handset makers, so GaAs PA manufacturers are looking to solve the heat problem associated with GaAs HBT for EDGE handsets in other ways, with a particular focus on improved thermal management through novel packaging.

If the packaging approach proves successful, then the arguments in favor of using InP in handset PAs could become less compelling.

Champaign-based research team and pure research is on hold for a few months, Brewer says that the company already has its epitaxy structure for InP devices worked out, and that the main challenge is to co-ordinate manufacturing. Taking charge of the technical side of the company for the moment is Keith Manssen, Xindium's vice-president of engineering and a 20-year veteran of the RF and cellular industry.

Of the departed technical team under Feng's control, Brewer said that while it was a “very, very capable” group of researchers,

it lacked expertise with regard to commercial products. “They did really good work for us. The difficulty is the small-group collegial environment, which can be quite insular,” he said. “Nobody in Champaign knew anything about GSM. The guys that we now have [in Crystal Lake] have all been working on GSM PAs for 10 years.”

“Research mode is always more comfortable, the time lines are less rugged. But when you're in commercial mode it's a case of get the thing working and get it tested. Get the technology to market as fast as you can.” ●

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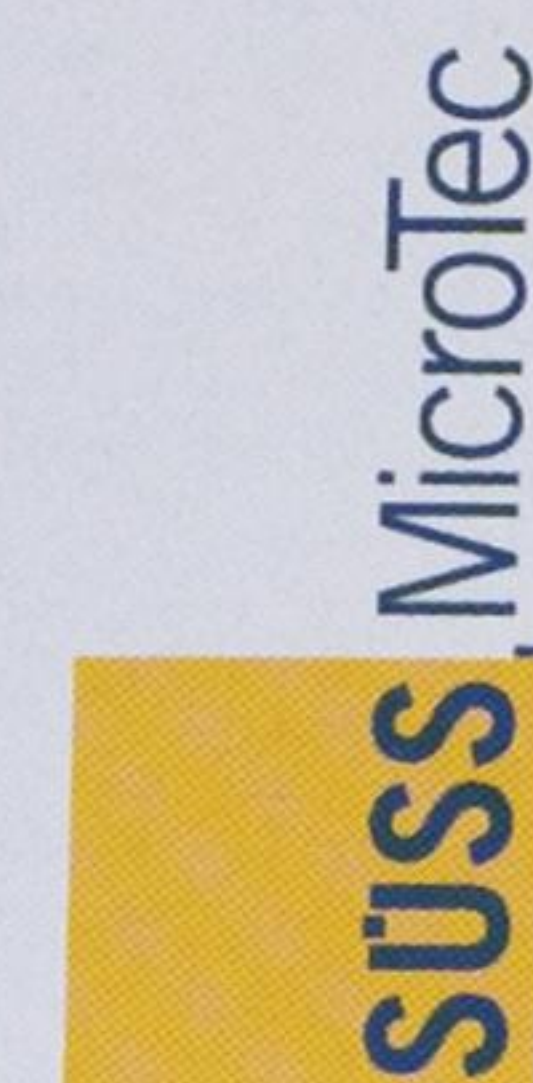
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AXT stung by charges

US-based substrate maker AXT was hit by \$3.5 million in charges and a shareholder lawsuit in its third fiscal quarter of 2004.

The company made a \$1.4 million payment following a "tentative settlement" with rival substrate vendor Sumitomo Electric Industries (SEI) of Japan. AXT will now pay royalties to SEI for products sold in Japan.

AXT and SEI have dropped any remaining legal action, and will enter into a worldwide four-year cross-licensing agreement for all intellectual property used by either firm related to compound semiconductor substrates, says Don Tatzin, AXT's interim CEO.

AXT also recorded a \$2.1 million charge for inventory unsold within two years of its manufacturing date. The two charges affected AXT's third-quarter results. Total revenue was \$8.5 million, in-line with its forecast, but net loss for the quarter was \$5.5 million.

AXT also faces a lawsuit from US law firms representing AXT's shareholders. The complaint alleges that AXT and its previous CEO, Morris Young, made false and misleading statements between February 6, 2001, and April 27, 2004, and inflicted damages on investors.

It appears that the rapid drop in AXT's share price earlier this year prompted the recent action by shareholders. Over April 28 and 29, AXT's stock fell from \$3.30 to \$2.20 after it was disclosed that the company was not complying with certain product-testing requirements. An investigation followed before AXT belatedly announced its first quarter 2004 results and Young was moved to head up AXT's China operations.

Tatzin countered: "The company intends to vigorously fight [this lawsuit]. We do not expect the litigation to affect our on-going business or our ability to serve customers."

Riber cuts staff despite bullish outlook

France-based MBE specialist Riber has reported sales of just €3.7 million (\$4.6 million) for the first half of its fiscal 2004, which ended on June 30.

The company made a net loss of €4.7 million during the period, compared with a loss of €3.5 million in the first half of last year.

Riber blamed poor sales, downward pressure on selling prices and the unhelpful euro/US dollar exchange rate for the disappointing figures. Owing to this lackluster performance, the company is to reduce its workforce and production expenses, partly by

concentrating its operations on a single site.

But with orders for 10 research machines in the pipeline, Riber expects sales to pick up next year as commercial device manufacturers gear up for increased production.

The firm predicts full-year 2004 sales to hit €13 million, before rising to €18–21 million in 2005, thanks to purchase demand for "wireless telecommunications, optoelectronics and new applications".

Riber says that it had cash and cash equivalents amounting to €8.4 million on June 30, down from €9.8 million in January.

In brief

- **Unaxis Wafer Processing**, a division of US-based Unaxis, will supply Sandia National Labs with 12 Versaline systems for MEMS and III-V applications at Sandia's Microsystems and Engineering Sciences Applications facility in Albuquerque, NM. Versaline is a modular system enabling etch and deposition processes.
- Germany-based substrate manufacturer **Freiberger** has appointed Klaus Romanek as CEO as of September 1. He joined Freiberger in October 2003 as managing director with responsibility for all commercial functions and has more than 20 years experience in the microelectronics

industry, previously holding management positions in Kontron, Wavetek (now Acterna) and Microtest (now Fluke).

- Japan-based chemical products manufacturer **Showa Denko K.K.** will start producing high-purity ammonia for LED applications in Taiwan from May 2005 through a new subsidiary Taiwan Showa Chemicals Manufacturing Company.

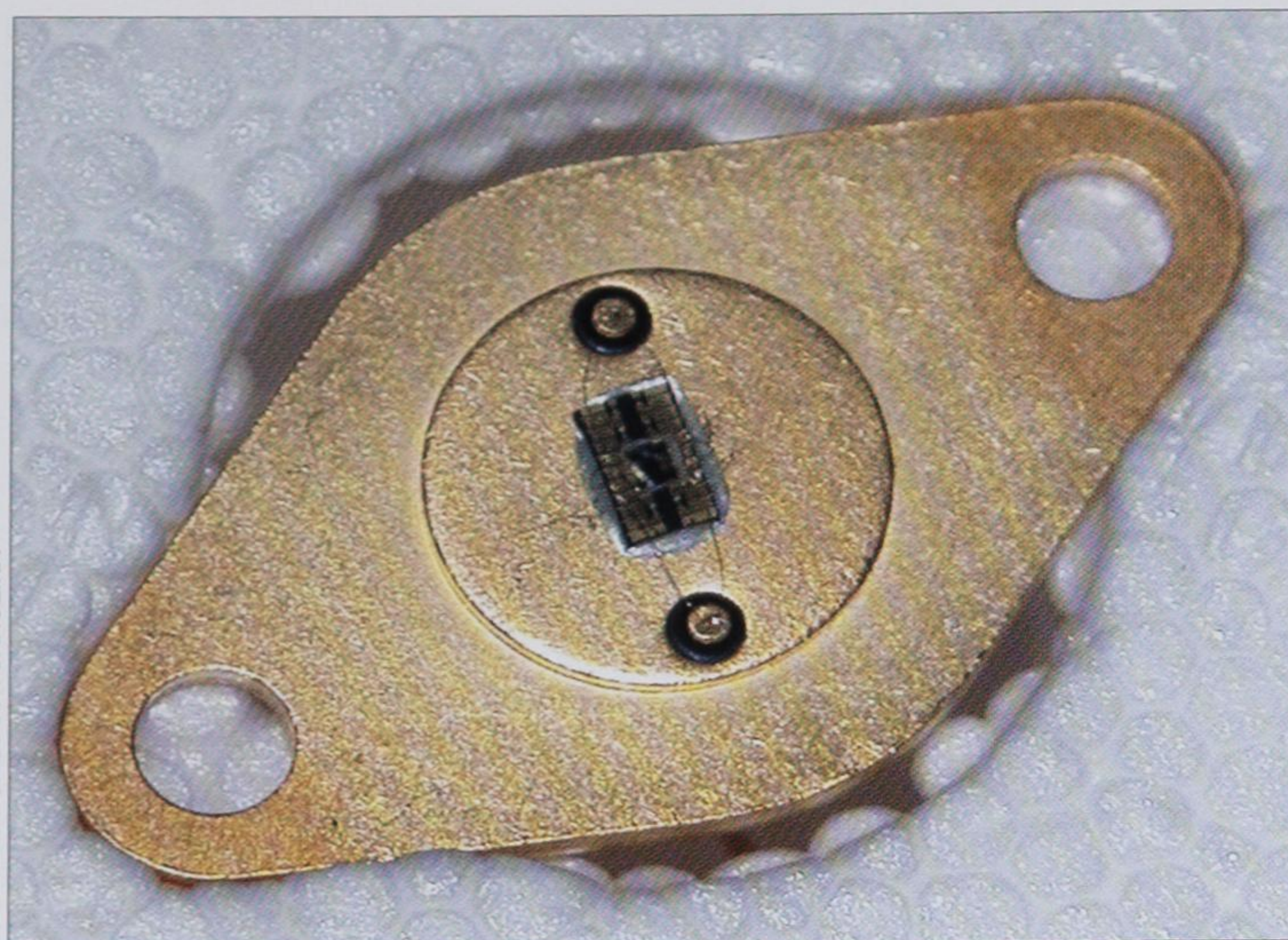
- **Oxford Instruments Plasma Technology** has officially opened its new MBE production facility in East Grinstead, UK. The company acquired the VG Semicon MBE business from Thermo Electron Corporation in October 2003.

UV LEDs reach shorter wavelengths

Asif Khan and his research team from University of South Carolina, SC, have fabricated unpackaged AlGaIn-based ultraviolet (UV) LEDs that emit 0.57 mW at 255 nm and 0.16 mW at 250 nm in pulsed mode. The team expects these power levels to increase by three to five times with flip-chip bonding (*Appl. Phys. Lett.* **85** 2175).

The LED is grown by migration-enhanced MOCVD on a sapphire substrate. It consists of an AlN buffer layer followed by a ten-period AlN/AlGaIn superlattice; an Al_{0.72}Ga_{0.28}N cladding layer that also serves as the n-type contact layer; an active region that has three 3 nm-thick Al_{0.58}Ga_{0.42}N quantum wells separated by 5 nm-thick Al_{0.65}Ga_{0.35}N barriers; a p-type Al_{0.72}Ga_{0.28}N cladding layer; and a GaN p-doped cap.

"The Al composition of 72% was chosen to provide transparency at 250 nm since our devices emit through the substrate. This layer is



AlGaIn-based LEDs grown by migration-enhanced MOCVD. The devices emit 0.16 mW at 250 nm when operated in pulsed mode.

critical for determining device performance," explained Khan and his co-workers. "We reduced the thickness of the AlGaIn cladding layer to 1.4 μm to mitigate cracking."

The researchers tested the LEDs, a 200 μm^2 device emitting at 255 nm and a 150 μm^2 device emitting at 250 nm, in pulsed mode to avoid self-heating. External quantum efficiencies of 0.015% and 0.01% were recorded for the 255 nm and 250 nm emitters, respectively.

The team, which is funded by the DARPA Semiconductor Ultraviolet Optical Sources (SUVOS) program, will now focus on improving the quantum efficiency of the deep UV LEDs and on device reliability. It also recently reported 280 nm LED

emission with a 1% quantum efficiency, almost a 10-fold improvement on its previous achievements (*Jpn. J. Appl. Phys.* **43** L1419). Khan believes that by using single AlN crystals, a novel design structure, and chip encapsulation, this efficiency could increase to more than 10%.

Sharp quadruples MBE-grown LED output power

Researchers at UK-based Sharp Laboratories Europe (SLE) claim to have produced the highest-power InGaIn-based LEDs grown by MBE (*Elect. Lett.* **40** 1299). The devices, which emit 3.75 mW at a forward current of 20 mA, have an output power more than four times higher than previously reported results, and are said to be comparable to MOCVD-grown devices.

The team used a VG-Semicon V80 MBE reactor, with ammonia (NH₃) providing the nitrogen content, to grow the LED structures. Lumilog's commercially available GaIn-on-sapphire templates were used – consisting of a 10 μm -thick Si-doped GaIn layer grown by MOCVD on a 330 μm -thick sapphire wafer that have a threading dislocation density of $8 \times 10^7 \text{ cm}^{-2}$. The active region comprised three

2 nm-thick In_{0.1}Ga_{0.9}N quantum wells separated by 12 nm undoped GaIn barriers. Silicon and magnesium were used for n and p doping, respectively. The p-contact was formed by thermal evaporation of 7.5 nm of nickel, and then 250 nm of gold. Bare and encapsulated devices were fabricated via a standard photolithography process, and the latter variant performed better.

Jonathan Heffernan, co-author of the paper and manager of the advanced optics division at SLE, believes that the dramatic improvements in LED output power resulted from using NH₃ instead of a N₂ plasma, and from optimizing the efficiency of the active region.

Although MOCVD dominates the growth of commercial GaIn-based emitters, Heffernan thinks MBE "is viable for efficient LEDs and laser diodes" owing to the cost savings that come from consuming less ammonia and hydrogen. The SLE team is aiming to improve the internal efficiency of its devices, although Heffernan admitted that SLE is focusing mainly on laser diodes.

GaN free-standing substrates boost HEMT mobility

A US-based collaboration between Cree and the US Naval Research Laboratory claims to have achieved the highest room-temperature Hall mobility, 1920 cm²/Vs, for an MBE-grown AlGaIn/GaN "HEMT" structure (*Elec. Lett.* **40** 1226).

The team believes that the performance of GaIn-based HEMTs is hindered by the density of threading dislocations (TDs), which in turn limits the mobility. The researchers attribute their progress to using free-standing GaIn substrates. These have a TD density that is one-tenth to one-hundredth that of widely used GaIn-on-sapphire templates.

The HEMT structures were grown on one of Cree's 10 $\times$ 10 mm² GaIn wafers, which has a TD density of $8 \times 10^6 \text{ cm}^{-2}$. The epiwafer

consisted of a 1 μm beryllium-doped GaIn isolation layer, a 0.5 μm undoped buffer, and a 25 nm undoped Al_{0.27}Ga_{0.73}N barrier, and was produced in a Vacuum Generators V80H (Mark 1) MBE system equipped with an EPI RF-plasma nitrogen source.

After HCl had been used to remove gallium droplets from the wafer surface, 10 Hall patterns were defined on the wafer. The average room-temperature Hall mobility on these structures was 1836 cm²/Vs.

The researchers say their work beats the previous highest value for room-temperature mobility, 1670 cm²/Vs, for an AlGaIn/GaN HEMT structure. This value was achieved by Manfria and co-workers (*J. Appl. Phys.* **92** 338).

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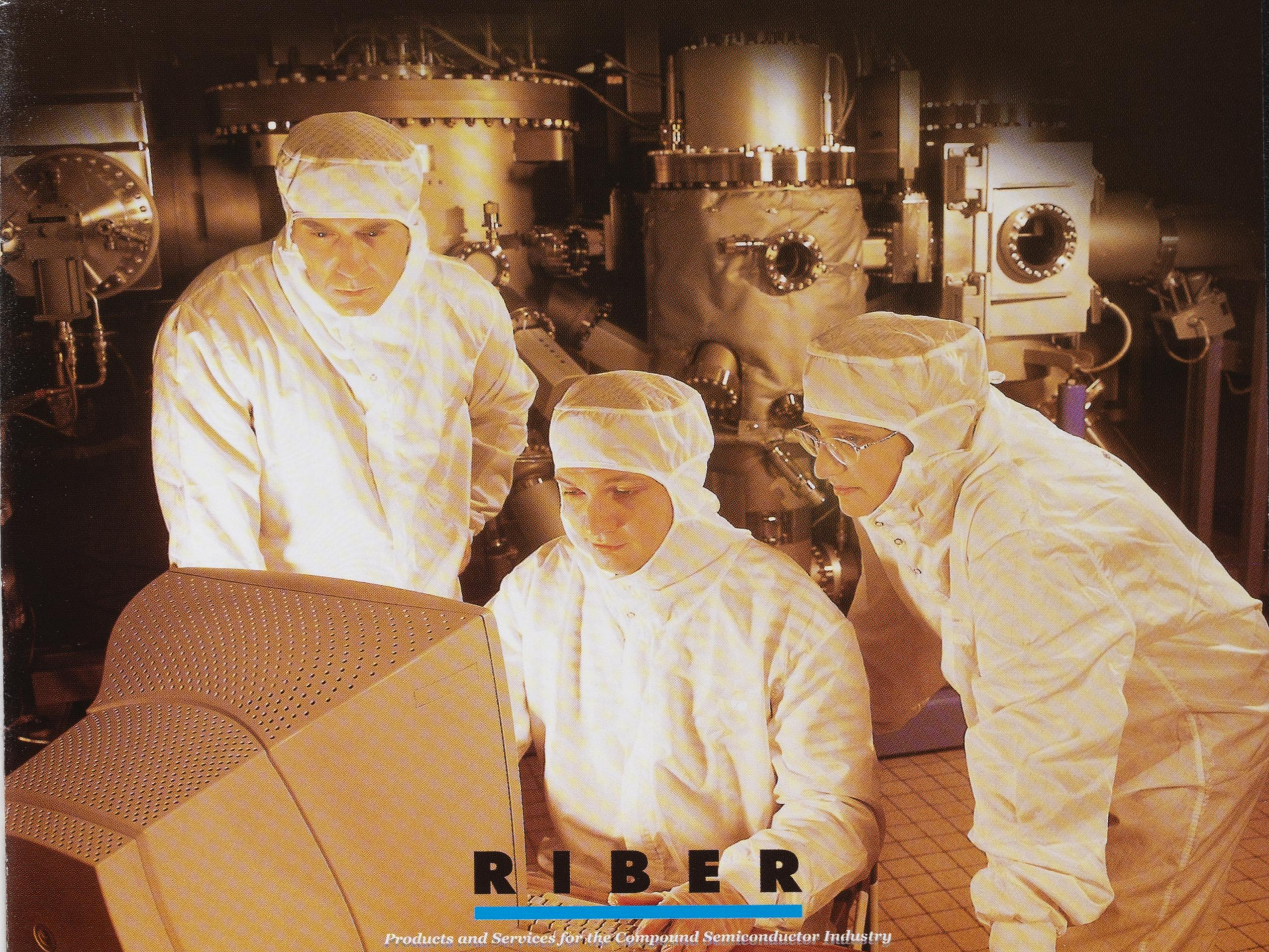
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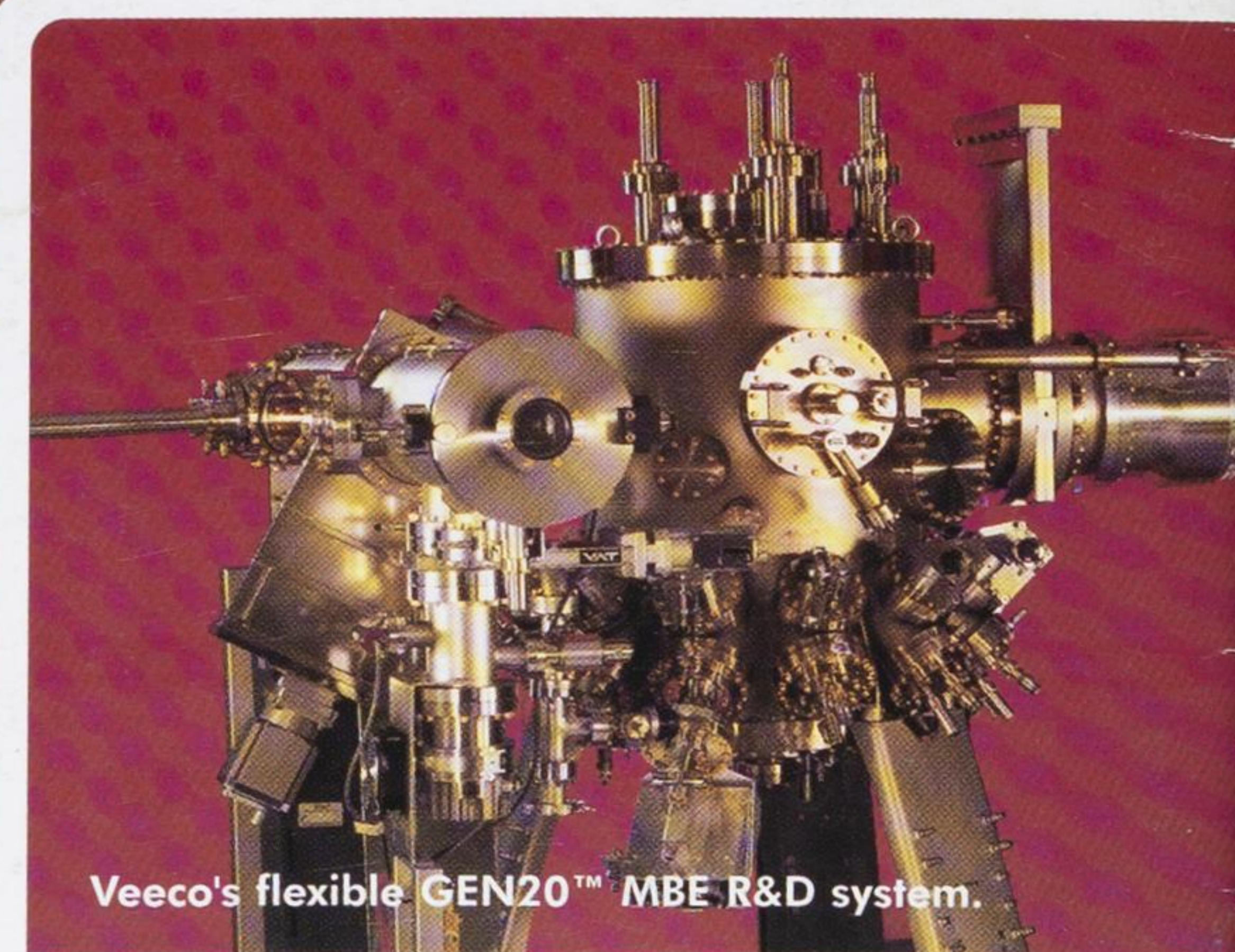
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