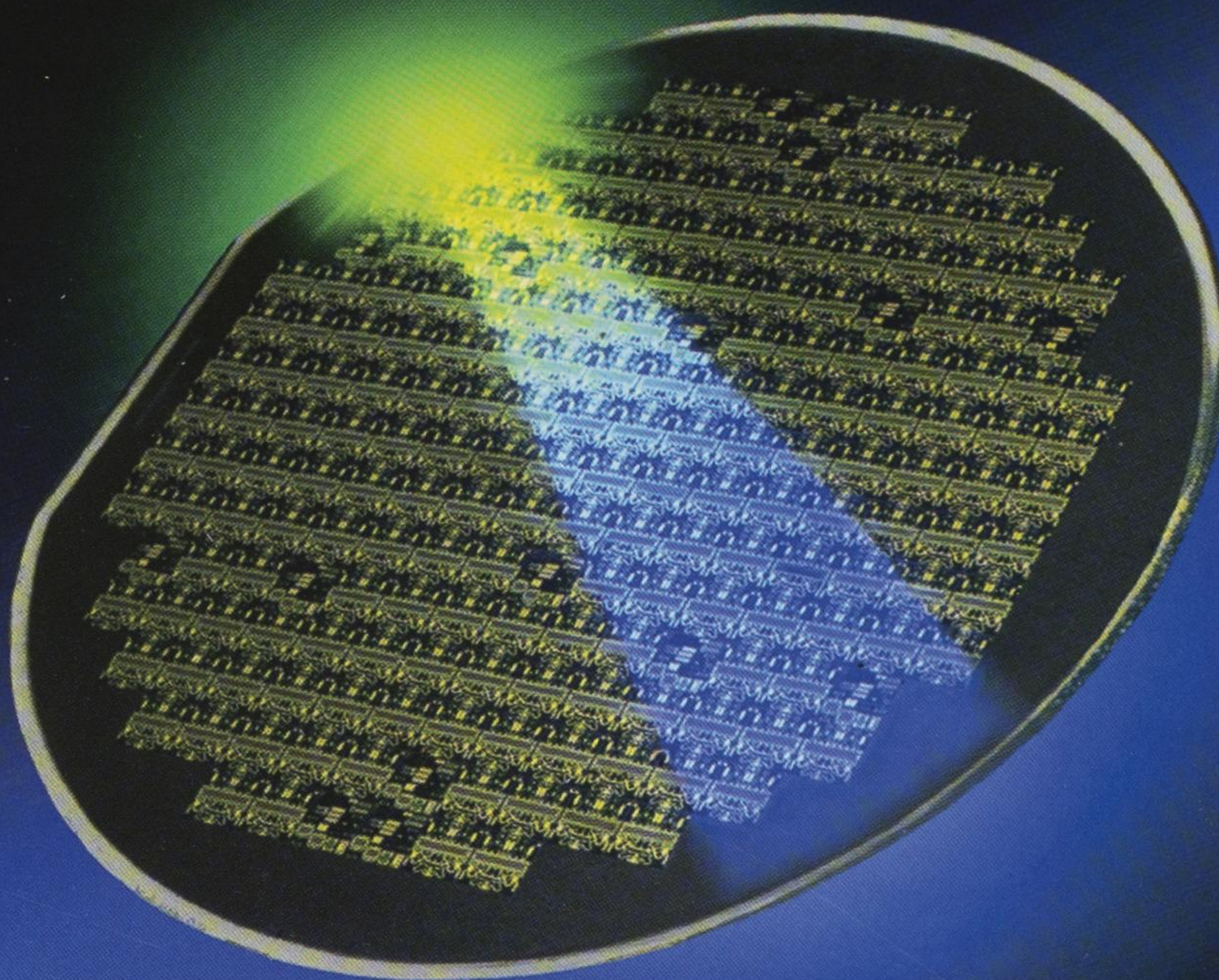


COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

September 2003 Volume 9 Number 8



SILICON CARBIDE

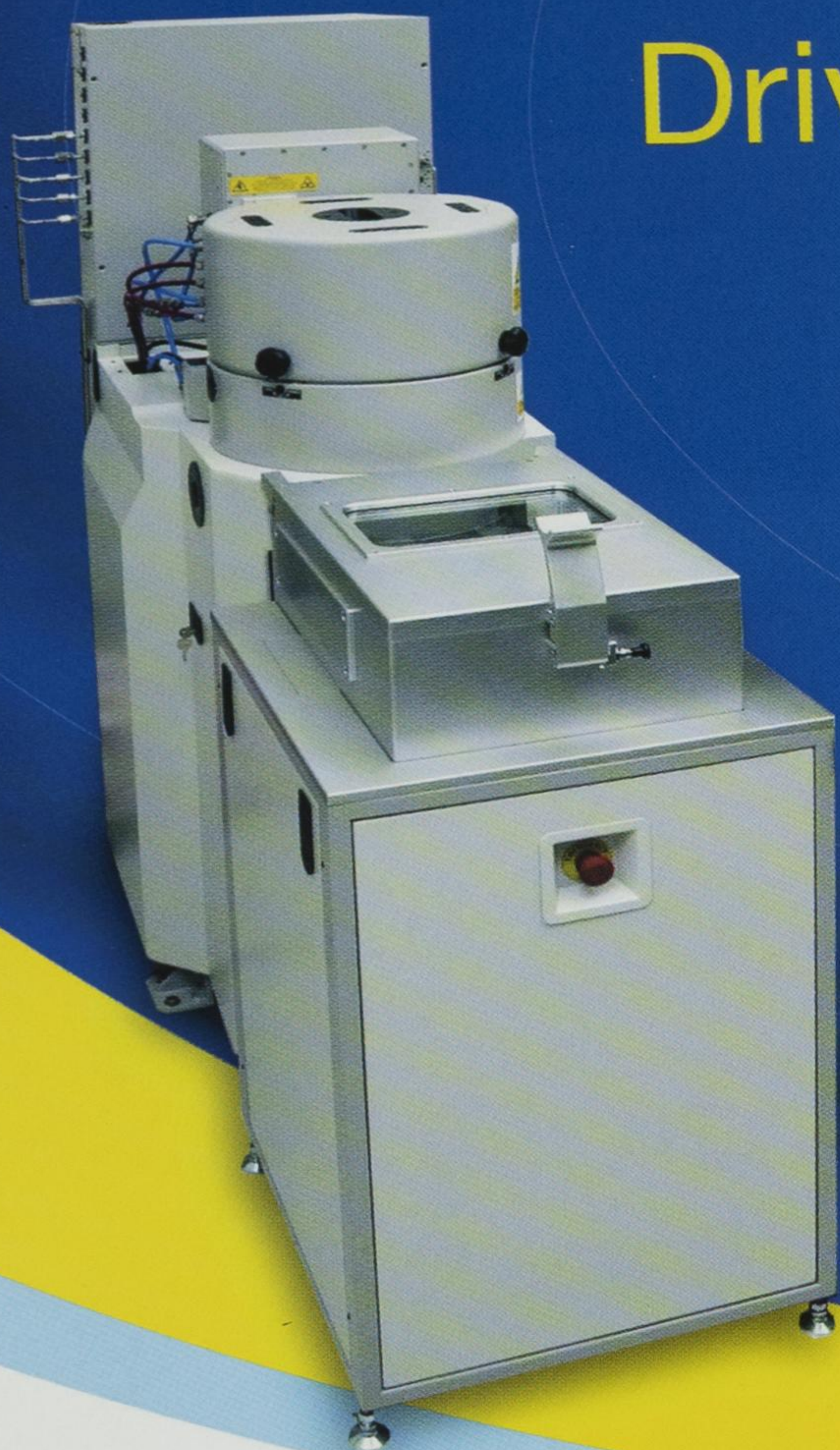
**Material improvements open
new markets for SiC devices**

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**More consolidation
in fiber optics**

**RFMD qualifies its
6 inch GaAs fab**

**Price trends in
market for indium**



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Three-Fives and Silicon Heterostructures

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25 The rapidly changing world of SiC materials and devices

SiC has evolved from being a laboratory curiosity to being a useful material for wide-bandwidth, high-power devices. Scott Allen and Jim Milligan of Cree describe the latest developments.

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31 GaAs IC Symposium celebrates 25 years with strong program

Now in its 25th year, the GaAs IC Symposium once again promises to cover the latest advances in high-frequency and high-speed compound semiconductor circuits and technology.

33 The indium market and compound semiconductors

The recent drop in demand for InP-based devices means that less indium is being consumed by the semiconductor industry, yet indium prices have risen sharply. Thomas Jansseune of Umicore explains why.

On the cover: 3 inch SiC MESFET-based MMIC wafers are now available for high-power RF applications (image courtesy of Cree) – see p25.

COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

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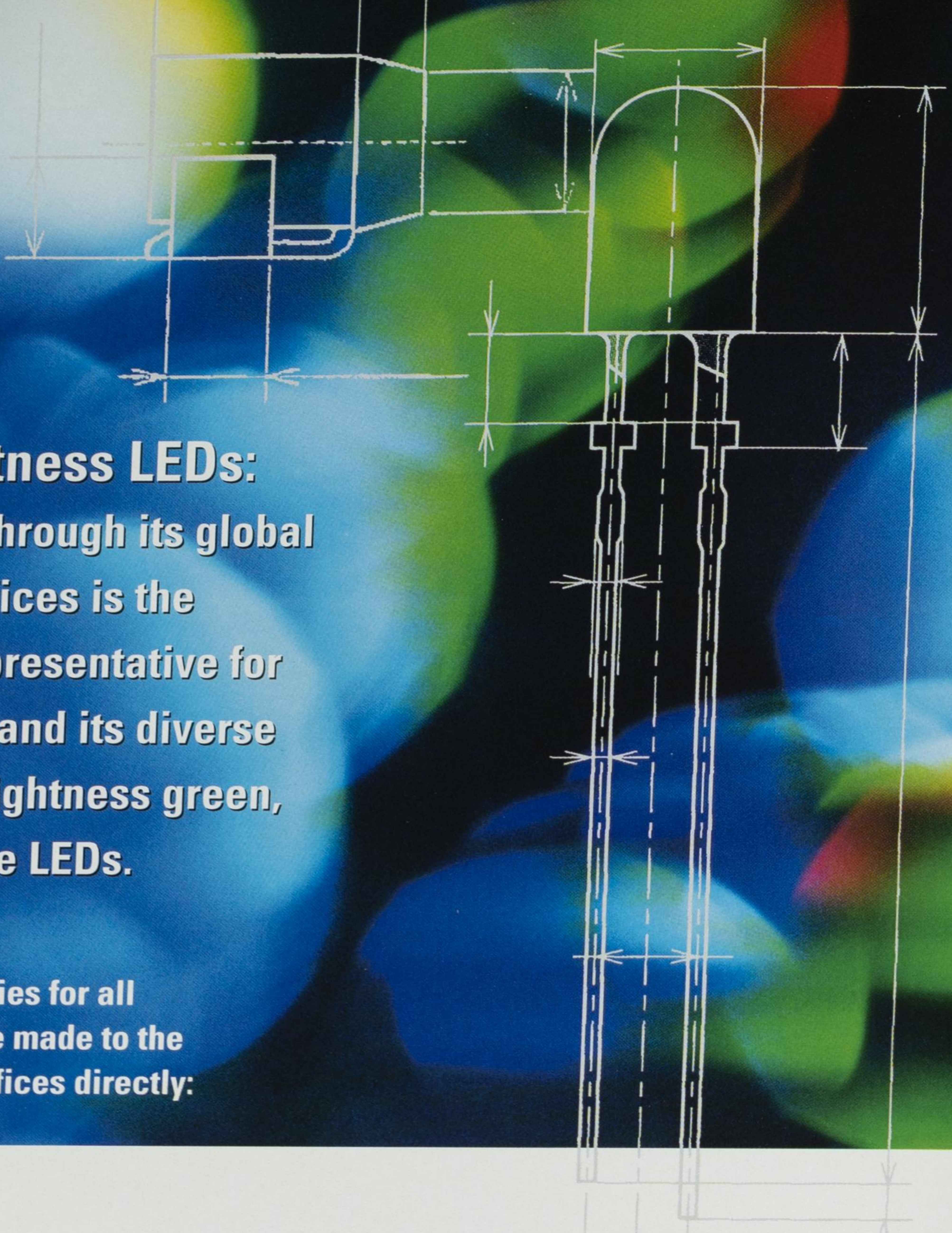
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Fiber market sees more consolidation

By Tim Whitaker

The fiber-optic components industry, which has witnessed an extensive shake-out since the bubble burst, continues to produce partnerships, further consolidation and closures. Optospeed, a European components maker, is the latest to fall into the latter category, while Infinera, a California-based manufacturer of InP-based components, has bucked the trend with a huge \$53 million series D funding round (see p19).

Elsewhere, in the first sign of consolidation among Japanese manufacturers of optical components, NTT Electronics Corp and Oki Electric Industry Co, Ltd have formed an alliance to combine their optical communication device businesses. Shortly afterwards, Infineon announced an agreement with Taiwanese epiwafer and device manufacturer United Epitaxy Company (UEC) to set up a joint venture that will manufacture optoelectronic chips for the fiber-optics market.

NEL and Oki

NTT Electronics (NEL) and Oki Electric have agreed to integrate their optical chip processing lines for the volume production of laser diodes, photodiodes, modulators and hybrid devices. Production has already commenced on joint production lines at NEL's facility in Ibaragi prefecture.

The alliance aims to enhance product performance, cost competition and management efficiency in the optical communication device market. NEL is proficient in process technology for high-speed (>2.5 Gbit/s) laser diodes, as well as passive wavelength multiplexing products. Oki's strengths lie in its abundant product line-up and volume production technology for 2.5–10 Gbit/s photodiodes and 2.5 Gbit/s laser diodes.

The optical components business has

undergone widespread changes in recent times, with companies such as Nortel, Agere, ADC and Marconi divesting or closing their components manufacturing facilities. Alcatel and Corning both transferred their components businesses to Avanex, which has also bought Vitesse's optical modules business.

"In the optical component area, many mergers and acquisitions have been reported, but this will be the first significant such alliance in Japan," said Hiroshi Yoshimura, director of the Photonics Business Group of NEL.

"Through the alliance, Oki will be able to further enhance its base in the optical communication device business, which can be expected to grow along with the expansion of broadband networks," commented the president of Optical Components at Oki Electric, Masaharu Nishiwaki.

As well as integrating their chip processing lines, NEL and Oki will collaborate in joint development programs for new optical communications devices, and will sell products through each other's sales channels. NEL and Oki also say that they will study the potential expansion of the alliance, including the integration of assembly processes and offshore manufacturing.

Infineon and UEC

The joint venture between Infineon and UEC will be based within the existing UEC facility at Hsinchu Science-based Industrial Park in Taiwan, and will be established in October 2003. Mass production is expected to commence by the fourth quarter of 2004.

Infineon and UEC will license their respective technologies relating to fiber-optic components to the joint venture, which will manufacture optoelectronic chips for both companies. The partners will each assemble and package the optoelectronic devices into

components and modules for the telecommunication and data communication markets.

Infineon will hold 56% of the shares of the joint venture, with UEC holding the remaining 44%. The two companies will invest a total of around \$12 million in the business, with each making an investment in proportion to its shareholding. When operating at its full capacity of up to 100 wafer starts per week, the venture will employ around 120 people.

Infineon currently manufactures a wide range of fiber-optic components including lasers, receivers, VCSELs, transceivers and parallel optical links. UEC, which claims to have the world's largest MOVPE manufacturing operation, produces conventional and high-speed infrared LEDs, ultra-bright AlGaInP and InGaN LEDs, laser diodes, silicon detectors and HBT epiwafers. UEC has two manufacturing sites at the Hsinchu Science-based Industrial Park, further sites in Taiwan at the Tainan Science-based Industrial Park and in Chung-ho, Taipei County, as well as a wholly-owned subsidiary in Wuxi, Jiangsu province, China.

"This joint venture is further recognition of Taiwan's role in the global IT industry," said Loh Kin Wah, president of Infineon Technologies Asia Pacific Pte Ltd. "It will ensure sufficient supply and develop the most competitive fiber-optics products for Infineon and UEC."

"The venture supports the Taiwan government's policies for industry upgrading, bringing in the world's cutting-edge optical communications technology," said Kuo-Hsin Huang, chairman of UEC. "The co-operation with Infineon is also expected to enhance R&D and manufacturing capability at the new company because of Infineon's global leadership in the fiber optics communications field and UEC's prowess in manufacturing."

Market snapshots

Wireless subscribers

The total number of worldwide wireless subscribers will exceed 2 billion by 2007, according to In-Stat/MDR. More than 930 million new subscribers will be added over the next 5 years, with the fastest growth coming in Africa, Eastern Europe and the Middle East.

Optical networking

KMI predicts a slight rebound in 2004 for the optical networking equipment market, after a 6% drop in 2003. The market peaked at over \$30 billion in 2000, then fell 29% in 2001 and a further 53% in 2002 to \$10.1 billion. The market should reach \$12 billion by 2007.

PDA shipments

Despite limited growth this year, the market for personal digital assistants will more than double from just over 11 million units in 2003 to around 24 million in 2007, according to In-Stat/MDR. New multimedia and wireless capabilities will help to drive growth.

Vitesse sells modules, closes GaAs fab

Vitesse is to sell certain assets of its Optical Systems division, located in San Jose, CA, to Avanex Corporation for 1.24 million shares. The deal is valued at around \$6 million based on the closing price of Avanex's stock on August 20, 2003.

As part of the deal, the two companies will be working together to develop new products for the optical transponder market. A supply agreement will see Avanex buying up to \$2 million in products from Vitesse over the next three years.

"During the June quarter we decided to exit the optical module business with a view to concentrating our efforts on silicon solutions for the metro, enterprise and storage markets," said Lou Tomasetta, president and CEO of Vitesse. "We look forward to expanding our relationship with Avanex, who we expect to be a significant player in the optical transponder market."

Avanex has been expanding its optical component business through a number of

Vitesse counts the cost

Charge in June 2003 quarter	Value (\$ million)
write-down of GaAs manufacturing equipment and maintenance contracts	27.4
write-down of excess and obsolete GaAs inventories	6.8
write-down of Colorado Springs building	20.6
severance and benefits associated with GaAs fab closure	0.5
write-down of assets of optical module business	17.3

Vitesse recorded various charges in its third fiscal quarter ended June 30, 2003, associated with its decisions to close its Colorado Springs 6 inch GaAs fab and sell its optical module business to Avanex.

recent acquisitions. In May it bought troubled Alcatel Optronics and also parts of Corning's business, including its optical components

plant in Milan, Italy, and its optical amplifier division in Erwin, NY (*Compound Semiconductor* June 2003 p5).

When reporting its June quarter results, Vitesse also announced that it would be closing its GaAs manufacturing facility in Colorado Springs, the industry's first 6 inch GaAs fab, by the end of September. The company had previously announced its intention to seek a foundry partner to operate the facility (*Compound Semiconductor* December 2002 p4).

"Over the past few quarters, we tried to find a suitable buyer for the Colorado Springs facility, but were unable to identify an economically viable opportunity," said Tomasetta. "I am very disappointed to see us lose some of our most talented and hard-working employees at both of these facilities. However, these are decisions dictated by the economic realities of the difficult environment we are currently in, and we believe they are in the best interests of our shareholders."

Lumileds sues Epistar over AlGaInP LED patent infringement

Lumileds has filed a patent infringement case against its Taiwanese rival Epistar relating to high-brightness AlGaInP LEDs. In a complaint filed in the US District Court for the Northern District of California, Lumileds has claimed that Epistar's AlGaInP LED products willfully infringe on Lumileds' US patent number 5,008,718.

The patent relates to the use of a transparent GaP window layer to enhance the brightness of AlGaInP LEDs. Several years ago, Lumileds had a dispute over the same patent with Epistar's Taiwanese rival UEC, which was resolved in fall 2001 (*Compound Semiconductor* October 2001 p18). As a result, UEC licensed various Lumileds patents.

The current complaint against Epistar seeks both enhanced monetary damages for past

infringement and an injunction against future importation or sale of the infringing products in the US.

In this same case, Lumileds had earlier alleged infringement by Citizen Electronics Co, Ltd and its subsidiary, Cecol, Inc, based upon their importation and sale of Epistar's AlGaInP LED products. The Citizen claims have now been settled and only the claim against Epistar is still in the case.

"Lumileds holds more than 100 patents in the area of high-brightness LEDs and continues to pioneer the development of solid-state lighting technology," said Mike Holt, CEO of Lumileds. "We will continue to vigorously guard the intellectual property enabling these advances. This includes enforcement of our rights in court when necessary."

Range of wireless technologies get on the Si roadmap

A number of wireless technologies, including GaAs, InP and SiGe, are likely to be added to the 2003 International Technology Roadmap for Semiconductors (ITRS). If the alterations are approved, this will mark the first time that the roadmap has included non-silicon technologies. The ITRS is developed and updated as part of International Sematech, a global consortium of leading semiconductor manufacturers.

The wireless chapter of the ITRS will include four working groups looking at power management, RF and transceivers, analog and mixed signal, and frequencies up to 100 GHz. Non-silicon nanotechnology devices may also be included in the roadmap. The proposed changes are seen as the first step towards building a bridge to the post-CMOS era, according to Paolo Gargini, chairman of the roadmap committee and director of technology strategy at Intel. "The industry has to get involved now or it won't be ready when silicon runs out of steam," he said. The roadmap activity will also study 450 mm diameter silicon wafers, starting in 2005.

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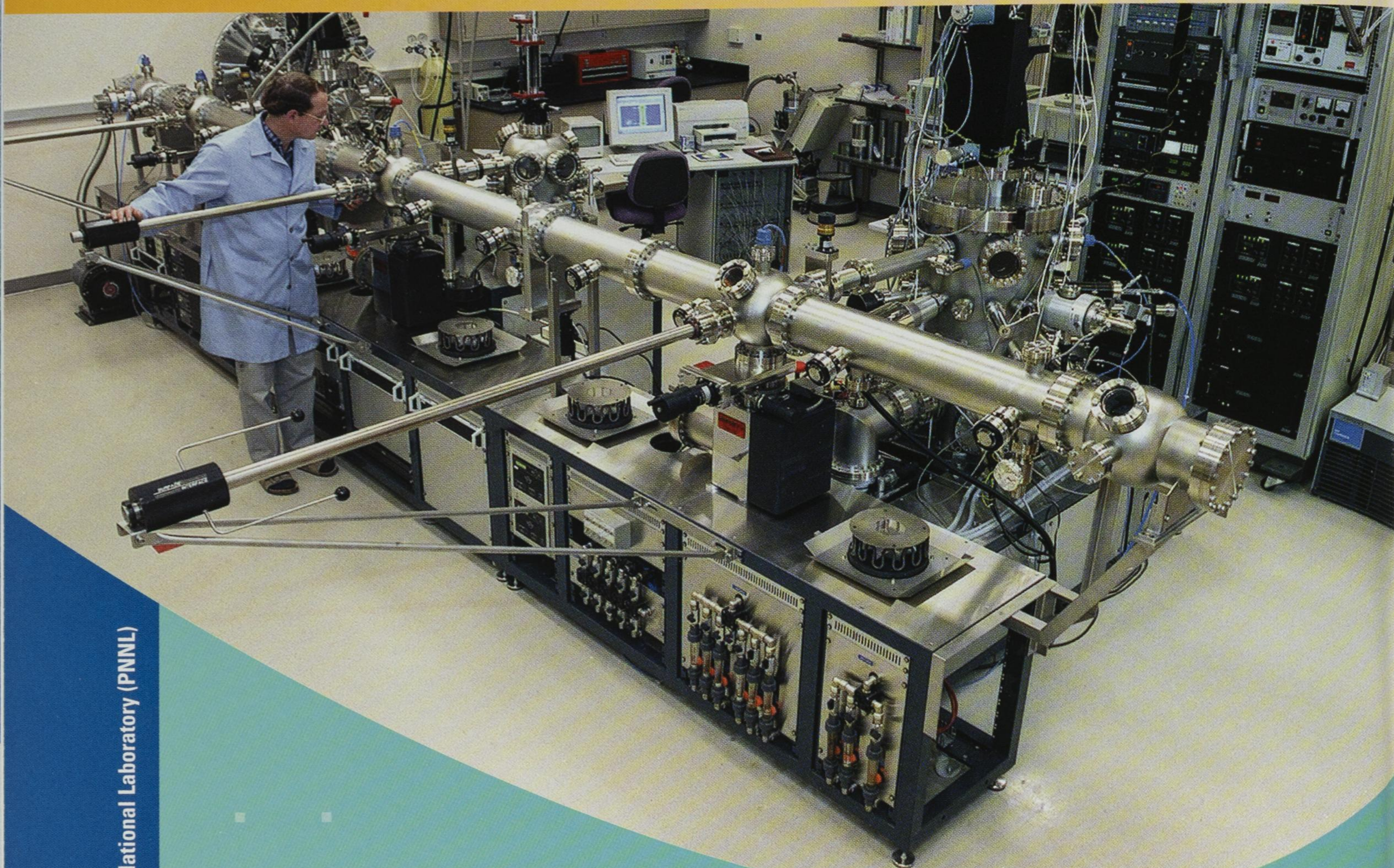
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INSTRUMENTS

SET reaches nitride HEMT milestone

Sensor Electronic Technology (SET) of Columbus, SC, has reached a milestone in its contribution to DARPA's Wide Bandgap Semiconductor Technology Initiative (*Compound Semiconductor* November 2002 p43). The company has successfully demonstrated the growth of its AlInGaN/GaN HFET structures on 4 inch sapphire substrates. Establishing such processes on 4 inch instead of 2 inch wafers will significantly contribute to lowering the cost of GaN-based HEMT technology.

SET says that it can now routinely achieve a sheet resistance lower than 500 Ω /sq with a standard deviation across a 4 inch wafer of <5%, figures which are comparable to currently available 2 inch material. The company has developed its transistor technology using a proprietary growth technique called migration-enhanced MOCVD (MEMOCVD), which allows growth at lower temperatures and at rates comparable to MBE. SET is planning to make samples of its 4 inch material available late this year or early in 2004.

While most researchers are concentrating

on AlGaIn/GaN HEMTs, SET believes that its AlInGaIn/GaN approach has several advantages, including better processing of ohmic contacts to In-containing materials. Incorporating large In atoms in the AlGaIn also significantly alters the material's lattice parameter without hugely affecting its bandgap and polarization effects. As a result, lattice-matched strain-free AlGaIn/AlInGaIn heterostructures, which retain a sufficient energy band offset, are possible. SET calls this strain energy band engineering (SEBE) and can use the approach to significantly increase the energy offset, and therefore the electron density, by raising the Al content while keeping strain under control through the In composition.

"We have demonstrated suppression of the notorious RF current collapse in our AlGaIn/InGaIn/GaN double HFET and AlGaIn/AlInGaIn/InGaIn/GaN triple HFET devices," said SET's president and CEO, Remis Gaska. "We attribute this to better carrier confinement at AlGaIn/InGaIn or AlInGaIn/InGaIn heterointerfaces, which prevent 2D electrons

from spilling over to the GaN buffer and getting trapped there." SET has submitted a patent application for the triple HFET design.

SET awarded MOSHFET patent

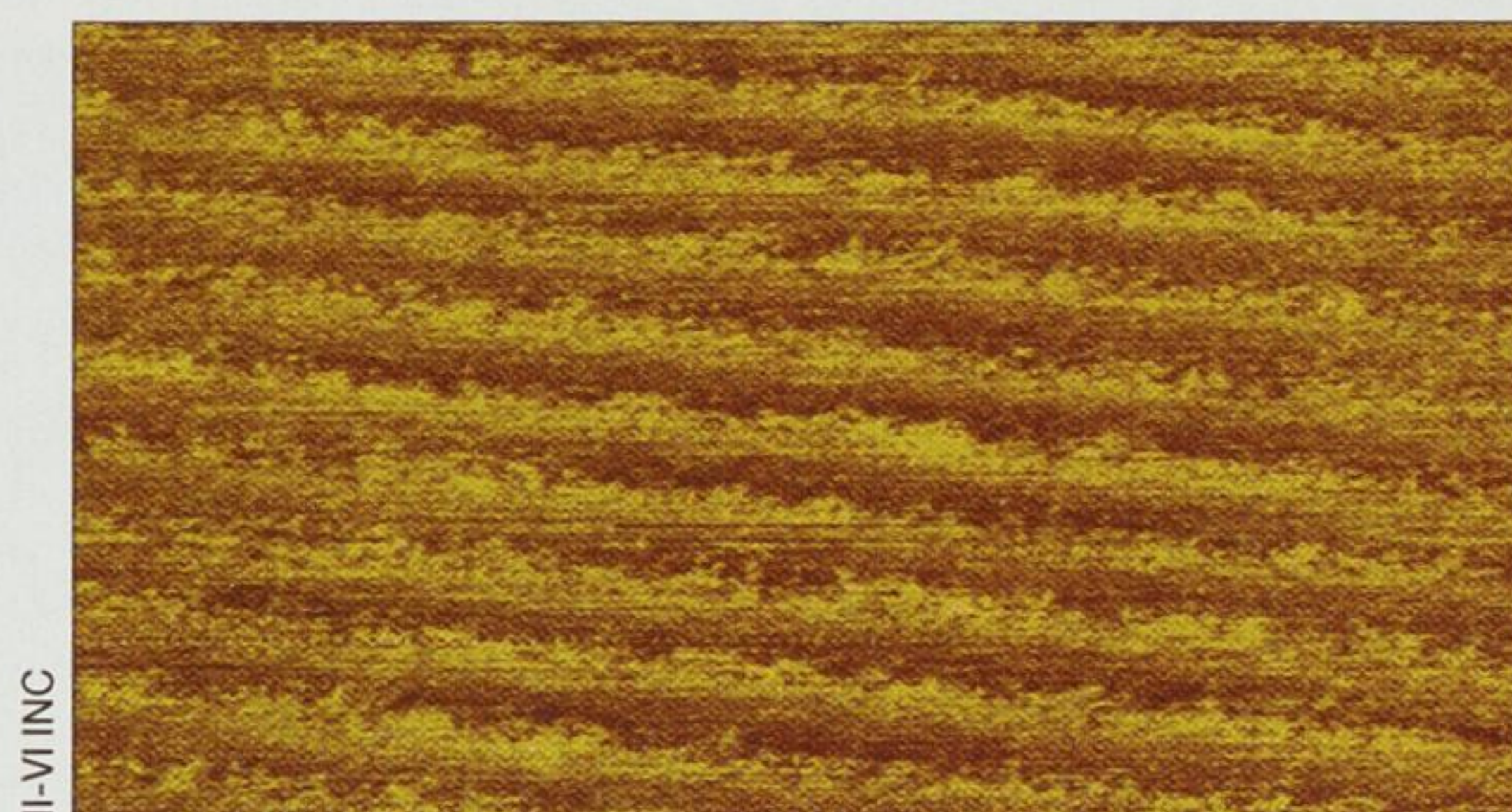
SET has received a patent for its metal oxide semiconductor heterostructure field effect transistor (MOSHFET). This AlGaIn/GaN device is expected to become the first commercially viable compound semiconductor MOS transistor. In the patented device, a dielectric layer is placed between the gate contact and the AlGaIn/GaN heterostructure to block the gate leakage current, resulting in higher drain current and breakdown voltage.

The MOS approach works for AlGaIn/GaN-based transistors because of their high electron sheet density in the device channel (more than 10–15 times higher than in comparable AlGaAs/GaAs-based HEMTs), which suppresses parasitic effects related to the charge trapped at oxide/AlGaIn heterointerface. Such high-power MOSHFET transistors are expected to be used as MPAs.

II-VI Inc wins funding and collaborates with SET

The Wide Bandgap Materials Group of II-VI Inc, a commercial supplier of SiC substrates, has obtained \$843,000 in funding for further development of its Advanced Physical Vapor Transport (APVT) SiC crystal growth technology. The contract, awarded through the US Air Force Research Laboratory, will support work to develop high-purity, low-defect-density, 3 inch semi-insulating substrates.

This contract builds upon work in both a recently completed contract with the Office of Naval Research for APVT development, and a current contract funded by the DoD's Title III office (see p29). These and other government contracts over the past two years have assisted II-VI in the development and commercial introduction of high-quality, 2 inch



A 5 μ m wide AFM image of a SiC wafer, showing the atomic steps that aid uniform epilayer nucleation. The wafer surface was prepared by chemical mechanical polishing and has an Ra value of 0.05 nm.

6H-SiC semi-insulating wafers.

In related news, II-VI and SET have suc-

cessfully combined SET's MEMOCVD-grown AlInGaIn/GaN HFET epitaxial wafer technology with II-VI's 6H-SiC substrates. The companies have demonstrated and started sampling 2 inch AlInGaIn/GaN HFET wafers with average sheet resistance below 300 Ω /sq, sheet resistance standard deviation less than 3%, and Al content variation less than 2%.

These epitaxial wafers are designed for fabrication of ultra-high-power transistors, which are key building blocks for microwave power amplifiers (MPAs). MPAs amplify radio-frequency signals and are central components in transmit/receive modules of both military and commercial radars and communications systems, including networks of base stations for wireless communications.

Cree buys ABB's SiC IP portfolio

Cree has purchased a portfolio of patents and patent applications relating to SiC technology from ABB, a company headquartered in Switzerland that specializes in power and automation technologies. Cree has not yet

disclosed the amount that it paid for ABB's SiC-related IP.

The patents cover epitaxial growth and device and circuit-level technology which ABB had been developing since 1991 at its facilities in Sweden. The portfolio includes 44 US patents and patent applications, together with corresponding international patents and applications. In addition, the

agreement calls for the transfer of certain knowledge related to the technology.

ABB made the decision to stop developing SiC technology as it was not seen as a core activity to its business. However, the company continues to recognize the importance of SiC technology for power handling and will be following developments in the field closely, purchasing SiC devices as it needs them.

GMI promotes SiC MEMS prototyping

The Glennan Microsystems Initiative (GMI) was established in 1999 by NASA Glen Research Center (GRC) and the state of Ohio to advance and cultivate MEMS technologies for use in harsh environments. Because of SiC's ability to maintain its electrical and mechanical properties at higher temperatures than silicon (600 °C for SiC compared with 200 °C for Si), SiC is proposed as a replacement material for Si MEMS for operation in harsh environments. However, questions over the relatively high cost of SiC and its ability to perform at the levels promised by theory have blocked the widespread adoption of SiC-based MEMS technologies.

GMI believes the answers to these questions can be found in a new, unique multi-user micromachining process known as MUSiC. By creating a number of different prototype devices from a single SiC wafer, MUSiC lowers the cost of prototyping by offering organizations the opportunity to test SiC's performance for their specific needs without having to order a full shipment of individual devices. Rather than purchasing an entire processed wafer of SiC devices, companies



A SiC micromotor produced by FLX Micro during a MUSiC run.

can purchase the wafer space required by one or more micromachined devices. Users can then take their prototype devices from the MUSiC process, test them and decide if the performance of the SiC MEMS device justifies its cost before initiating higher volumes of production. In short, MUSiC allows companies to try before they buy.

To make the MUSiC prototyping phase as cost-effective as possible, GMI has supplied FLX Micro, a GMI member based in Solon, OH, that specializes in microsystems technologies, with approximately \$1 million funding for the development and execution of the

MUSiC process. FLX Micro is well suited to develop this technology. The company's founder Mehran Mehregany researches the use of SiC for MEMS at Case Western Reserve University (CWRU) and brings his specific expertise in this field to the company. Thanks largely to the investments by GMI and other sources, FLX Micro has reduced the cost of participating in a MUSiC run to as little as \$1000. So far the response to the MUSiC service has been very encouraging, with the first MUSiC run in January attracting 13 participants, 26 contributing to the second and 16 in the third run in August. Devices manufactured in these early runs included optical scanners, cantilevers, various types of sensors, and micromirrors.

GMI, along with partners NASA GRC, Makel Engineering, CWRU and Ohio State University, is also creating new SiC MEMS technologies. These include a pressure sensor capable of 600 °C operation and an exhaust gas sensor array that can measure multiple gas species and has been tested in various engines.

For more information, visit www.glennan.org and www.flxmicro.com.

SemiSouth wins SiC contract

SemiSouth Laboratories, a developer of SiC transistors, diodes and epiwafer products based in Starkville, MS, has received a \$2.67 million contract to develop key fabrication processes for SiC RF transistors targeted at high-power radar systems. The small business innovative research phase III contract was awarded by the Office of Naval Research to a team lead by SemiSouth, and including the General Electric (GE) Global

Research Center and Mississippi State University (MSU) as primary subcontractors.

The project aims to accelerate the development and operational capability of SiC RF transistors specifically for high-power radar systems. GE's role will be to fabricate and test SiC MESFETs. MSU will help to qualify a new reactor to be purchased by SemiSouth for MESFET epiwafer production through its material characterization facilities.

Dow Corning forms compounds business

Dow Corning has brought its various wide-bandgap semiconductor activities together under a new business unit, Dow Corning Compound Semiconductor Solutions (DCCSS), located in Midland, MI. The unit includes in-house research and development into 3C-SiC deposition on silicon, which is being extended through university partnerships to include GaN epitaxy on 3C-SiC. Also included is the bulk SiC business acquired from Sterling Semiconductor in 2002, and the GaN epitaxy

activities of GaN Semiconductor, a start-up in Sunnyvale, CA, in which Dow Corning was an early-stage investor.

"Our strategy in consolidating our wide-bandgap semiconductor business is to be a materials and service provider focused on meeting the needs of device manufacturers," said Robert Johns, global director of DCCSS. "We are moving people and assets to our Midland facility to bring the activities closer to our other semiconductor capabilities."

Bandgap aims to block micropipes

Bandgap Technologies is to enter production with its bulk SiC growth technique, which drastically reduces the occurrence of micropipe defects. Micropipes appear as holes on SiC wafer surfaces where hollow-core screw dislocations terminate, and can seriously impact device yields.

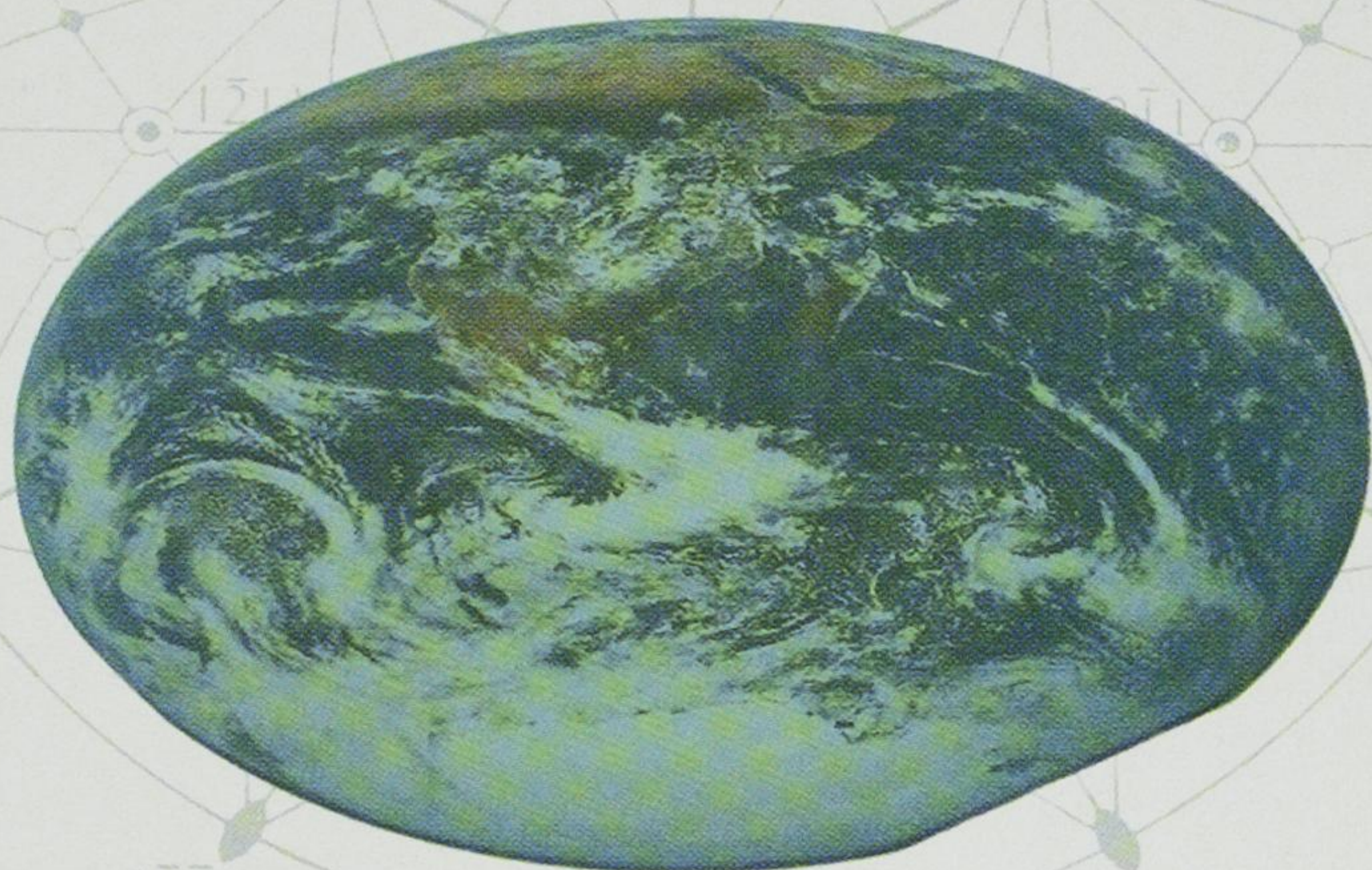
The company's process has been applied to the bulk growth of semi-insulating and low-resistivity 6H-SiC, giving a consistent micropipe density of less than 50/cm², with densities as low as 5/cm² being possible. Application of the process to 4H-SiC is under way, and Bandgap will discuss this at the ICSCRM in Lyon, France, on October 5–10.

Bandgap, which was founded in 2000 as a spin-out from the University of South Carolina, currently produces 2 inch epi-ready SiC wafers. Using the new process, the company expects to begin initial production of 4H-SiC for high-power and high-frequency applications early in the first quarter of 2004. It will also make the transition to the production of larger-diameter wafers.

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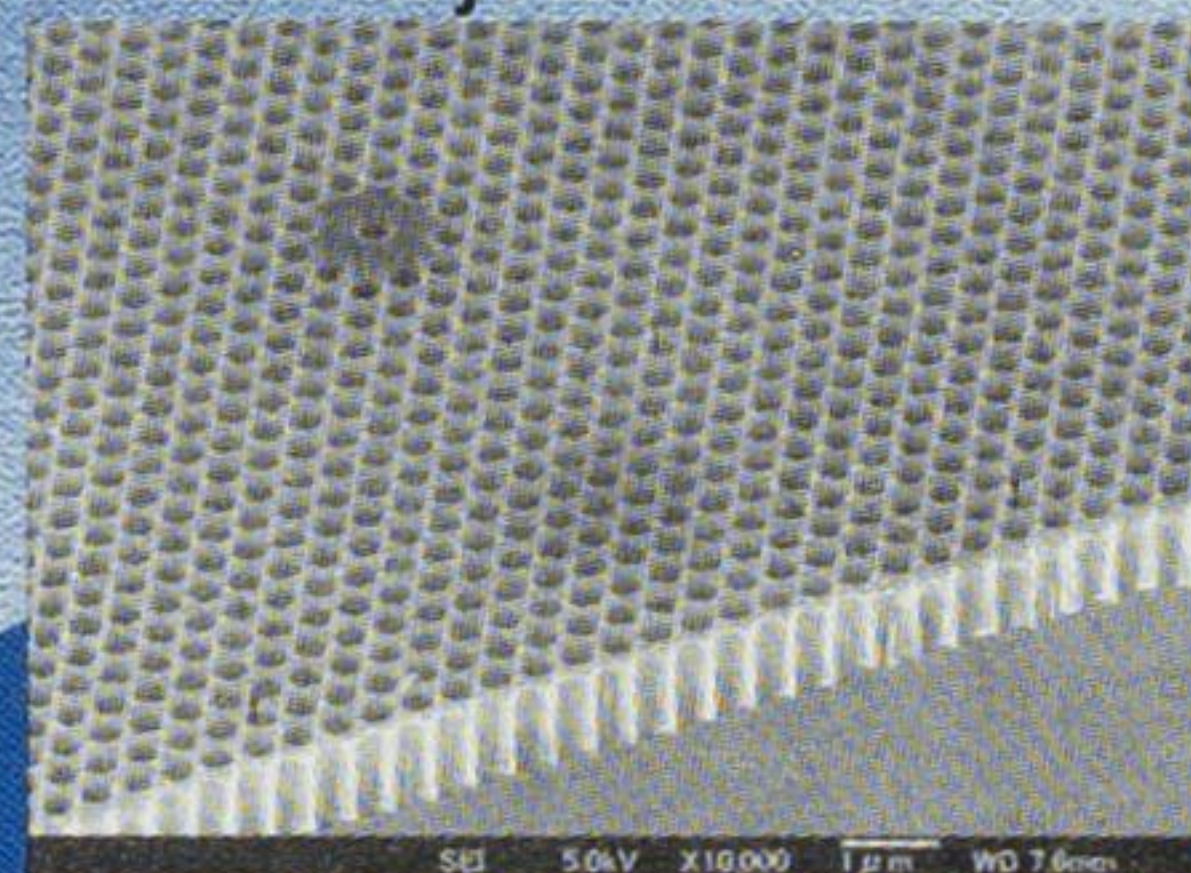
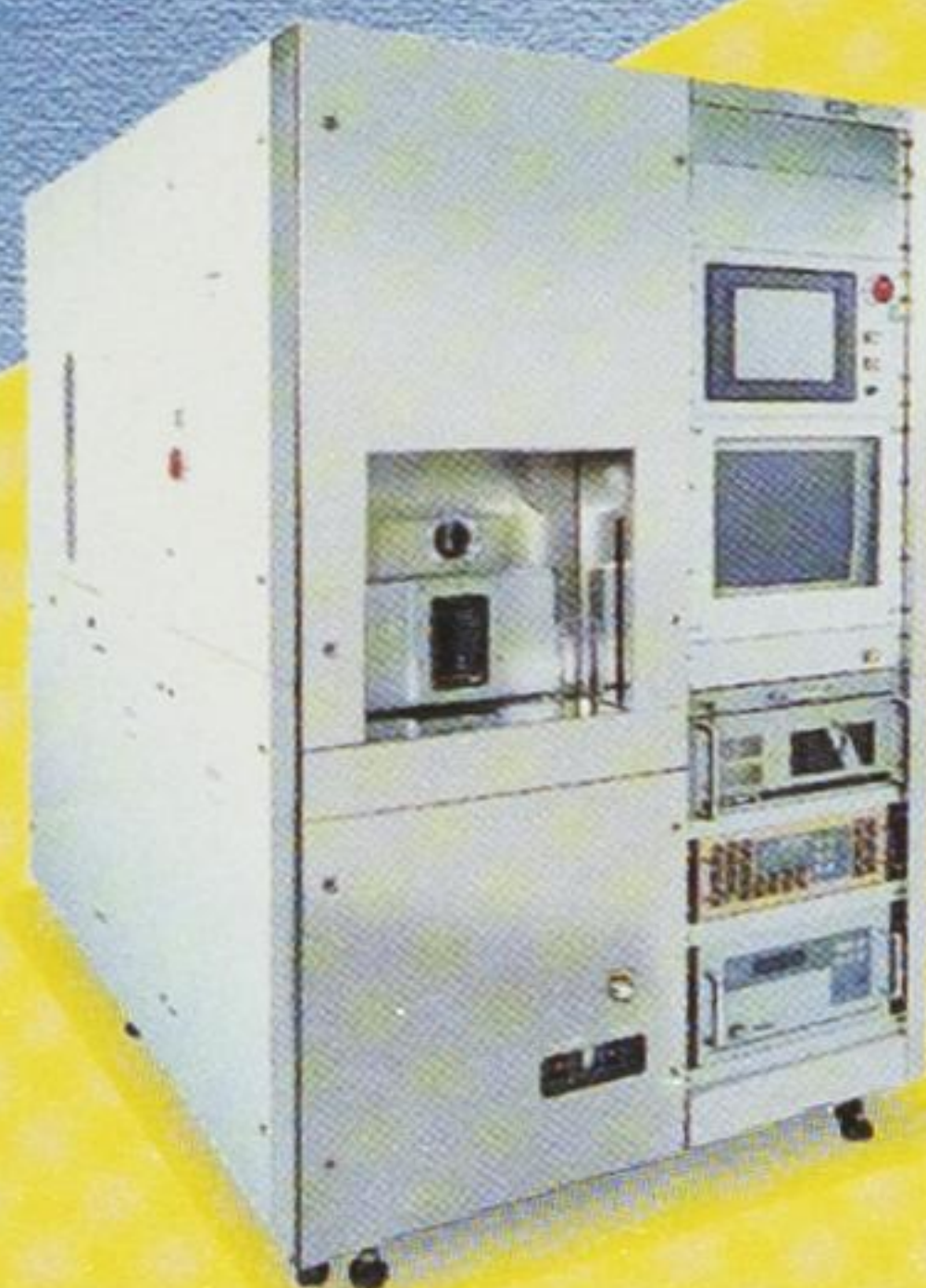


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In alliance with the future

Kopin licenses LED-related patents

Kopin is continuing its relationship with North Carolina State University (NCSU) by taking exclusive licenses for three patents relating to the fabrication of LEDs. These include a patent on domain epitaxy and two patents on cubic ZnMgO and ZnCdO.

Kopin has been working closely with Jagdish Narayan and his team at NCSU on the development of its CyberLite blue LED prod-

ucts. In November 2002, Kopin and NCSU announced the development of a process for the epitaxial growth of nominally lattice-mismatched materials. The technique is now being applied to the formation of very-low-resistance ohmic contacts for Kopin's CyberLite LEDs (*Compound Semiconductor* December 2002 p8).

The two patents on cubic ZnMgO and

ZnCdO cover the epitaxial growth of these materials on silicon (100) substrates with the aim of creating inexpensive LEDs for integration with microelectronic devices. These materials are seen as important because they can be used to produce LEDs and lasers of any color across the visible spectrum, including the three primary colors that are necessary for white LEDs.

New Wave Research receives sapphire scribing patent

New Wave Research, a manufacturer of laser-based systems for microelectronics and analytical applications based in Fremont, CA, has been awarded US patent number 6,580,054 for its method of scribing sapphire substrates.

The patent covers scribing sapphire substrates using solid-state UV lasers and describes the hardware configurations, processes and parameters used in the company's AccuScribe sapphire wafer scribing systems. "Our process reduces the overall cost of LED manufacturing by decreasing the number of consumables and improving yield," said May Su, New Wave's VP of marketing.

More than 30 AccuScribe wafer scribing systems have been installed worldwide. New Wave claims that the system reduces LED production costs by 25–50% compared with scribing systems that use diamond scribes and saws. The company says that other laser-based sapphire scribing methods have higher costs principally due to the use of excimer lasers, which require consumable gases and are substantially more expensive to operate and maintain than solid-state lasers.



Viewing images on the small screens of cell phones and digital cameras can be frustrating, and downloading to a PC is not always convenient. This prototype pocket-sized (15 × 9 × 3 cm) personal projector from Lumileds and Philips contains red, green and blue LEDs, and projects color images.

DoE office to host two-day solid-state lighting workshop

The US Department of Energy's (DoE) Office of Energy Efficiency and Renewable Energy will host a two-day solid-state lighting workshop in Washington, DC, on November 13–14. The meeting will introduce a new government–industry program aimed at saving energy by supporting the research and development of solid-state lighting, and will outline the structure, purpose and timeline of the first few years of the program. The workshop will focus on the prioritization of relevant research topics, and on setting early performance milestones. For more information, see compoundsemiconductor.net/events/3443.

Attendance at the workshop is open to all companies, universities, trade associations, research institutions and national laboratories that meet the eligibility requirements for funding under DoE programs. One requirement for DoE funding is that the organization's participation should be in the economic interests of the US; that considerable contributions to employment in the US should result; and that technology development should lead to manufacturing within the US.

Coming in December

**LEDs and
solid-state
lighting**

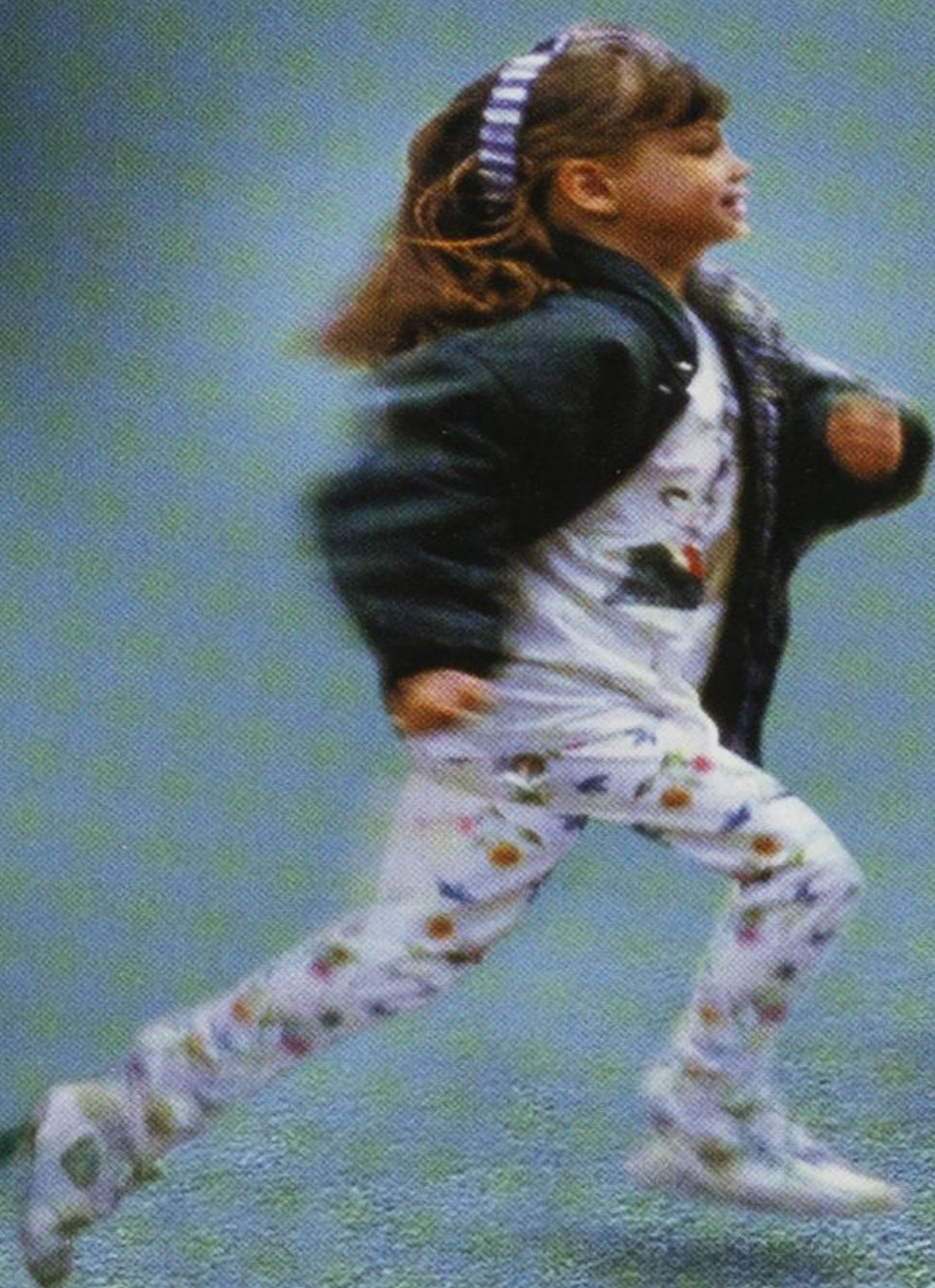
A special issue of
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AXT files counterclaims against Cree and Boston University

AXT is filing counterclaims against Cree Lighting and Boston University in a dispute concerning devices manufactured using a GaN-based buffer technology (*Compound Semiconductor* July 2003 p5). AXT has denied the accusation that it infringed on US patent 5,686,738 (Highly Insulating Monocrystalline Gallium Nitride Thin Films). It has filed coun-

terclaims alleging that the plaintiffs' actions were intentionally designed to interfere with AXT's prospective business relationships, and has requested that the complaint be dismissed with prejudice and that AXT receive damages and injunctive relief.

In June 2003, AXT announced plans to discontinue production of optoelectronic devices.



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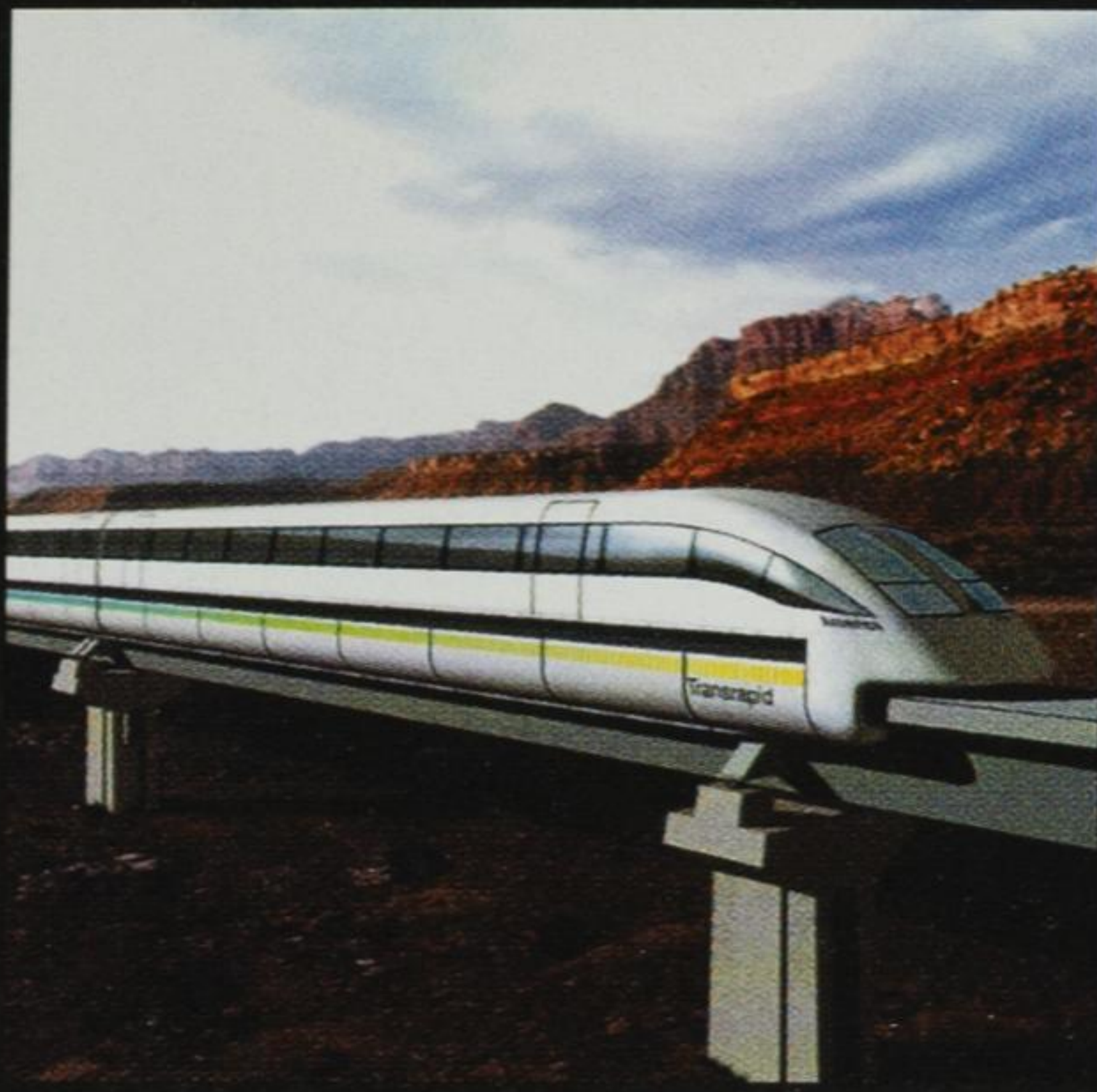
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RFMD achieves 6 inch customer qualification

RF Micro Devices (RFMD) has successfully completed the first major customer qualification of its 6 inch GaAs wafer manufacturing capabilities. "The migration to 6 inch manufacturing represents the realization of a major initiative launched by RFMD to reduce manufacturing costs," said Curt Barratt, VP of wafer fab operations at RFMD. "The conversion to 6 inch wafers will more than double the number of die per wafer without a significant increase in processing cost per wafer."

The 6 inch wafers are processed in RFMD's second fab in Greensboro, NC, which originally began production in early 2002 as a 4 inch facility with a capacity of 40,000 wafer starts per year. Plans were announced in November 2002 to convert the fab to handle 6 inch wafers in order to cope with rising demand and the need to lower costs. The production of 6 inch GaAs HBT wafers began in the March 2003 quarter. The company's first

fab, which still handles 4 inch wafers, is now operating close to its maximum capacity of 60,000 wafers per year.

RFMD ships 250 millionth PA module

Supporting evidence of RFMD's need to increase its capacity came with the announcement that it has shipped its 250 millionth PA module. After passing the 200 million mark in May, the company has successfully maintained an aggressive pace in a very demanding business environment.

Eric Creviston, VP of wireless products at RFMD, puts the company's success down to the popularity of its PowerStar products, which feature integrated power control. "Our patent-pending PowerStar solutions have helped RFMD become the leading supplier of PAs for the GSM air interface standard, which accounts for approximately two-thirds of the world's cell phones," he said.

TriQuint to collaborate with Amkor for CuFlip bump bonding

TriQuint Semiconductor is collaborating with Amkor Technology, one of the world's largest chip test and assembly service providers, to commercialize a low-cost flip-chip assembly process for GaAs devices based on TriQuint's CuFlip bump-bonding technology.

TriQuint has already introduced the copper bump-bonding process for the manufacturing of its 6 x 6 mm TQM 7M4009 GSM power amplifier module. Replacing wire-

bonding with a bump-bonding process allows higher-density interconnects, and has enabled a 40% size reduction and improved RF performance for the TQM 7M4009 compared with its predecessor.

The direct thermal connection to the surface of the substrate provided by CuFlip bumps is especially valuable in PA design, as it brings improved long-term reliability due to lowered die operating temperatures.

Anadigics receives patent for GaAs MMIC multi-band amplifier

Anadigics has added another patent to its growing portfolio of intellectual property. US patent number 6,501,331 was awarded for the development of a GaAs MMIC dual-band amplifier for use in wireless handsets for operation in either the 800 or 1900 MHz bands.

The patent describes switching impedance networks used at the input and output of the amplifier to provide matching input imped-

ance and desired output impedance for operation in the two bands. Switching impedance networks are also used between any successive stages of the amplifier to provide proper inter-stage impedance. The dual-band amplifier includes a bias control circuit that biases the amplifier to operate in A, B, AB or C mode. The amplifier can be switched between bands by simply applying a proper control signal.

Endwave and SafeView begin mm-wave imaging project

RF subsystems supplier Endwave has entered into an agreement with SafeView, a privately held developer of security screening systems, to develop and manufacture millimeter-wave transceiver modules.

Most mm-wave imaging development work to date has been carried out under military R&D projects for imaging through fog and cloud. However, mm-wave technology is attracting interest from suppliers of security equipment because of its ability to image

objects concealed beneath clothing or even in the back of trucks. Security systems will use low-power mm waves to scan people passing through security checkpoints.

Under the agreement, Endwave will design and develop the mm-wave module that transmits the RF signal and receives the signal reflection. Following the design phase, the company will manufacture and supply prototype units of the transceiver module for design qualification and system testing.

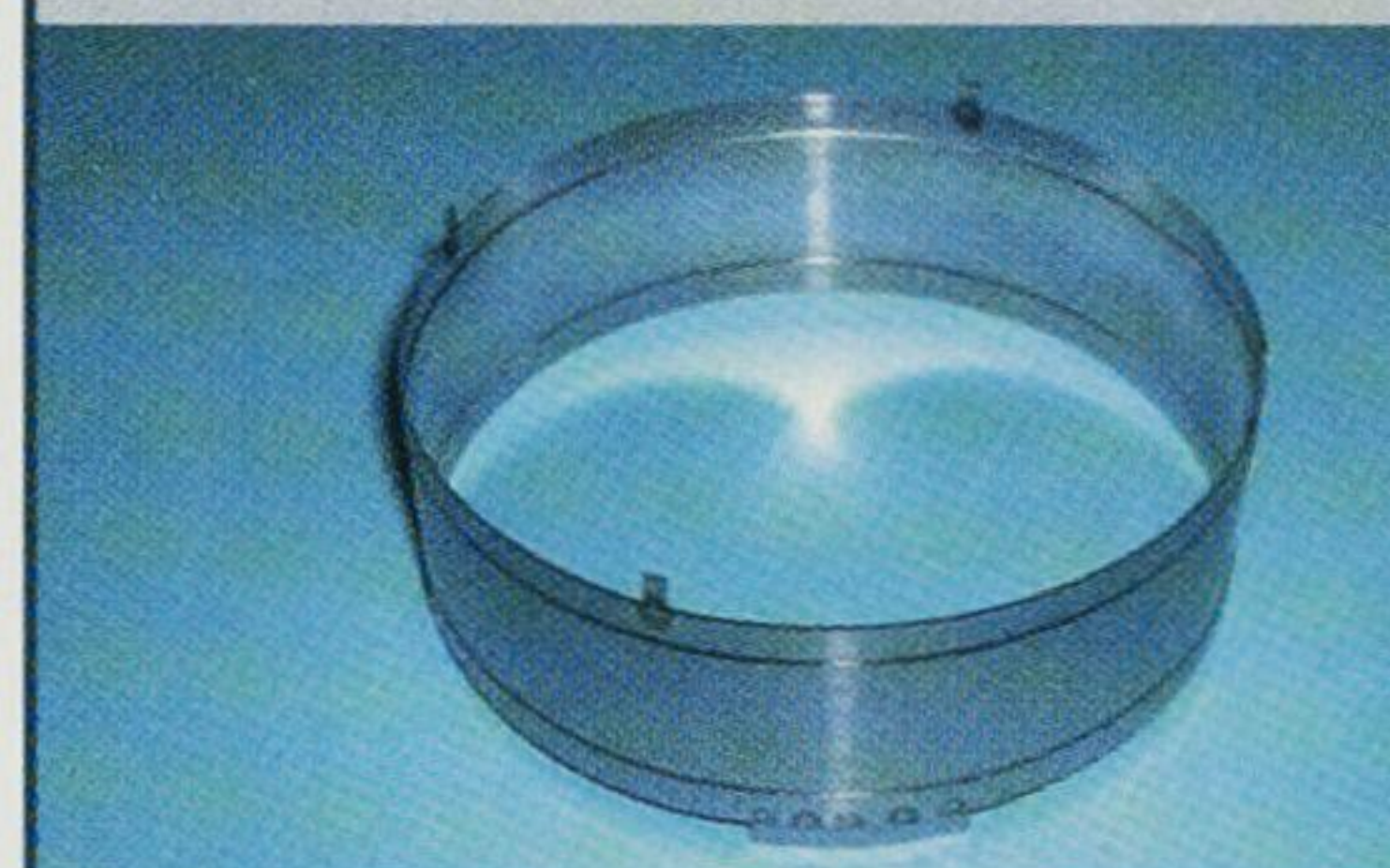
New product from Skyworks Solutions

• **Skyworks Solutions** has introduced a $6 \times 6 \times 1.2$ mm module for tri-band GSM/GPRS cellular handsets. The SKY77321 offers handset makers a single PA product for their GSM phones, regardless of geographic region or frequency band.

The module consists of an EGSM900, DCS1800 and PCS1900 PA block, and 50 W fully matched input/output ports to reduce the number of external components required for a tri-band design. The part is priced at \$2.75 in quantities of 10,000.

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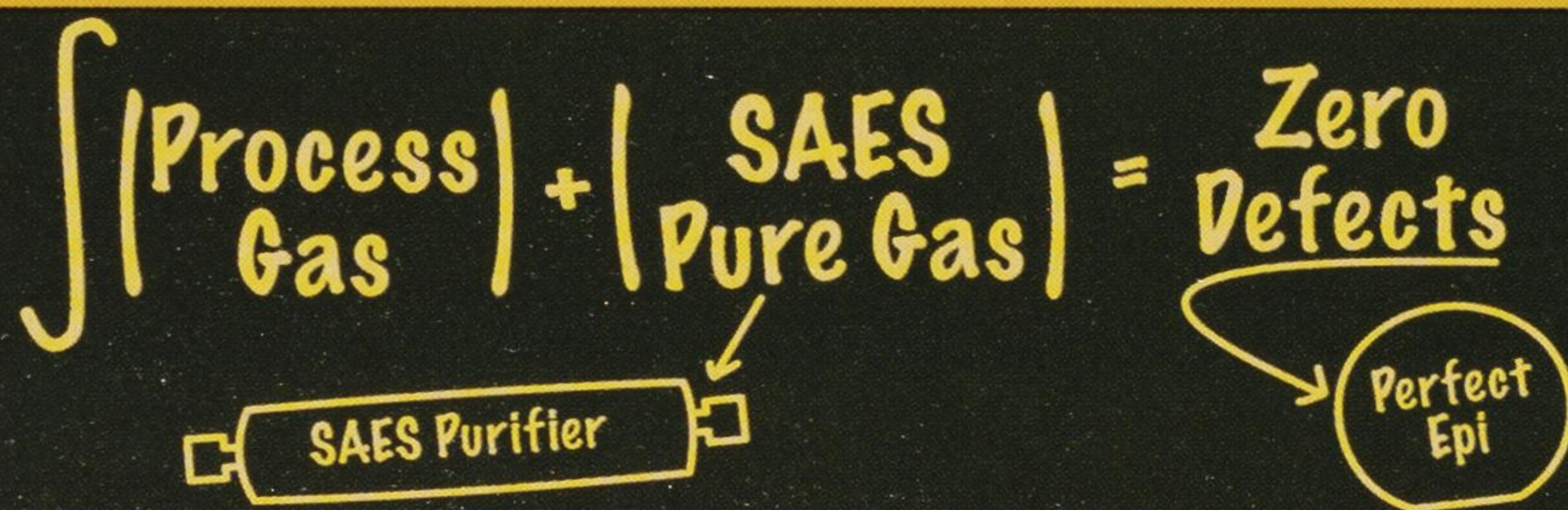
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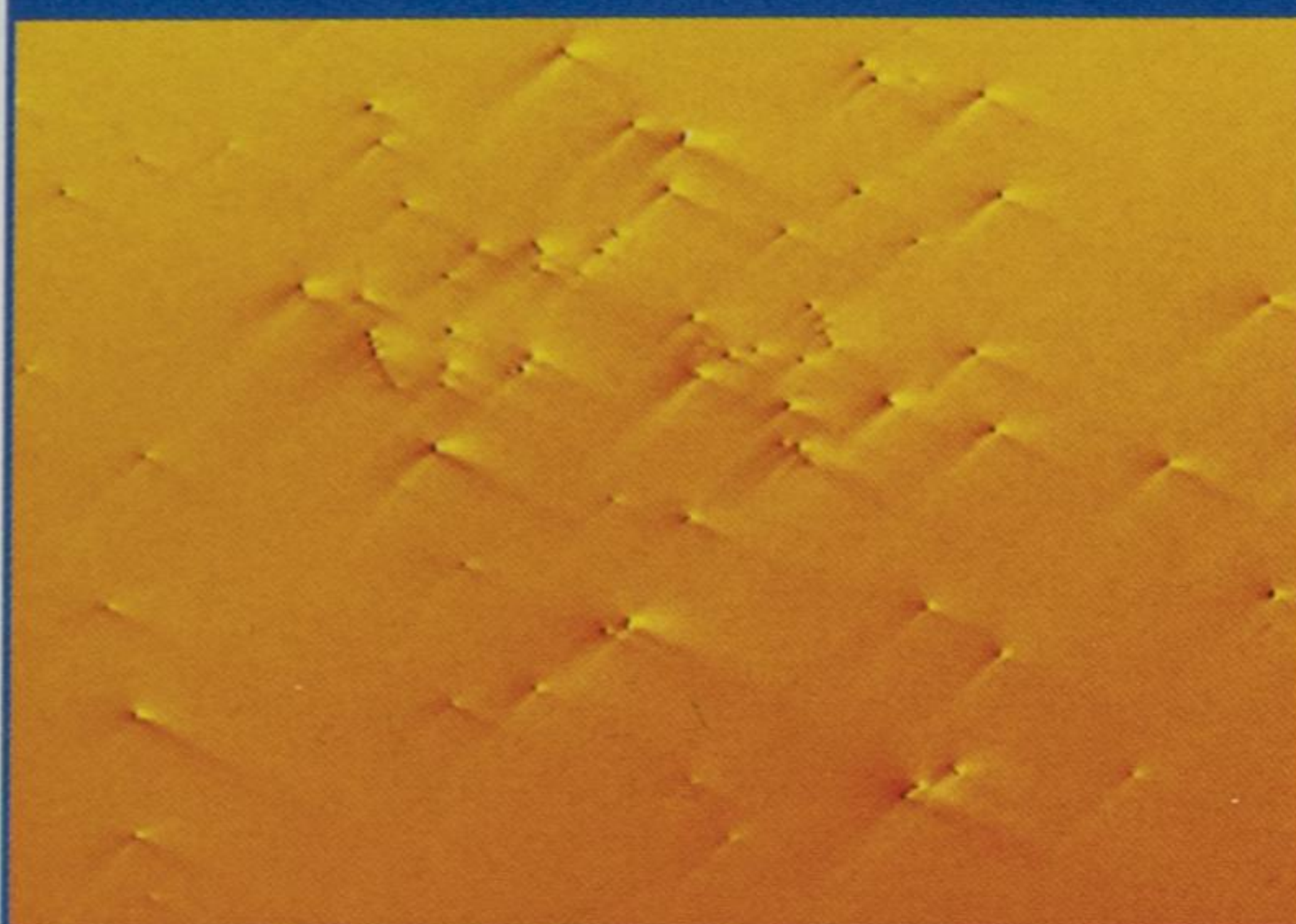


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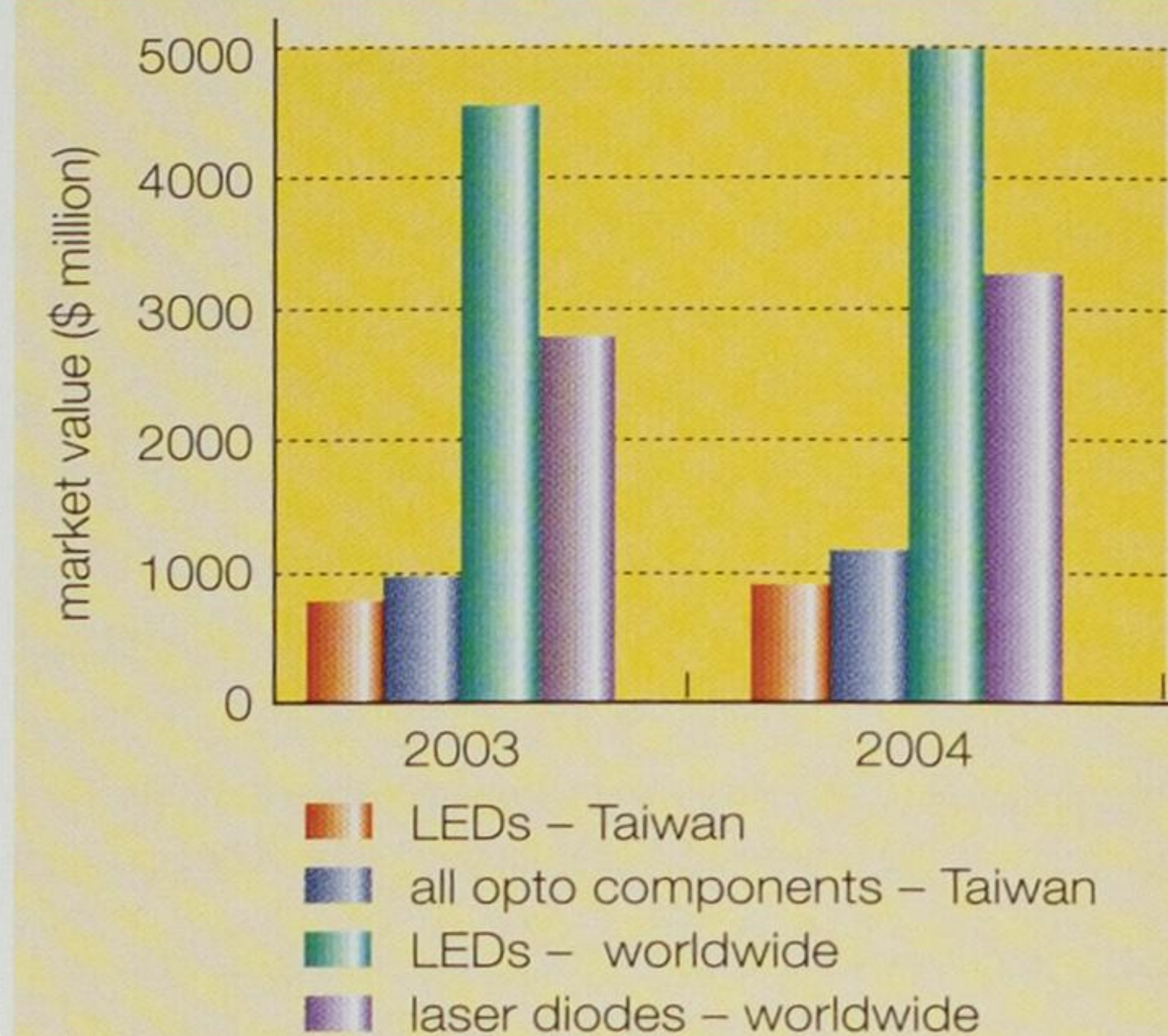
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Taiwan's LED industry set to grow stronger

Sales of LEDs manufactured in Taiwan are set to grow by 14% in 2003, reaching \$775 million, according to the country's Photonics Industry Development Association (PIDA). The organization estimates that the LED industry represented about 85% of Taiwan's production of optoelectronic components in 2002, while laser diodes represented only 4% of the country's output of components, with a total market value of \$34 million. The laser market is expected to grow by about 10% in 2003.

On a global scale, Taiwan's LED industry will represent about 17% of the LED market in 2003. PIDA expects that the worldwide markets for LEDs and laser diodes in 2003 will reach \$4.5 billion and \$2.8 billion, respectively. The total worldwide market for optoelectronic components should reach \$10.6 billion in 2003, with Taiwan accounting for 9%.

Opto components markets



Taiwan's LED industry currently represents about 80% of the national optoelectronic components market, and about 17% of the global LED market.

Toshiba develops 140 mW red laser diode for DVD recording

Toshiba has developed a 140 mW red laser diode that will enable DVD recording equipment to operate at 8x. The structure of the laser, which has a 40% higher output power than current DVD lasers, has been altered to minimize the deterioration in performance

that arises as a result of heat generation. Using the new laser, the recording time for two hours of video can be halved from 30 to 15 minutes. Toshiba says it will sell the laser diodes for ¥1000 (\$8.5) each and will manufacture about 100,000 units per month.

Citizen Electronics opens China plant for LCD backlights

Citizen Electronics, a Japanese LED manufacturer, began production of LCD backlight units at its new plant in Suzhou, China, in early September. The factory will be able to produce 4 million of the units each month. The backlights incorporate Citizen's LEDs and are destined for cell phone displays.

The new plant is part of Citizen's plan to have a capacity of 9 million backlight units per month. In early 2002, Citizen signed a licensing deal allowing it to use technology licensed from Nichia to manufacture white LEDs, which are used as backlights in full-color LCD screens.

Partners develop VCSEL-based POF transmission system

Fuji Photo Film and Fuji Xerox have collaborated to develop a 1 Gbit/s optical transmission system using plastic optical fiber (POF) and visible 650 nm VCSELs. The Lumistar system uses graded-index POF developed by Fuji Photo Film and transmit/receive modules from Fuji Xerox, the first Japanese company to commercialize VCSEL-based products. The system should enable economical, long-lifetime Gigabit Ethernet links and is also suitable for linking large flat-panel displays with projectors or tuners. Signal degeneration in conventional electric wires makes it difficult to establish links longer than 10 m.

Forepi develops super-bright blue LEDs

Forepi, a Taiwanese manufacturer of blue, green and UV LED chips and epiwafers, has developed a new range of super-high-brightness blue LEDs. Known as digital penetration ITO (DPI) devices, the blue LEDs have a higher external extraction efficiency, resulting in a brightness level 50% higher than Forepi's current blue LEDs.

According to Charles Wei, assistant VP of marketing and business development at Forepi, the DPI technology combines a patented digital epitaxial layer to reduce the forward voltage, together with a higher transmission ITO material as the top contact layer.

"The blue LEDs will be used as the back-lighting source of the display screen in cell phones," said Wei. "Forepi started to ship DPI blue LED chips to the packaging factories in August, and DPI epitaxial wafers will be released in September."

Wei says that Forepi's monthly production capacity of DPI blue LEDs will be increased to 5 million pieces in the last quarter of 2003. Strong demand from cell phone manufacturers has substantially increased the need for GaN-based LEDs.

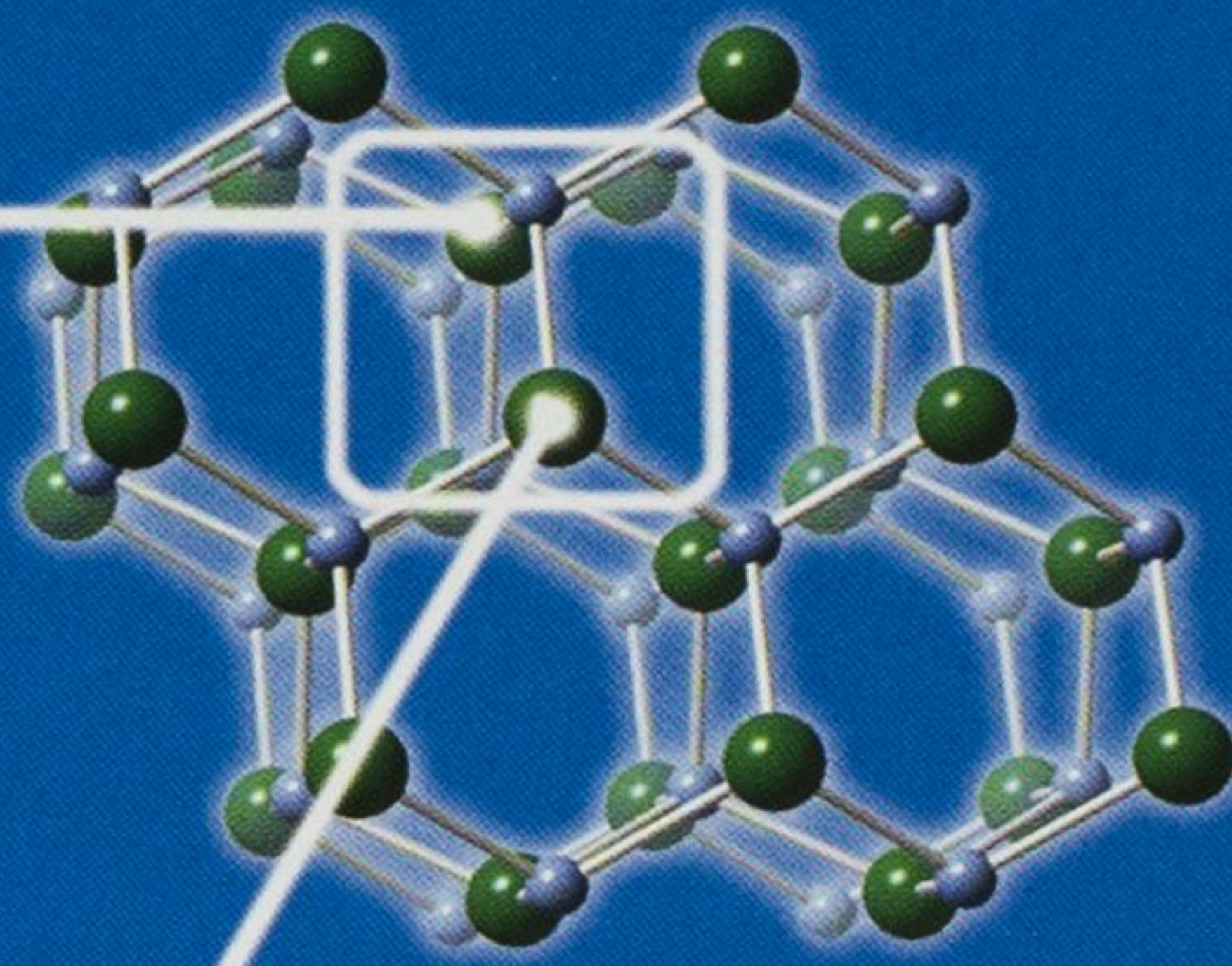
In related news, Forepi plans to establish a long-term strategic alliance with another Taiwanese company, in order to supply it with large quantities of blue LED epitaxial wafers. Wei says that the company, one of Forepi's largest clients, has its operations focused on blue LEDs, packaging and applications.

Novel optical disc stores 200 Gb of data

Samsung Electronics of Korea and Japan's National Institute of Advanced Industrial Science and Technology (AIST) have developed a new optical disc technology capable of storing 200 Gb of data on a disc, compared with 23 Gb for the emerging Blu-Ray Disc system. The technology uses a violet laser diode to write data onto a spinning disc made from a special resin film on a glass substrate. The resin expands when heated by the laser, creating a 50 nm bump that functions as the data bit. The storage density is increased without narrowing the laser beam spot.

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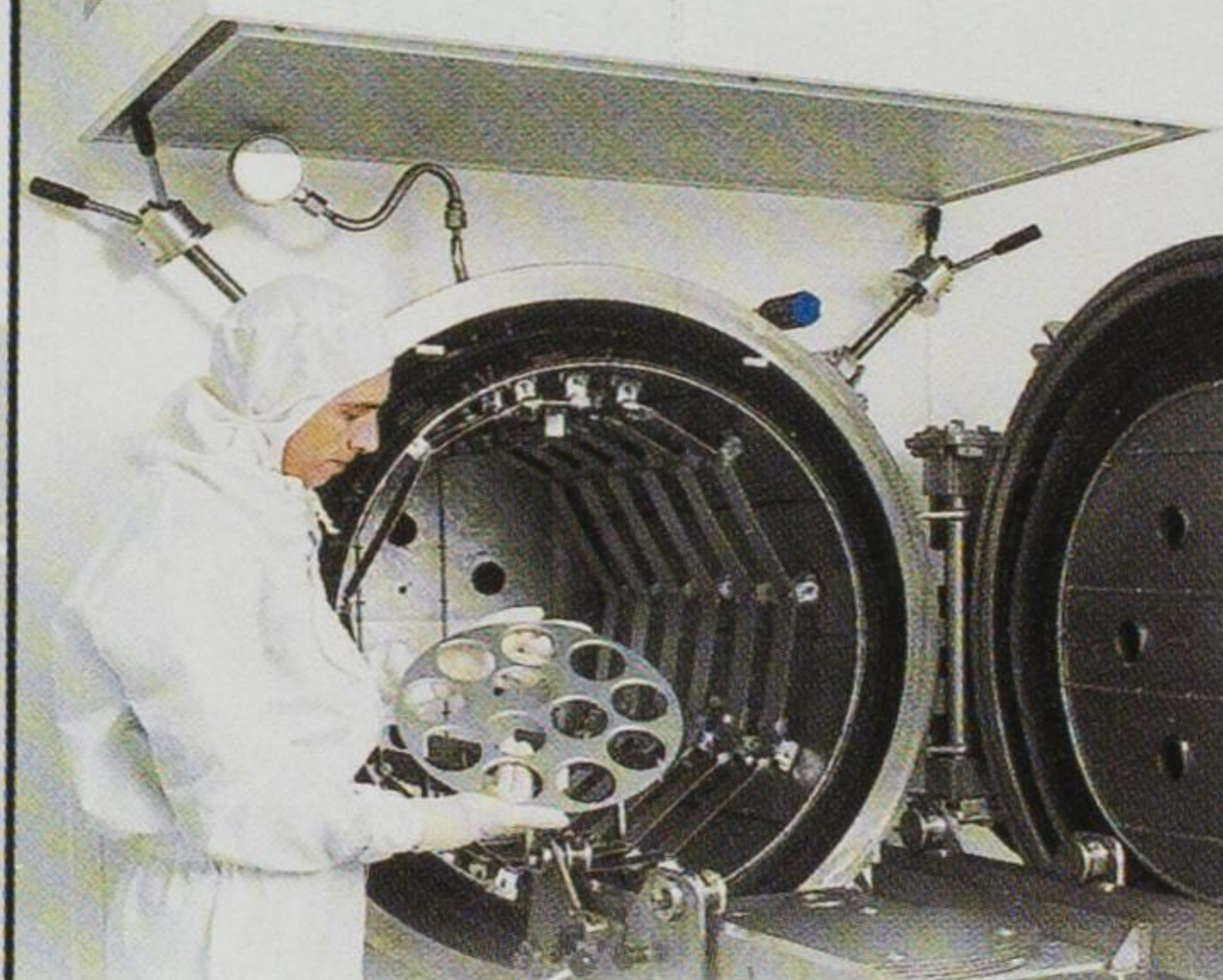
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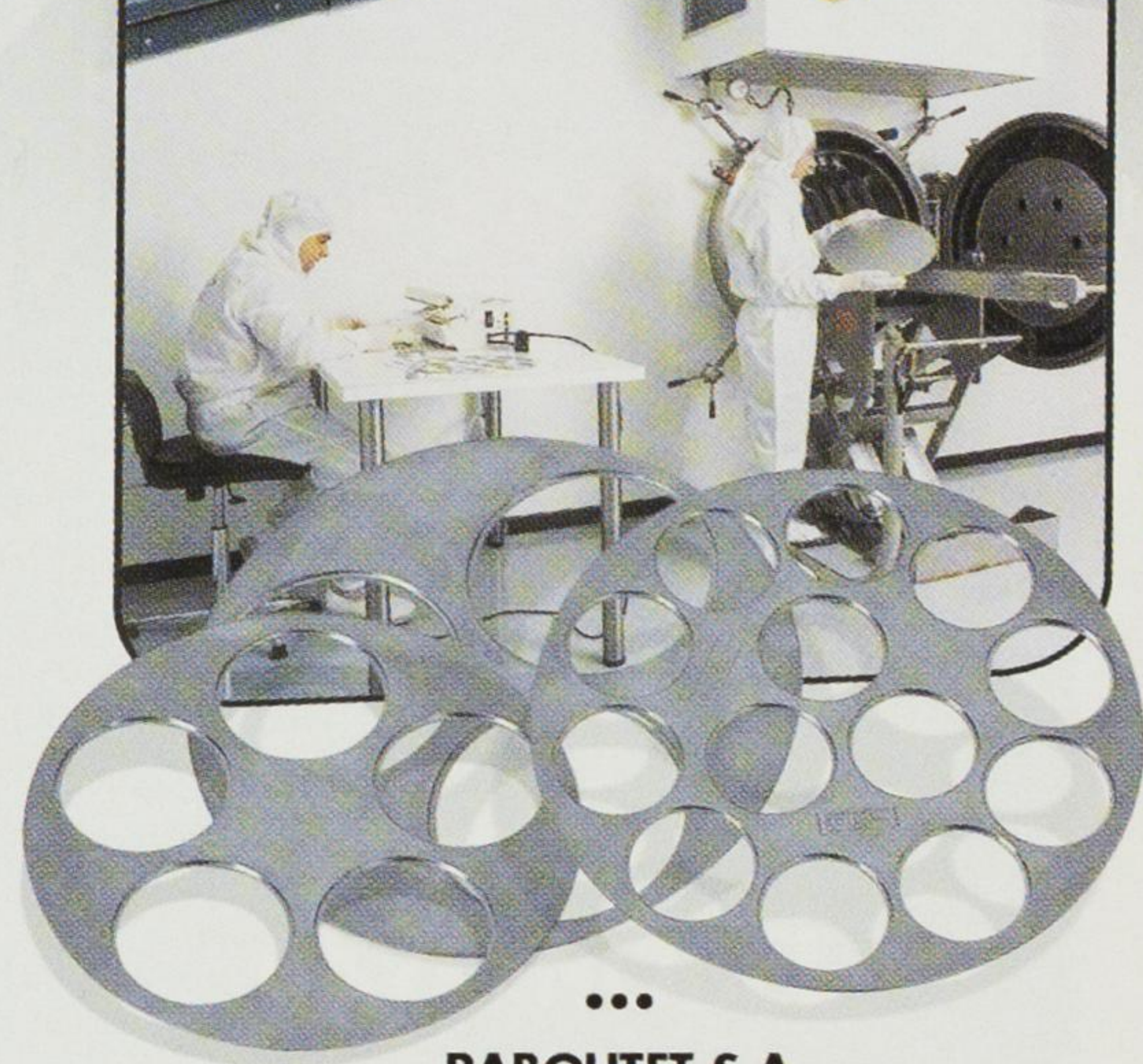
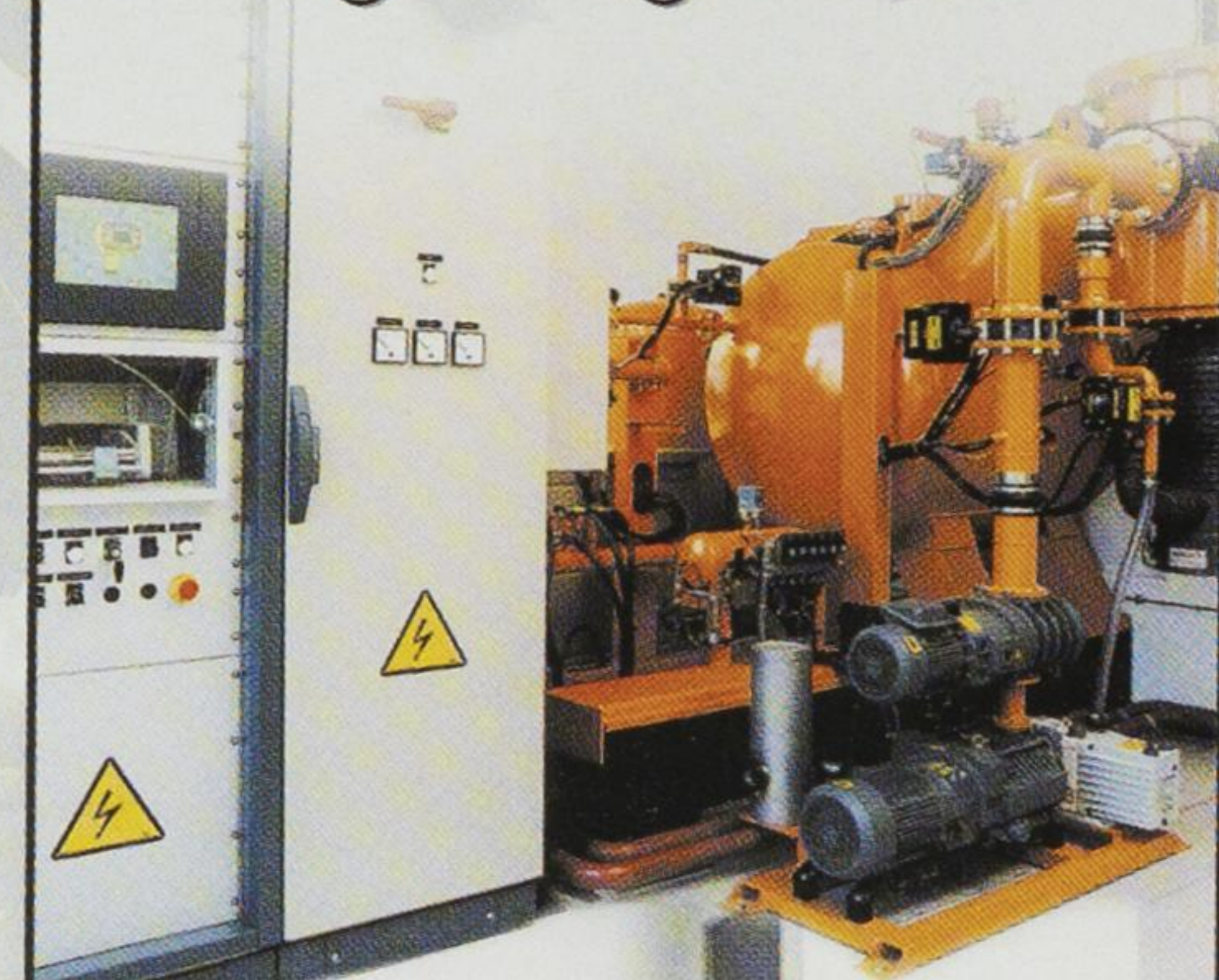
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Infinera closes \$53 m series D funding round

Infinera Corporation, a privately held company developing InP-based integrated photonic components, has closed its series D round with a massive \$53 million in new capital. The company has raised more than \$130 million in total equity financing to date.

"Infinera's disruptive technology, strong customer endorsements and world-class team make for a uniquely compelling investment opportunity," said Gary Rieschel of Mobius Venture Capital, which led the series D round.

Although Infinera has yet to describe its plans in detail, it is known to have a fab in Sunnyvale, CA, and to be developing InP-based photonic circuits that combine multiple functions on the same chip. Among its staff are industry luminaries such as Dave Welch,

former CTO with SDL, and Fred Kish, an LED expert formerly with Agilent who is now Infinera's VP of manufacturing.

In an interview in 2002, CEO and founder Jagdeep Singh said that the company's initial product will represent the first optical integrated circuit. "We do not underestimate what it takes to go from proof-of-concept to shipping product," he said. "It will be some time before we can perfect the process to produce and package these devices."

Infinera is looking to hire people with expertise in telecom systems engineering, hardware, software, passive and active optical components, semiconductor and packaging technologies, as well as candidates for its development center in India.

DMG buys Demeter from Finisar

A new company, DMG Technologies, has acquired the assets and IP rights of Demeter Module Group from Finisar in a privately funded deal. The company will design and manufacture optical subassemblies at its 11,000 sq. ft facility in City of Industry, CA.

Demeter was founded in August 2000 and acquired by Finisar in November 2000 in a stock-based deal, valued at the time at \$146 million. In April 2003, Finisar acquired Genoa and announced that it was relocating Demeter to Genoa's facility in Fremont, CA.

Malcolm McLean, DMG's president and CEO, is a former VP of sales at Lyte Optronics, a manufacturer of visible laser compo-

nents that was acquired by AXT in May 1999. Demeter was later established as a stand-alone fiber-optic component maker by former employees of AXT and Lyte Optronics.

McLean says that DMG has an aggressive new product roadmap to address the needs of a number of markets including sensors, biomedicine, spectroscopy and government, as well as telecom and datacom. "These products include 2.5 and 10 Gbit/s APD-TIA receivers, and 2.5 and 10 Gbit/s DFB TOSAs," he said. "As a result, DMG has embarked on a significant program to add highly qualified staff and state-of-the-art equipment to our already excellent team."

In brief... mixed news for Opto Speed and Picolight

Opto Speed closes doors after loss of funding

Opto Speed, a Swiss manufacturer of lasers, *pin* detectors and optical front ends, has been forced to file for bankruptcy after two of its biggest investors decided against continuing to fund its activities. The company's 40 staff have been laid off and creditors will decide whether to liquidate Opto Speed's assets or to continue the business under different management.

Picolight begins shipping 1310 nm VCSELs

Picolight has begun sampling small-form-factor pluggable (SFP) transceivers employing 1310 nm VCSEL sources. The company says that the single-mode transceivers offer performance advantages over competing products using Fabry-Perot sources at the same or lower cost. Products include 2 Gbit/s Fibre Channel transceivers operating over 10 or 20 km.

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Silicon carbide material, d evaluating the current ma

There are strong opportunities for growth in the SiC market, particularly in electronic applications, provided that material quality continues to improve. **Philippe Roussel** of Yole Developpement reports.

While silicon carbide material was initially used for its mechanical properties, the production of SiC ingots, developed in the 1990s, opened up new applications in the fields of power electronics and optoelectronics.

SiC is used to manufacture devices in the power electronics and RF/microwave field, as well as being used as the substrate for epitaxial growth of nitride-based device structures. In optoelectronics, SiC is again used as the substrate material for the heteroepitaxy of nitride layers for LEDs and lasers. Finally, in the MEMS and microsystems fields, it is considered as a suitable material with which to design microsystems dedicated to harsh environments, because of its thermal and chemical properties.

Bulk crystal growth of SiC

As summarized in table 1, numerous techniques have been developed to grow SiC ingots. These are as follows:

Sublimation In the most commonly used technique, ultra-pure SiC powder is sublimed from a crucible in order to deposit SiC material along the length of a crystalline SiC seed. This method is used today to produce 4H and 6H SiC crystals.

High-temperature chemical vapor deposition (HT-CVD) This process is carried out at about 2200 °C and involves the recombination of two gases, for example silane and propane, to form a thick SiC layer and then a SiC ingot. This method is just reaching the production level and is mainly used to manufacture 4H semi-insulating SiC wafers.

Techniques for bulk crystal growth of SiC

Technique	Typical growth rate (µm/h)	Growth temperature (°C)	Polytypes obtained	Main proponents
sublimation	200–400	2200–2500	4H, 6H	Nippon Steel, Sixon (both Japan), SiCrystal (Germany), Bandgap, Cree, Dow Corning, II-VI Inc (all US)
HT-CVD	300	2200	4H, 6H	Okmetic (Sweden)
VLS	100 (1000 in future)	1450–1500	3C	CRHEA (France) – R&D only
heteroepitaxy	50	1350	3C	Hoya (Japan)

Table 1. There are three crystal growth techniques for SiC currently in production, while VLS and Soitec's Smart Cut layer transfer process are at the development stage.

Heteroepitaxy of SiC on silicon In this procedure, the silicon is used as a sacrificial substrate, allowing epitaxial growth of cubic SiC. Once the SiC layer is thick enough, the silicon substrate is removed. Sample wafers are now available, and large-diameter substrates are expected to be obtained by this technique.

Vapor liquid solidification (VLS) This R&D-level technique is based on the "conversion" of a silicon surface in the liquid phase under a carbon atmosphere to produce SiC at the interface. The process begins with carbonization of the silicon surface (using a standard SiC CVD process at ~1500 °C). The sample is then placed in a carbon atmosphere to start the conversion process. Due to the cubic silicon substrate, the SiC is also cubic (3C).

Other new techniques are also under development. For example, it was recently proved possible to combine sublimation with HT-CVD to achieve high-quality material with a high growth rate. Also, the Smart Cut technology developed by French company Soitec makes it possible to transfer a thin SiC layer from a high-quality wafer to a low-quality SiC substrate. The final material is a bulk conductive or semi-insulating SiC wafer.

Typical SiC growth rates range from 100 µm/h to values in the order of mm/h, depending on the technique. Sublimation or HT-CVD processes provide ingots of about 20 mm in length, and each ingot is expected to give 5–20 SiC wafers depending on the polytype and orientation.

Roadmap for SiC material

	2002	2003	2006
micropipe density (/cm ²)	15	1	0.1
maximum available area (mm ²)	8	16	40
wafer size (inches): conducting	3	3	4
wafer size (inches): semi-insulating	2	2–3	3

Source: National Compound Semiconductor Roadmap and Yole Developpement

Table 2. Key challenges for manufacturers of SiC material include reducing the number of micropipes and increasing the area available for device fabrication.

Market issues for SiC wafers

Although larger wafers have been demonstrated, SiC material is currently only commercially available in diameters of up to 3 inches. Moreover, it suffers from defects that limit the range of applications for components, as shown in table 2.

Micropipes are larger defects that look like cracks in the bulk material and limit the available active area of the wafer. High-power-density components require large micropipe-free areas, but current micropipe densities only allow active areas of about 20 mm².

According to numerous component manufacturers, the compatibility of 4 inch wafers with standard processing equipment makes

devices and applications: market and future trends

SiC wafer production volumes

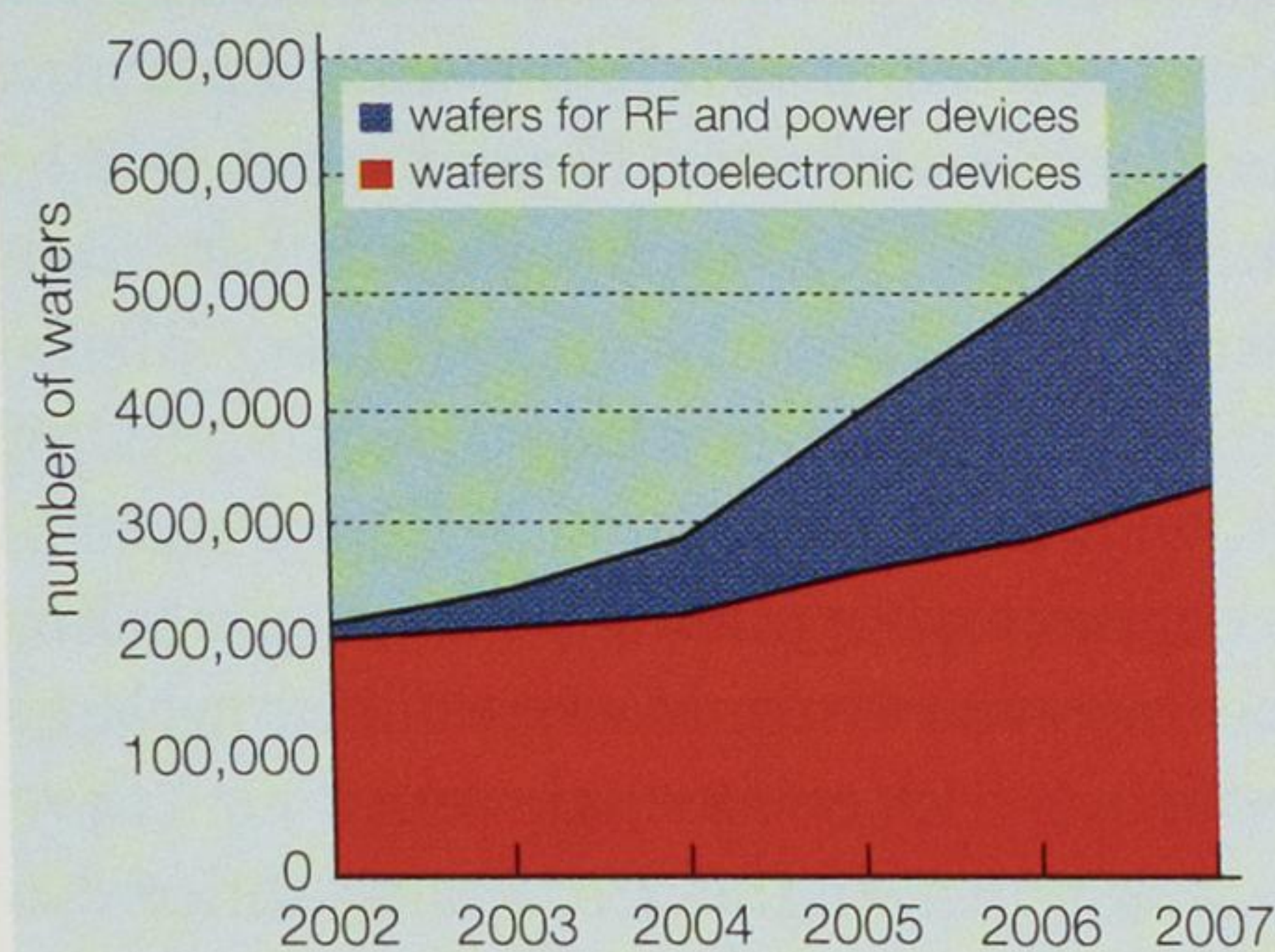


Fig.1. While most SiC wafers are currently consumed by the growth of optoelectronic nitride devices, the next few years will see rapid growth in the use of SiC as a substrate for SiC- and GaN-based electronic devices.

the realization of this wafer diameter a key issue if the SiC market is to grow substantially.

With an estimated 250,000 SiC wafers (mainly 2 and 3 inch) produced in 2003, the SiC wafer market is at the start of a steep growth curve. We estimate that the volume of SiC wafers will reach more than 600,000 units in 2007.

At present, SiC wafer production is dominated by Cree, which has about 85% of the market. However, challengers such as Okmetic, Hoya and Soitec are using new growth techniques, and are expected to make inroads. Due to Cree, Dow Corning (formerly Sterling), II-VI Inc (formerly Litton Airtron) and several smaller companies, around 94% of SiC wafer production is carried out in the US, with 4% in Asia and 2% in Europe.

Until now, 90–95% of SiC wafers have been consumed in optoelectronics applications, where they are used as substrates for blue and green LEDs and violet laser diodes (figure 1). However, other substrates, in particular sapphire and also silicon or even free-standing or bulk GaN, have been used to grow nitride-based epitaxial structures.

Nitride devices that use SiC as a substrate (as fabricated by Cree and Osram Opto Semiconductors) represent about 25% of the

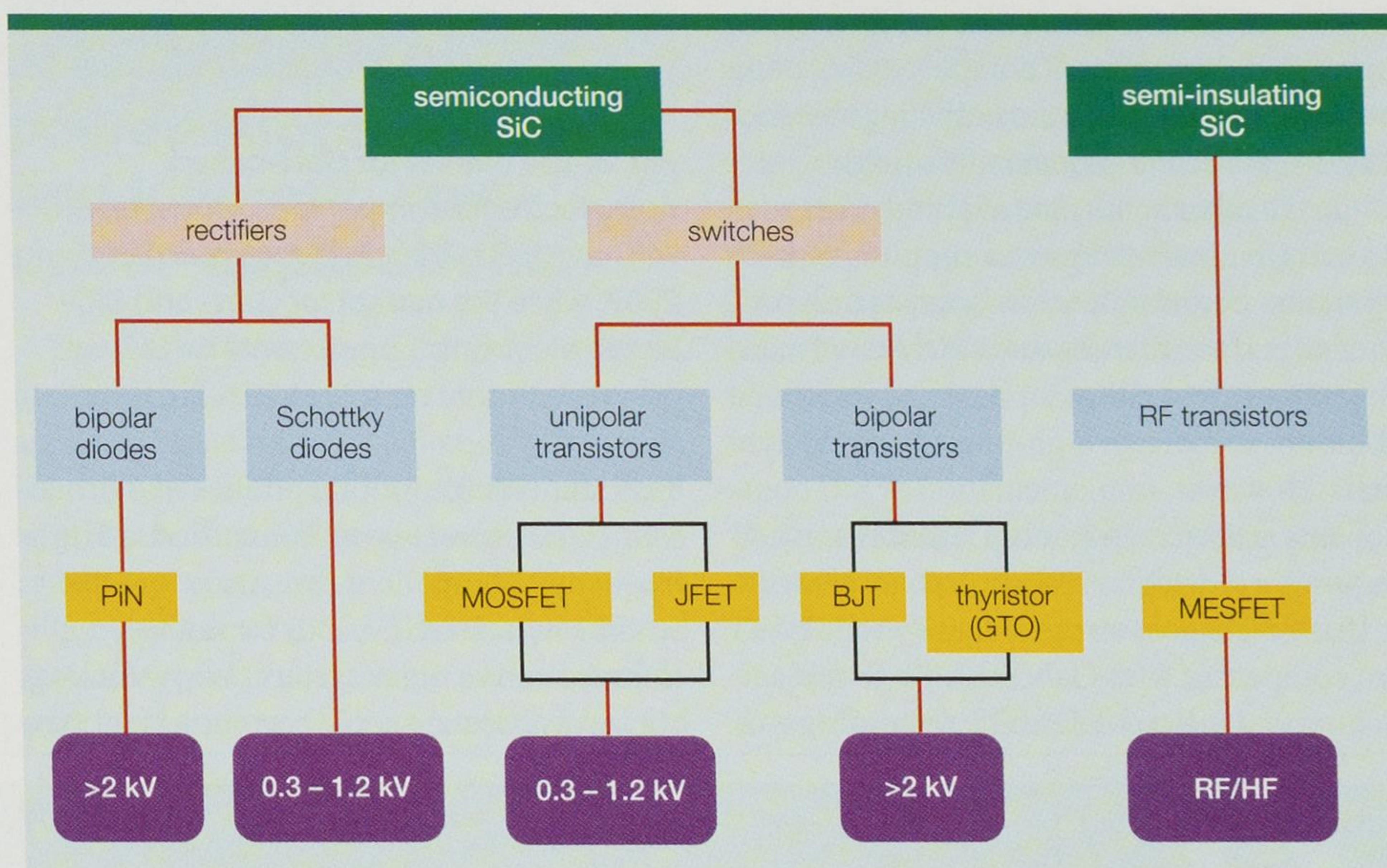


Fig. 2. Summary of the numerous electronic device applications for both semi-insulating and semiconducting SiC material. Schottky diodes are in production at Cree and Infineon.

total nitride optoelectronics market. Since no new players are entering the market using SiC substrates, we expect the SiC market share in optoelectronic applications to remain the same or decrease.

Power electronics

The challenge for SiC is to move from the optoelectronics market to power electronics, where components can benefit from the material properties of SiC, resulting in high power densities and high-temperature operation.

Depending on the power range, many SiC components can be manufactured using semiconducting or semi-insulating material (mainly 4H or 3C polytypes; figure 2). The first commercial SiC components were Schottky diodes and MESFET RF transistors.

SiC Schottky diodes are the most advanced components using SiC heterostructures as the active layers. These components are currently in production at an estimated level of 5 million units in 2002. This is a very low figure compared with the production of standard silicon Schottky diodes; one single European producer, STM, manufactured 220 million

silicon Schottky diodes in 2002.

The only two producers of SiC Schottky diodes are Infineon (through its SiCed R&D lab) and Cree, in collaboration with Microsemi. A number of other companies including Fuji, Hitachi, International Rectifier, Matsushita, STM and Toshiba have strong R&D programs related to SiC Schottky diodes, but have not commenced production.

Schottky diodes target the high-speed, high-power-density switching market. This includes products or functions like high-frequency power supplies, power factor correction and power conversion in motor controls or power management appliances. The use of SiC components will dramatically reduce the number and the size of all passive components in such systems.

Today, SiC Schottky diodes are mainly targeting the market for components operating at 6–8 A and 600 V, for power factor correction in high-end AC/DC power supplies and uninterruptible power supplies (UPSs). The total accessible market for this segment is estimated to be 200 million parts per year.

The next promising market for SiC diodes

SILICON CARBIDE

is low-end power supplies for use with PCs and home appliances. These markets will be accessible only when the average selling price (ASP) of the SiC parts falls below \$1.

Technical and financial bottlenecks are still slowing down the emergence of commercial products. The SiC material accounts for about 40% of the cost of a typical SiC Schottky diode, a further 50% is processing costs, and the remaining 10% is packaging and test. Due to the cost of materials and the need for highly specialized equipment and processes, components manufacturers are hesitating to launch large-scale development in this field.

On the other hand, potential end users such as manufacturers of power supplies or UPS systems, communication base station providers, and rail traction and automotive manufacturers are waiting for new and improved solutions to manage high-power-density systems. However, implementation of SiC components is not a chip-to-chip replacement and requires a redesign of the electronic circuits.

In the RF/microwave field, SiC MESFETs are competing with GaN HEMTs to replace incumbent silicon LDMOS technology in

Components grown on SiC

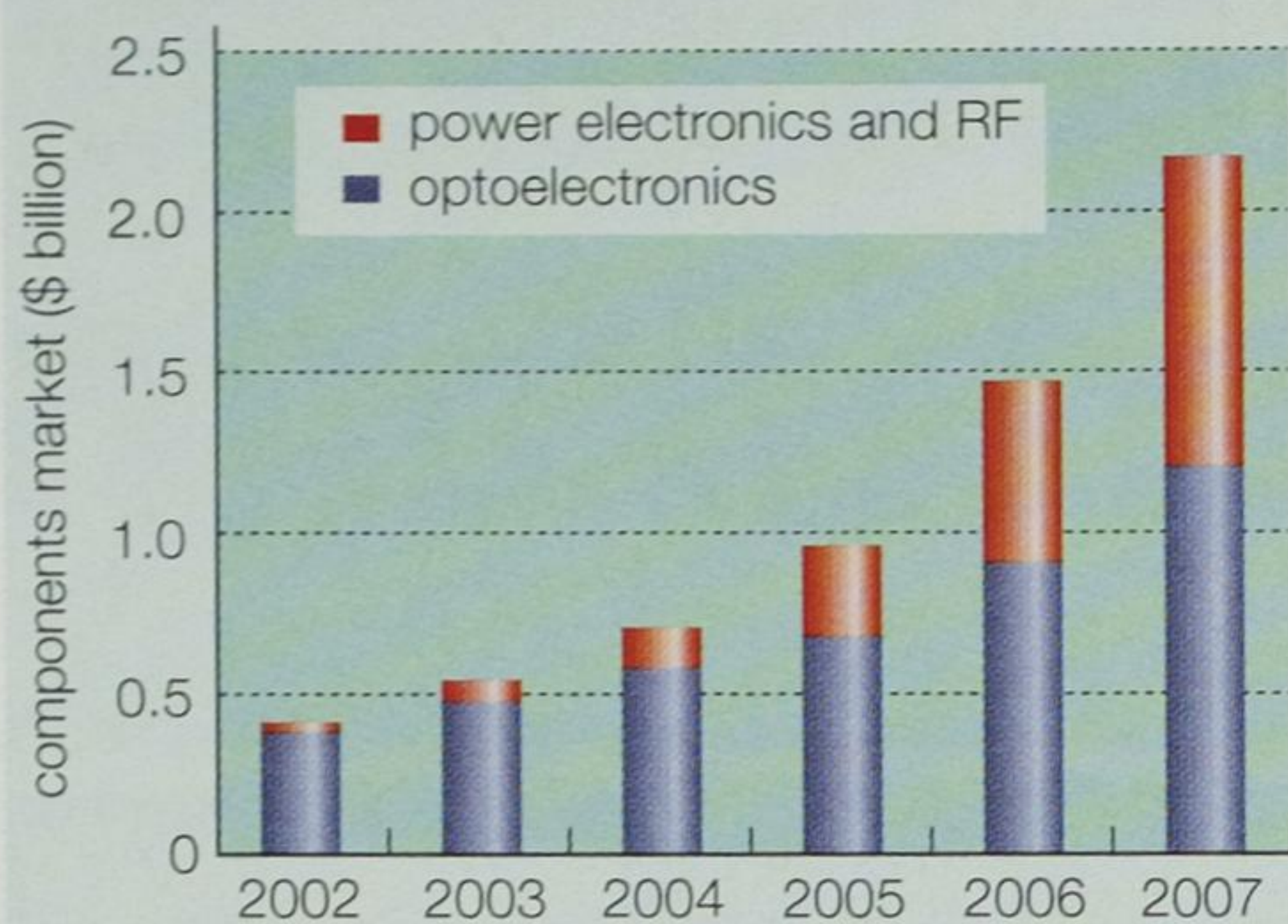


Fig. 3. The market for GaN-based optoelectronic components grown on SiC will have a CAGR of 24% between 2003 and 2007, while the market for GaN- and SiC-based electronic components on SiC will grow even more rapidly at 70%.

base stations for mobile phones and broadcast (UHF band) communications. High-frequency components are also expected to be used in the L and S bands for military applications such as radar systems and jamming. Microwave heating could become a huge mar-

ket if the ASPs of SiC MESFETs become compatible with the cost of the currently used magnetron technology.

SiC MESFETs have entered a pre-production level at Cree, Thales and others, but lifetime and production yield remain key issues when moving to full production.

Conclusions and future trends

SiC material offers a wide range of characteristics, with three polytypes covering the main applications. Three inch semiconducting SiC and 2 inch semi-insulating wafers are now available, but the real breakthrough will be the emergence of 4 inch wafers that are compatible with standard semiconductor tool sets.

There are three production techniques for growing SiC (sublimation, HT-CVD and heteroepitaxy), but micropipe density remains too important to manufacture numerous large devices (>2 kV) on a single wafer.

The SiC material market certainly suffers due to the Cree monopoly, with the company acting as a reference for quality and price level. No clear challengers are emerging, but the market will benefit from having a robust second source.



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In terms of markets, optoelectronic applications are the leading consumer of SiC material, and consumption is forecast to increase by more than 20% per year. On the other hand, blue LEDs are now available on silicon (although brightness and yield must be improved), the first violet laser diodes on the market use sapphire substrates, and major R&D efforts are focusing on the development of free-standing GaN. This situation means that SiC will lose market share in the future, even if it shows the best lattice mismatch with nitrides and allows the growth of devices with back-face contacts. The market for optoelectronic devices grown on SiC is forecast to reach \$500 million in 2003 and \$1.2 billion in 2007, a compound annual growth rate (CAGR) of 24% (figure 3).

The alternative market is power electronics, where SiC enables a high switching capacity at high frequency, with no recovery time, compared with silicon. Only Schottky diodes have reached commercial production to date. The cost of these components allows SiC Schottky diodes to target high-end markets with volumes of about 200 million units per

year. By reducing ASPs, Schottky diodes will be able to target the PC power-supply market and low-end, cost-driven applications. We consider that the 2003 market for power devices is worth about \$60 million, and will grow to around \$500 million in 2007, at a CAGR of 70%.

By reducing ASPs, Schottky diodes will be able to target the PC power-supply market and low-end, cost-driven applications.

The market is waiting for full SiC switching cells (SiC diodes and SiC transistors) for applications such as 42 V automotive systems, but SiC MOSFETs are not yet ready, and only hybrid solutions (SiC diodes and silicon transistors) are emerging.

For high-power (>2 kV) devices, *pin* diodes and BJT or GTO devices are not compatible with high micropipe-density wafers and the

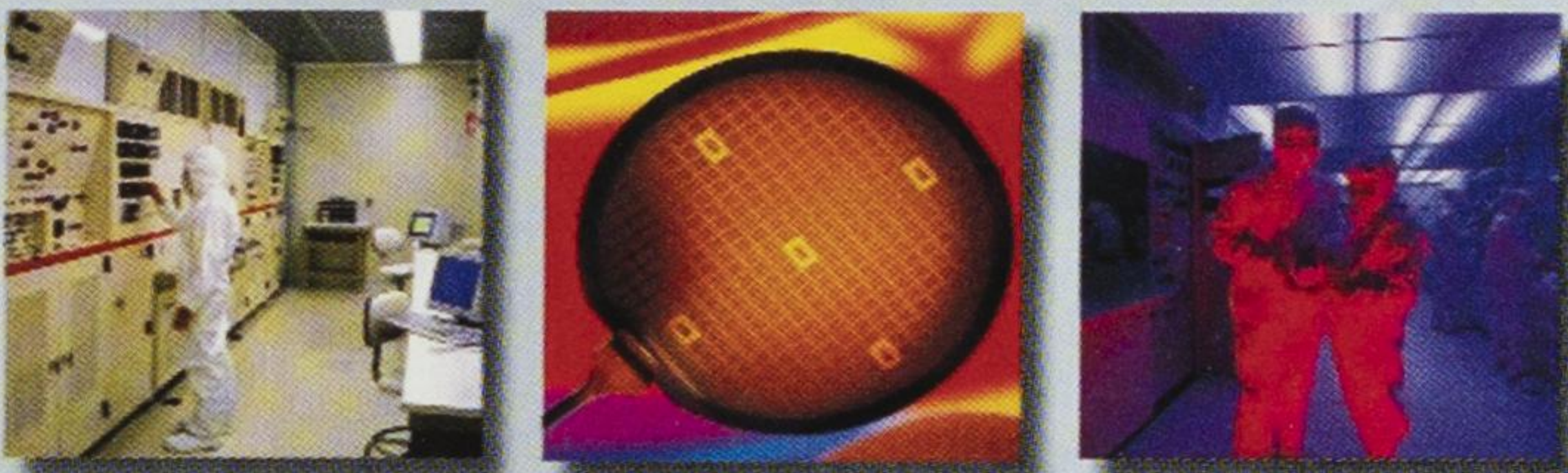
quality of thick (>100 μm) SiC epitaxial layers has to be improved.

In the RF field, a single SiC (or GaN) transistor is supposed to replace 10 standard transistors (mainly silicon LDMOS or GaAs transistors) as used in today's base stations. This market represents a potential for 1 million components per year including defense applications. The next challenge will be the replacement of magnetrons in microwave ovens. The market for RF transistors using SiC or GaN is expected to reach \$400 million by 2007.

However, SiC components do not offer chip-for-chip replacement, and systems have to be redesigned in order to accept SiC components. This constitutes the main challenge for SiC component manufacturers, who will have to teach their own customers (the end users) how to implement this new component in their systems. ●

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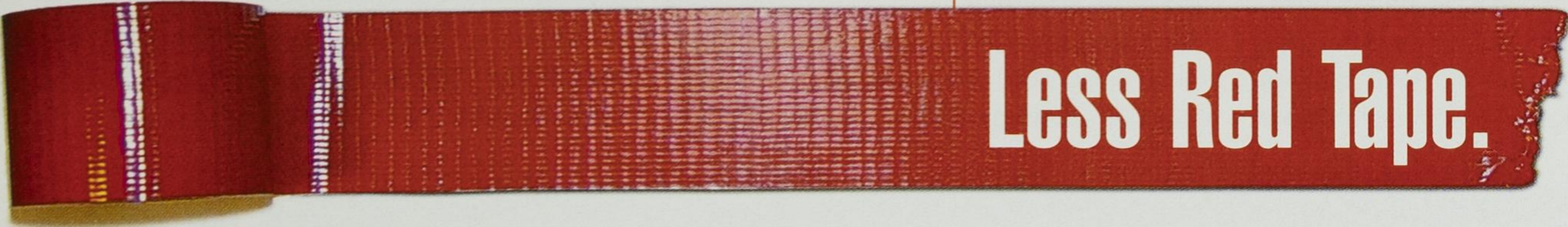
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The rapidly changing world of SiC materials and devices

SiC has evolved from being a laboratory curiosity to being a useful material for wide-bandwidth, high-power devices. **Scott Allen** and **Jim Milligan** of Cree describe the latest developments.

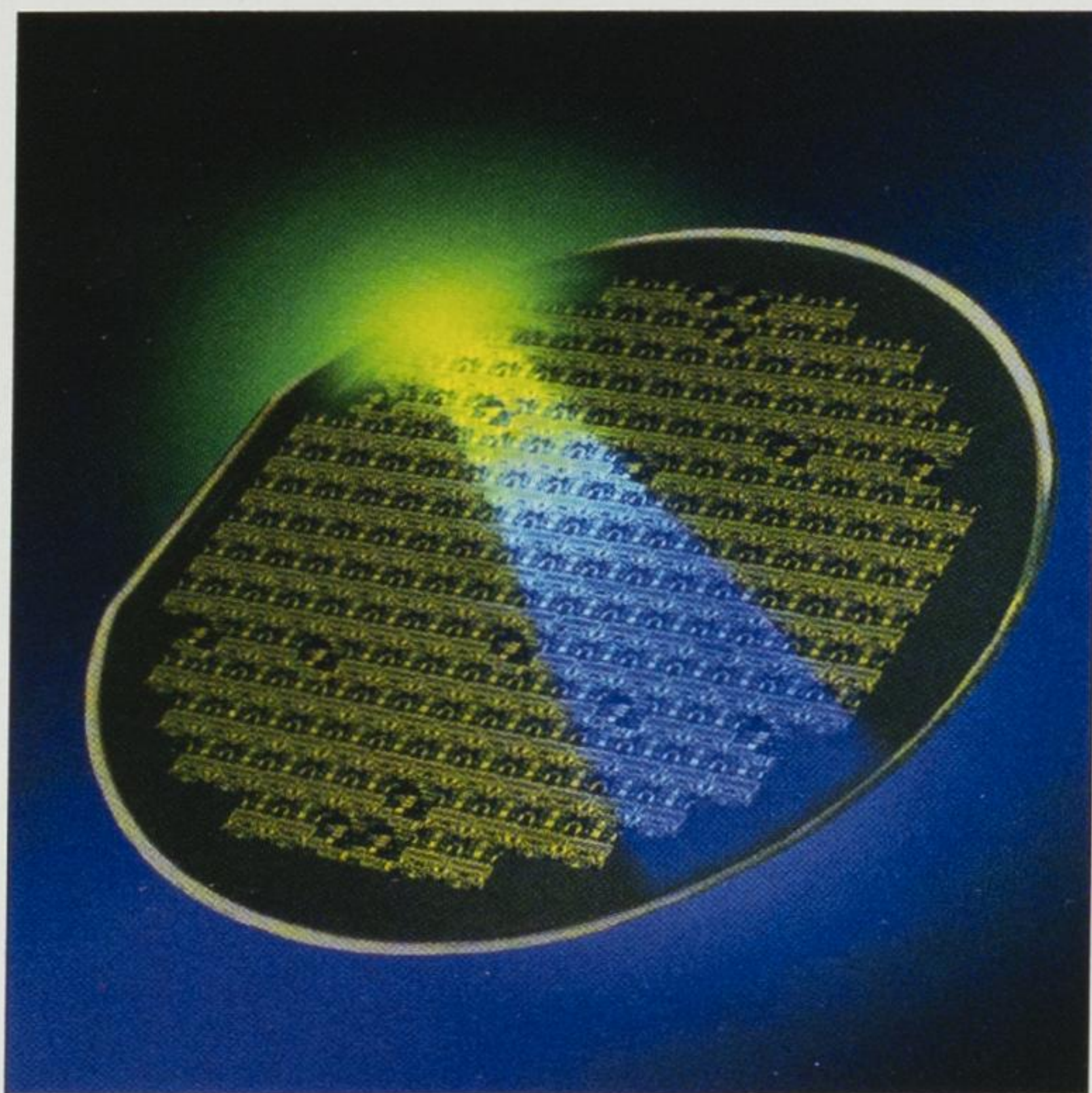


Fig. 1. A completed 3 inch SiC MESFET MMIC wafer from Cree: the company now offers a commercial foundry service.

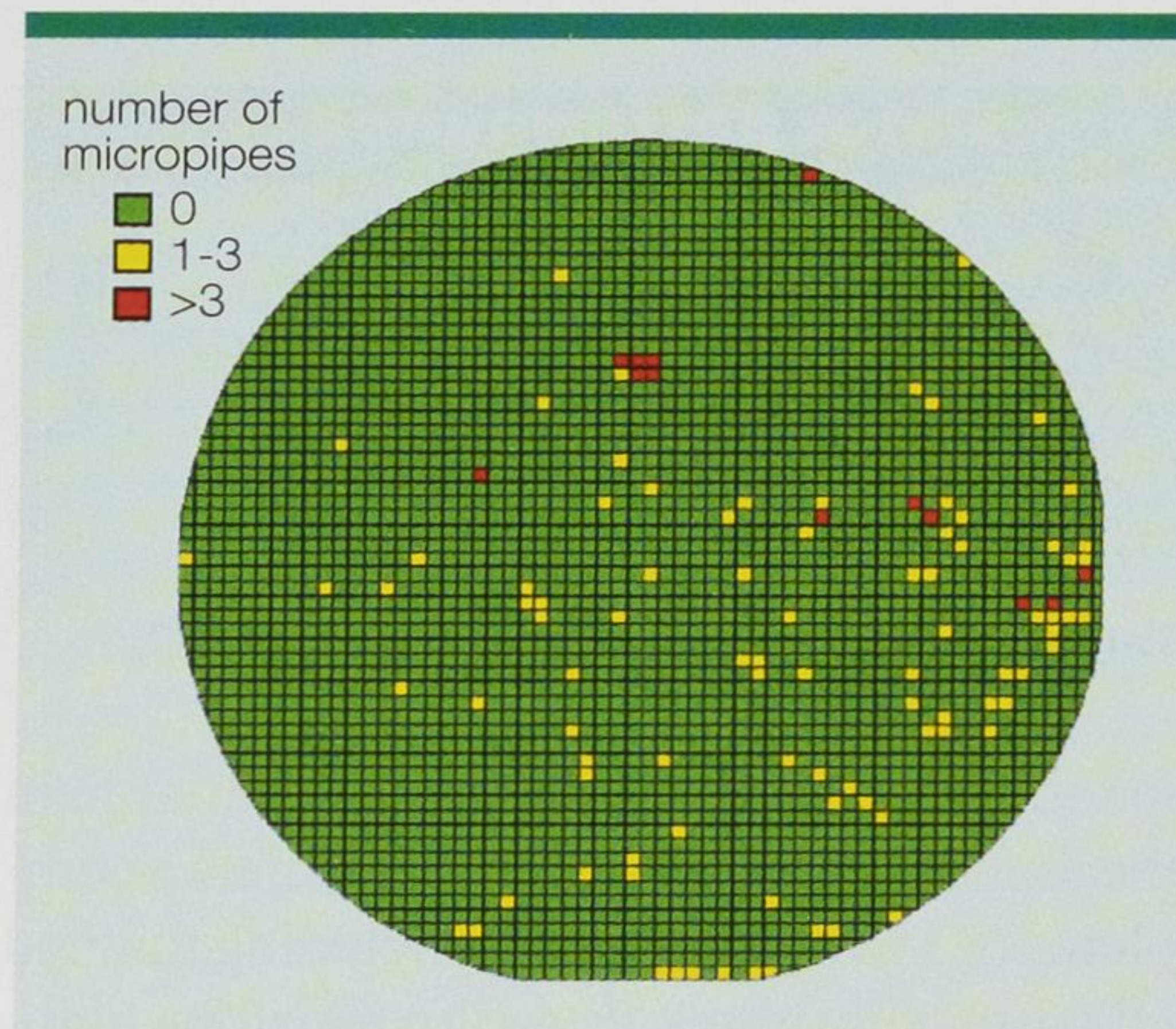


Fig. 2. A map of micropipe defect count on a 3 inch HPSI 4H-SiC substrate, showing an average micropipe density of only 3/cm² and 96% of the area to be micropipe-free. Each sampled area is 1.25 × 1.25 mm.

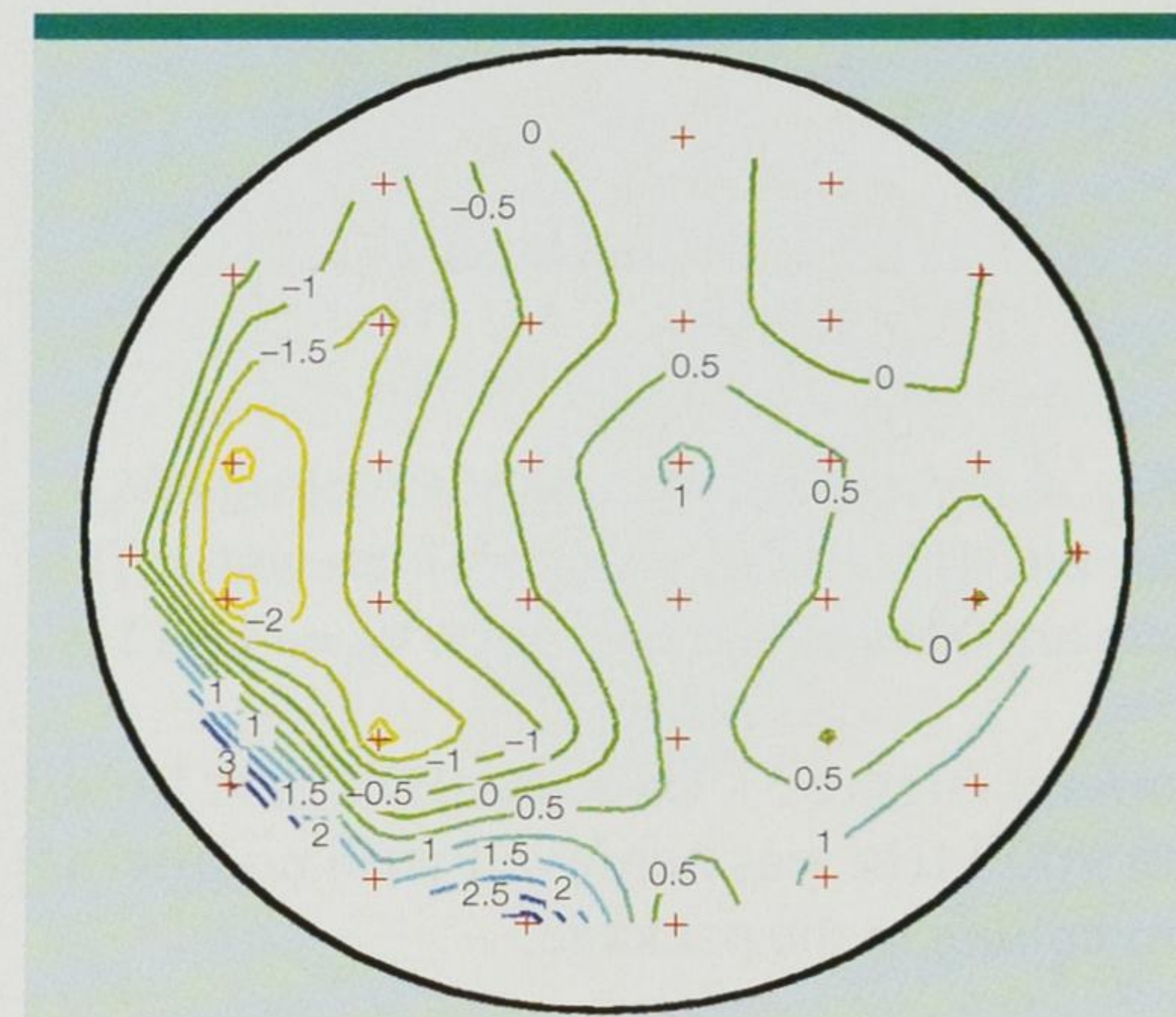


Fig. 3. Eddy current sheet resistivity map showing excellent epi uniformity (1.4% σ /mean) across a 3 inch MESFET wafer. Contours indicate the percentage difference from the epiwafer average.

Wide-bandgap semiconductors have long promised many advantages for high-power RF amplifiers, and SiC MESFET technology has matured to the point where RF transistors are now commercially available. The main advantage of wide-bandgap semiconductor devices is a very high operating voltage – up to 50 V for commercially available SiC MESFETs (figure 1), which results in a higher power density than is achievable with other solid-state microwave devices. The higher power density translates to a higher number of watts per pF of parasitic capacitance, making these technologies particularly suitable for very-wide-bandwidth applications. When these transistors are fabricated on SiC substrates, their thermal handling capability is also higher than for devices fabricated on Si, GaAs or sapphire.

SiC material supply

One of the key enablers for commercializing wide-bandgap semiconductor devices is the progress in SiC substrate technology. 3 inch diameter high-purity semi-insulating

(HPSI) 4H-SiC substrates have been available in prototype grade since the beginning of 2003, and are planned for release as a standard commercial product later in the year.

One of the historical issues with SiC substrates, other than diameter, was the density of micropipe defects, which are screw dislocations in the crystal that have an open core, typically a few tenths of a micron to a few microns in diameter. The typical micropipe density on the 3 inch HPSI substrates has been reduced to 35/cm², which is low enough to have a minimal impact on the yield of typical RF power transistors. Figure 2 shows a map of the micropipe defects from a 3 inch HPSI substrate grown at Cree that is representative of an R&D best result. The average micropipe density on this wafer is 3/cm², and 96% of the wafer area is micropipe-free.

SiC epitaxial processes have had to keep pace with the progress in substrate technology, with high-quality, uniform epitaxial material now routinely achievable on 3 inch substrates. A resistivity map taken with an eddy current measurement system of the epi-

layer for a 3 inch SiC MESFET wafer is shown in figure 3. The standard deviation is only 1.4%, and the maximum deviation from the mean is less than 5%, enabling extremely high yield to a production threshold voltage tolerance of $\pm 10\%$. Figure 4 shows a histogram of the distribution of the threshold voltage of SiC MESFETs recently fabricated on 3 inch substrates with such epi material.

SiC MESFETs

The quality of material now available has led to the commercial availability of 10 W SiC MESFETs targeted primarily at wide-bandwidth applications. At 2 GHz, with a quiescent bias of $V_{DS} = 48$ V and $I_{DS} = 500$ mA, the typical P_{1dB} is 40.8 dBm with an associated gain of 15 dB and a PAE of over 45%. Saturated power is typically 42 dBm with a PAE of over 50%. When biased at a quiescent current of 300 mA, linear gain at 2 GHz is greater than 15 dB and the third order intermodulation products are less than -30 dBc at P_{1dB} .

An example of the wide-bandwidth capability of these devices is the demonstration

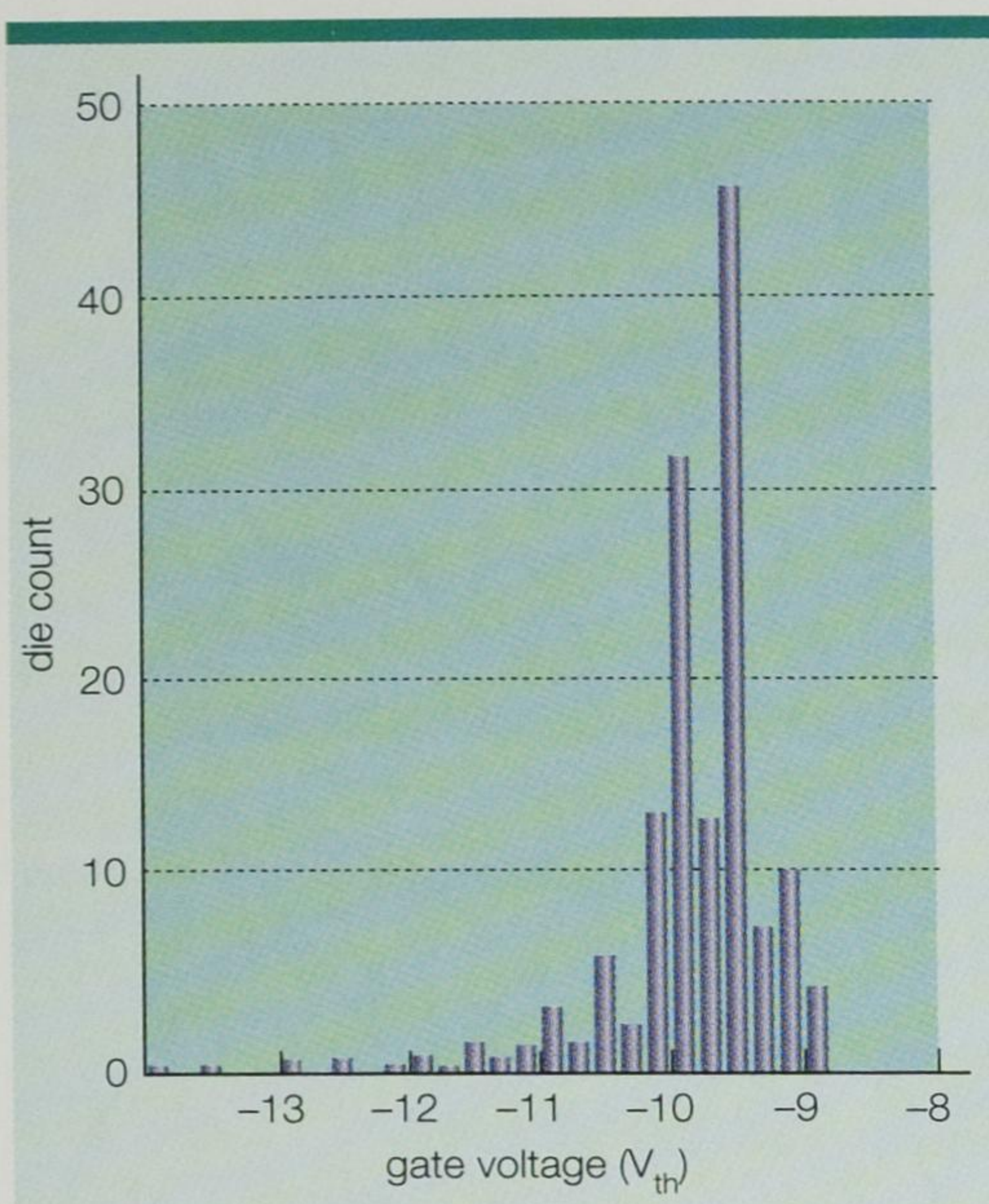


Fig. 4. Histogram of threshold voltage (V_{th}) for SiC MESFETs across a 3 inch wafer. The die are 90% within the range $V_{th} = -10 \pm 1$ V.

circuit (figure 5). Over 10 dB of gain from 1 to 900 MHz was achieved with no internal matching in the package.

SiC MMIC foundry services

SiC MESFET technology has now advanced to the point where high-power and wide-bandwidth SiC MESFET-based MMICs can be demonstrated. In July 2002, a three-year effort was begun at Cree for the conversion of the SiC MMIC process to 3 inch wafers, with funding from the US Navy, the Missile Defense Agency and the US Department of Defense's Title III program. This program builds on prior demonstrations of SiC MMIC capability in a 2 inch process, and aims to enhance the producibility of SiC MMICs to reduce the timeline for insertion into a variety of DoD applications.

The program has three primary thrusts: improving yield and quality of 3 inch diameter HPSI 4H-SiC substrates; improving the uniformity of SiC epitaxy on the 3 inch substrates; and conversion of the wafer fab to a 3 inch line. The conversion has been successful and Cree is now offering commercial products from this line, including 10 W RF MESFETs and a family of Schottky diodes for power-switching applications.

The rapid progress on this program has allowed Cree to offer the first wide-bandgap semiconductor MMIC foundry service based on the 3 inch SiC MESFET process described above (*Compound Semiconductor* July 2003 p10). Table 1 summarizes the typical perfor-

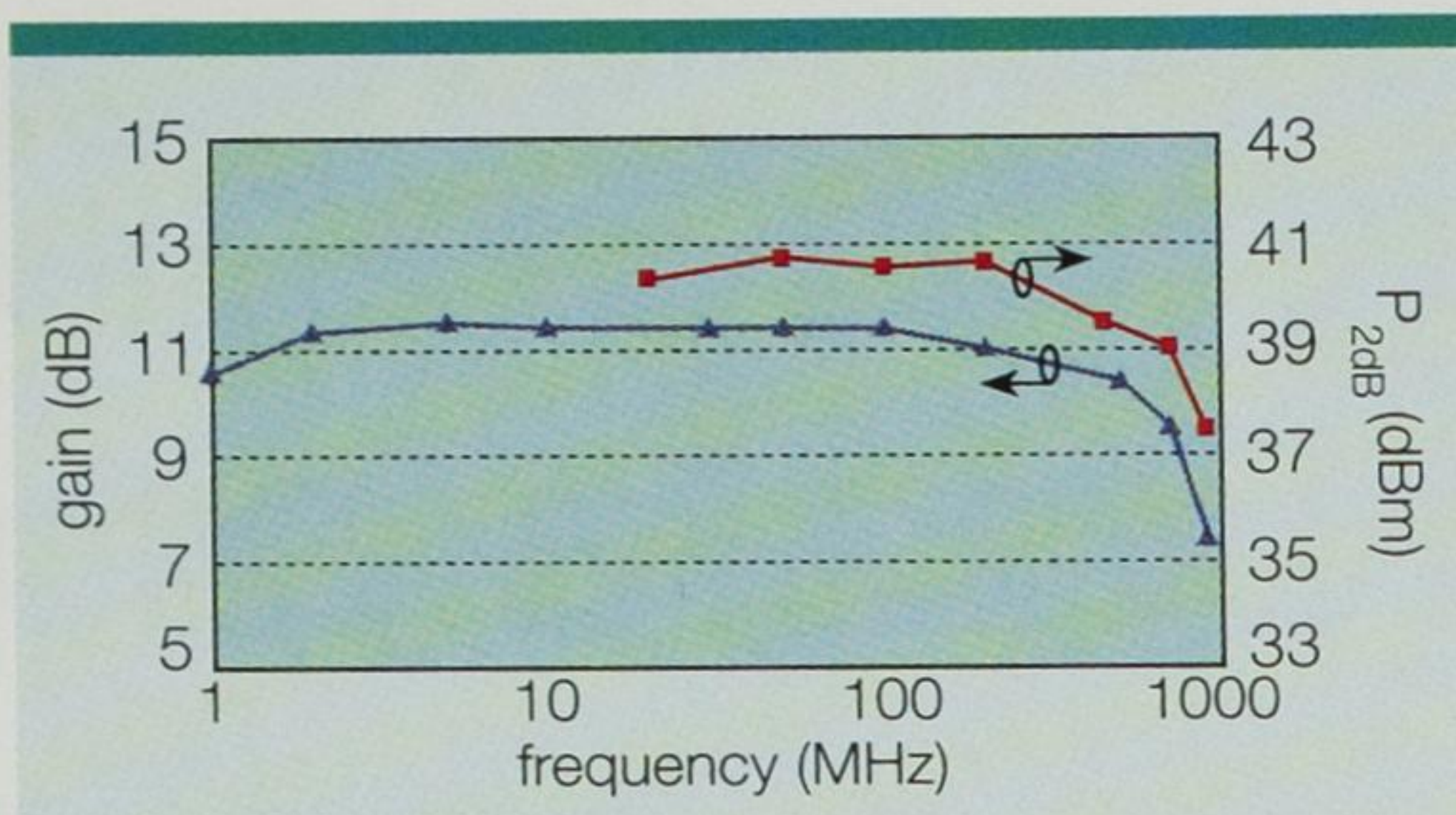


Fig. 5. Measured broadband response of a demonstration circuit with a gain of >10 dB from 1 to 900 MHz, achieved with no internal matching in the package.

Transistor performance

drain voltage	50 V
gate length	0.45 μm
$P_{3\text{dB}}$ power density	4 W/mm
PAE at $P_{3\text{dB}}$	50%
linear gain at 3.5 GHz	12 dB

Table 1. Properties of Cree's SiC MMICs.

mance of the unit cell transistor available in the foundry process. The process offers a complete RF MMIC capability, including thinned (100 μm) substrates, thin-film resistors, high-voltage capacitors, and through-wafer vias to accommodate microstrip transmission line designs for high-power amplifiers.

The promise of SiC device technology for wider bandwidths and higher operating temperatures and voltages has become a reality.

The foundry service includes MMIC design, fabrication and testing to the customers' design specifications. The service is expected to be expanded in early 2004 to include the support of external customer designs which use device models and layout design rules supplied by the foundry.

Reliability testing

Preliminary reliability data is now available on the commercial SiC MESFETs. These devices have passed a high-temperature reverse bias test carried out according to JEDEC guidelines. The test consisted of stressing the MESFETs under bias conditions of $V_{DS} = 100$ V and $V_{GS} = -26$ V, for 1000 h at a base-plate temperature of 150 °C. There

were zero failures among the 20 devices under test after 1000 h, and virtually no change in any RF parameters.

Further trials have been performed involving DC high-temperature operating life (HTOL) testing for 1000 h of 42 packaged MESFETs from multiple wafers. The devices were biased at $V_{DS} = 48$ V, $I_{DS} = 500$ mA on a 90 °C hot plate, yielding a junction temperature of 175 °C. The devices were held at a constant voltage and the drain current was measured *in situ* at temperature every 12 min. The average reduction in I_{DS} after 1000 h under these conditions was only 2.5%. Equally important is that no early failures or out-of-family behavior were observed, indicating a well-controlled process.

An RF HTOL test is in progress in which 16 MESFETs have been operating for 2200 h (35,000 accumulated device hours) with zero failures at a junction temperature of 150 °C and running at a 2 dB compressed power of 42 dBm at 2.6 GHz.

DC accelerated life testing has also been performed on a sample of 20 SiC MESFETs at a junction temperature of 240 °C. Some degradation was observed after stressing the devices under these conditions for 2000 h. Further accelerated life testing is currently under way to determine an activation energy for the degradation mechanism.

Maintaining momentum

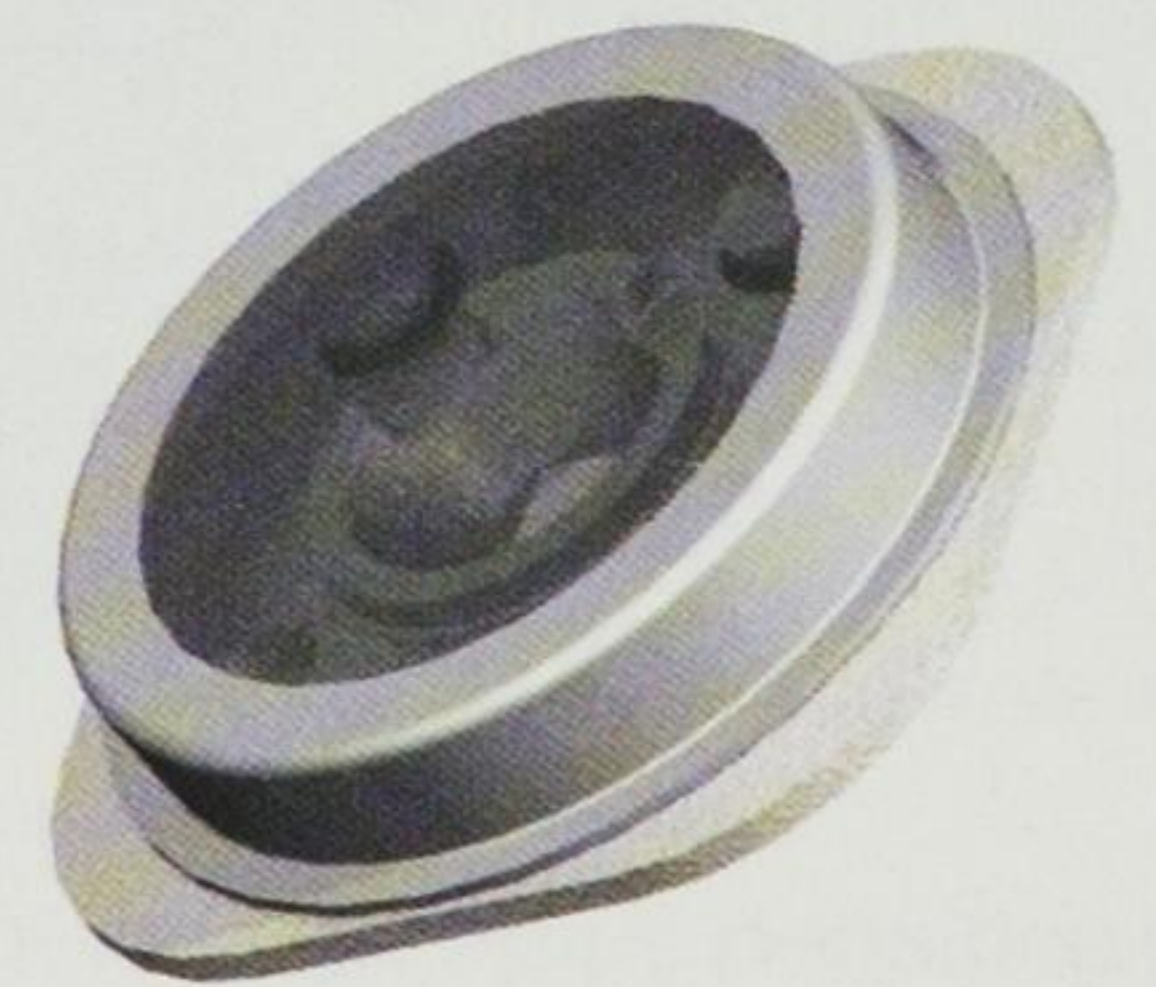
With rapid progress seen in the manufacture of large-area SiC substrates, SiC epitaxy and SiC MESFETs over the last 18 months, the promise of SiC device technology for wider bandwidths and higher operating temperatures and voltages has become a reality. System designers and architects now have additional freedom in creating higher-performance, lower-cost systems than were previously possible. Packaged SiC devices at 10 W are now commercially available, and higher-power 60 and 120 W packaged parts are planned to follow. This will provide customers with RF transmitter solutions for a host of commercial and defense applications.

For higher levels of integration or ultra-wide bandwidths with reduced size, SiC MMIC foundry services are now also available. With the announcement earlier this year of Cree's demonstration of 100 mm 4H semi-insulating SiC substrates, a critical milestone on the path to larger substrates and further product cost reduction has been passed. SiC can now fulfill its potential to make a major impact in the world of high-power electronics. ●

365nm, 100mW.

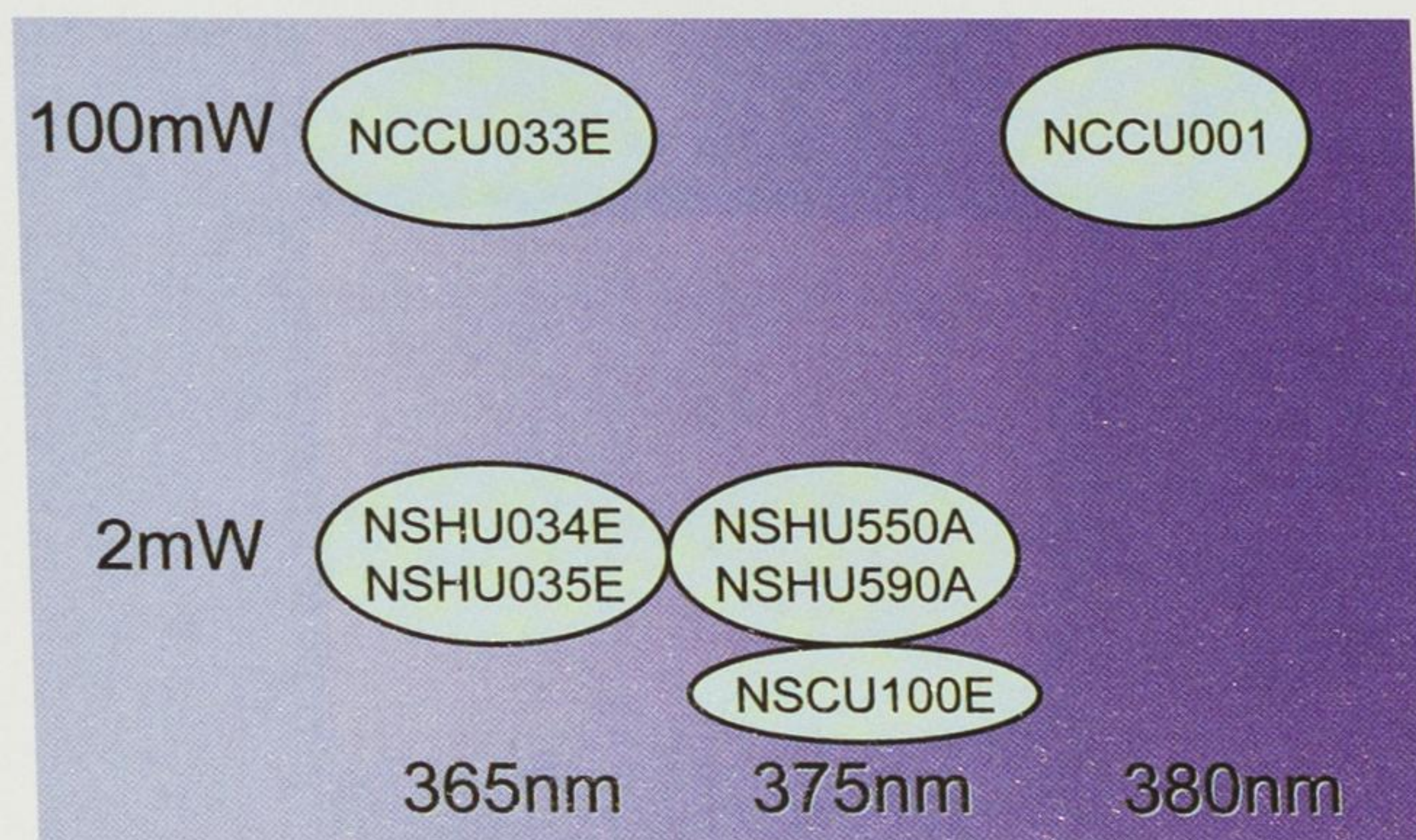
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NSHU550A	375nm	2.0mW	Flat	Now
NSHU590A	375nm	1.4mW	Lens	Now
NSCU100E	375nm	*1.0mW	SMD	2003/11
NCCU001E	380nm	100mW	Flat	2003/12

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- InP via and feature etching
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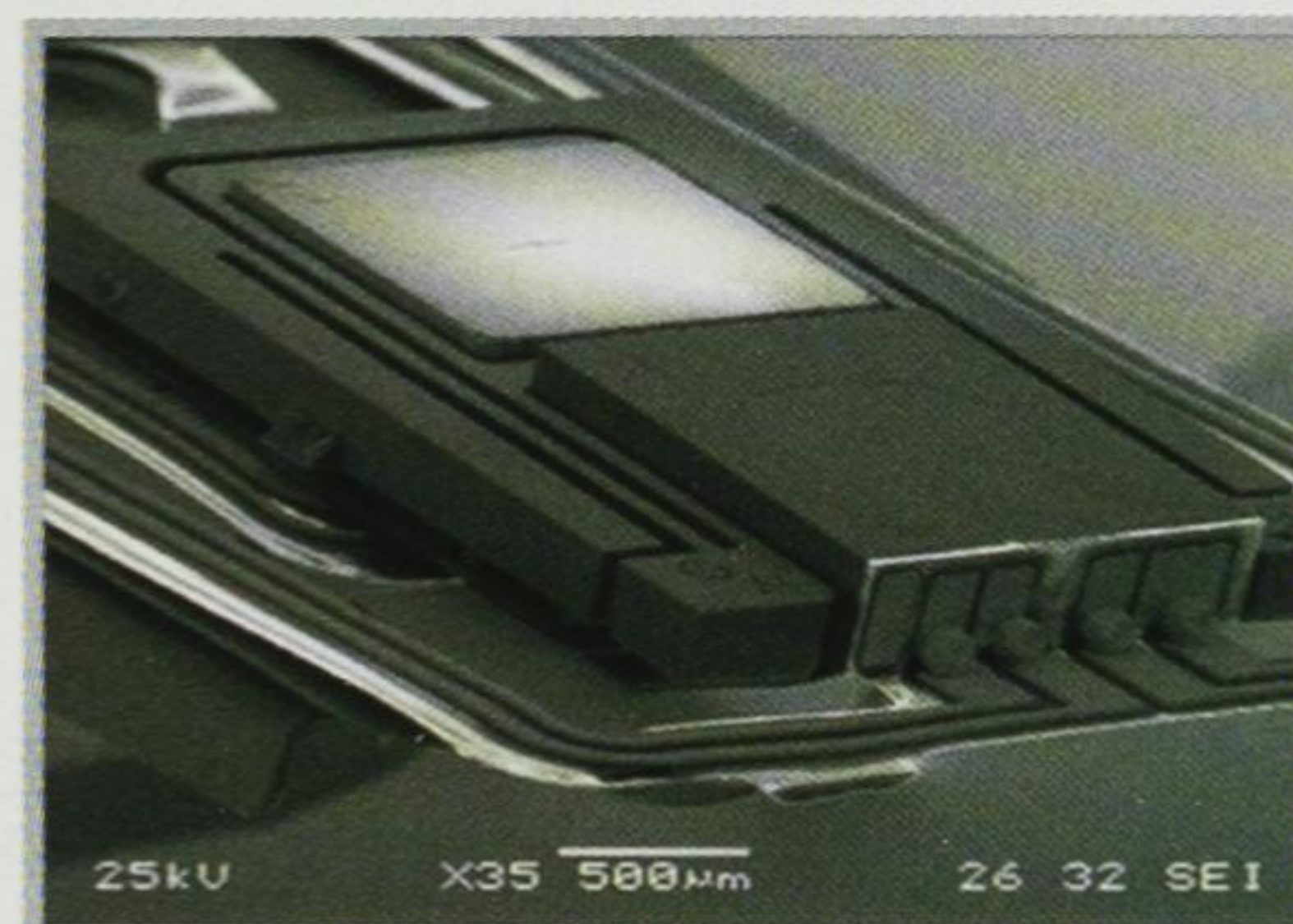
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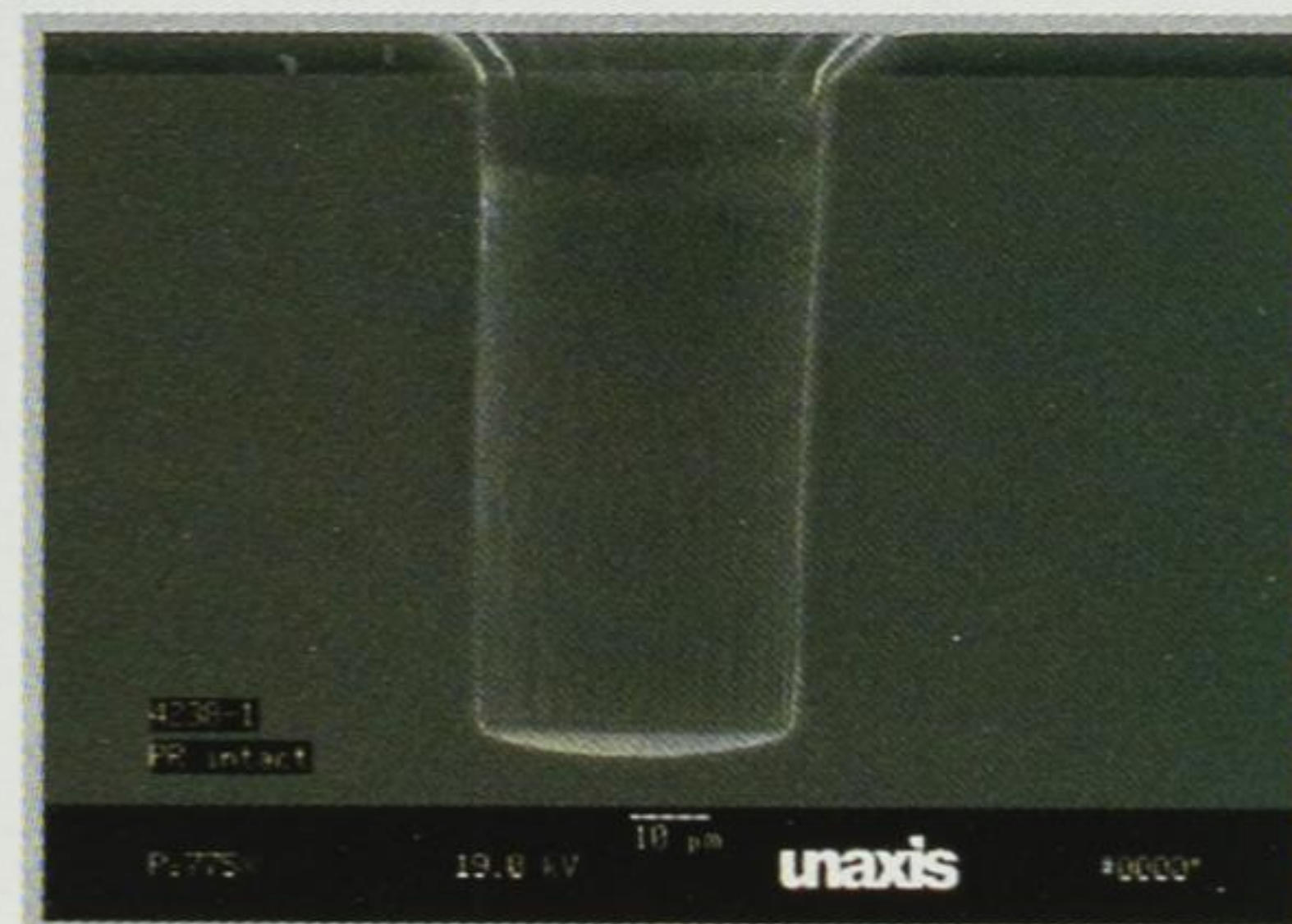
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SiC benefits from Title III effort

After working wonders for the US GaAs substrate industry in the 1990s, the Title III program has been attempting to do the same for SiC substrates, as **Jon Newey** describes.

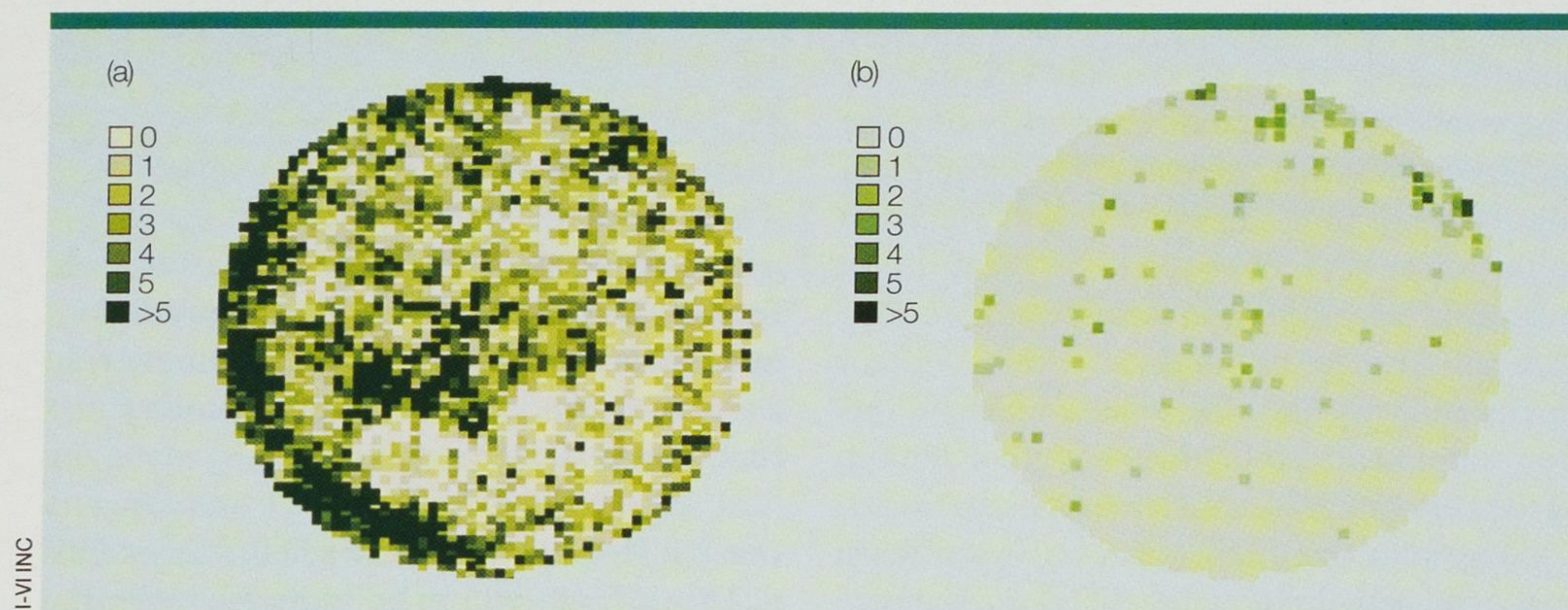


Fig. 1. A good illustration of the progress made in SiC wafer quality is the reduction in micropipe density. A typical 2 inch SiC wafer map prior to the Title III program (a) shows a micropipe density of 544/cm². Typical current material (b) shows less than 10 /cm².

For about 50 years now, the US Department of Defense (DoD) has had a very powerful legislative tool at its disposal that gives it license to nurture and develop domestic industries that it sees as crucial to its needs. This is known as the Title III program, which was borne out of the Defense Production Act passed in the 1950s. Title III of this act dealt with the ability to create, expand and maintain US domestic industrial capacity and supply of resources and technology for national defense. Responsibility for the overall management of the Title III program lies with the deputy under-secretary for defense for advanced systems and concepts. However, the US Air Force is responsible for the execution of individual projects within the program. Matthew Seaford is the manager of the Title III Program Office, which was established within the Air Force Research Laboratory Materials and Manufacturing Directorate, the director of which is Charles Browning.

At present, the Title III program consists of nine projects, worth about \$75 million annually and covering an impressive range of technologies including structural materials, polymers, superconductors and semiconductors. The various programs have one common aim – to establish a production base that is self-sustaining after Title III involvement ends. This means that contractors are required

The program focused on improving yields, reducing production costs, and developing longer-term business and marketing plans.

to focus on business planning and marketing, as well as manufacturing capabilities. This combination brings long-term viability to industries seen as critical by the DoD.

GaAs: a big Title III success

Over the years, the benefits to defense programs resulting from Title III contracts have been substantial. The most noteworthy success concerning compound semiconductors was the program covering semi-insulating GaAs substrates, which began in 1994. Back then, non-US firms dominated the global market for GaAs wafers and US producers were struggling financially, meaning that they lacked the financial muscle to invest in order to improve their products and market positions. The goal of the Title III program was to develop the domestic US capability for manufacturing high-quality, low-cost semi-insulating GaAs wafers in order to satisfy the

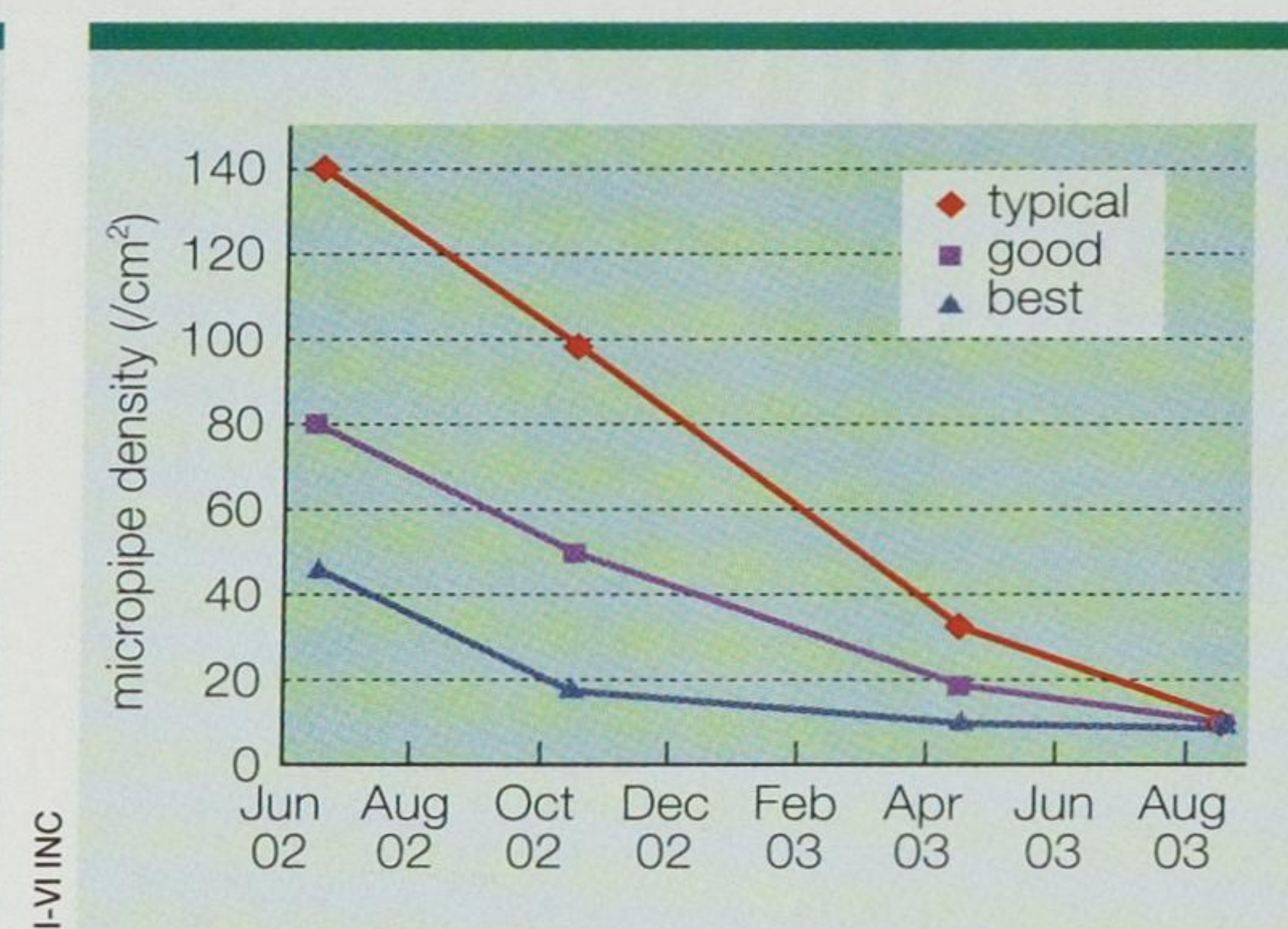


Fig. 2. There has been a steady convergence of the micropipe densities in typical and best material produced by II-VI during its Title III effort.

growing military need for GaAs ICs. The program focused on improving yields, reducing production costs, and developing longer-term business and marketing plans.

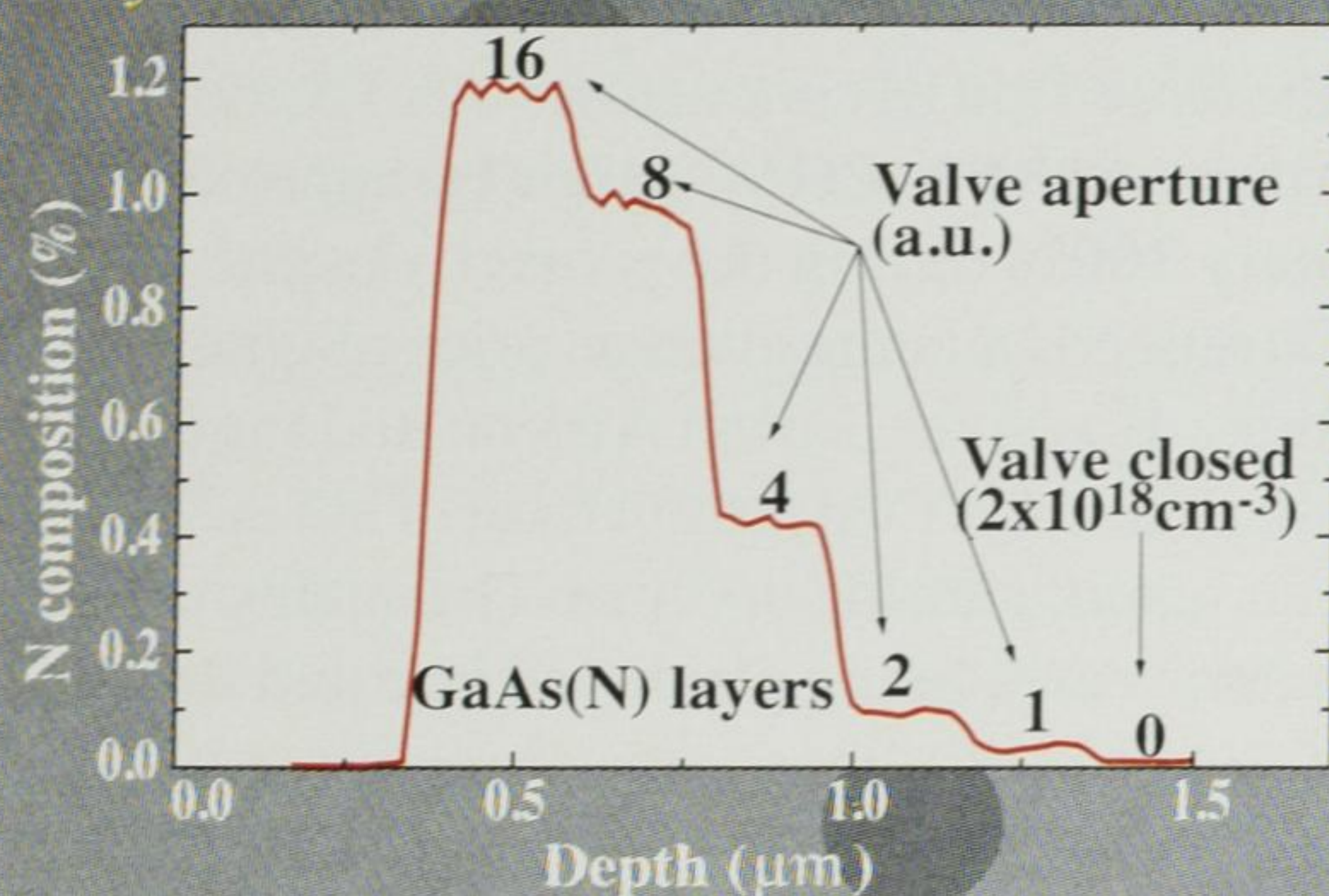
The project was successful in turning around the fortunes of the US GaAs wafer industry. The dollar value of GaAs wafer sales of the three Title III contractors – AXT, Litton Airtron and M/A-COM – grew by approximately 300% during the project, despite a 40% reduction in the average price of GaAs wafers. However, Litton Airtron no longer exists, while AXT carries out most of its GaAs wafer manufacturing in China. The quality of the substrates being produced boosted the yields of MMIC device manufacturers, who in turn were able to lower their prices to the military, with GaAs ICs eventually finding their way into consumer electronic goods.

SiC comes to Title III's attention

In 1999 the SiC wafer industry became the subject of a new Title III program, which aimed to emulate the runaway success of the GaAs wafer project. Three contracts were awarded to Cree, Sterling Semiconductor (now Dow Corning) and Litton Airtron, whose SiC activity is now part of II-VI Inc. In 1999 only 2 inch wafers of questionable surface quality were available, and the goal of the SiC program was to develop the US capabil-

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ity to produce high-quality 3 inch SiC substrates. With the project due to end in early 2004, 4 inch wafers are now being demonstrated, although they are not yet in widespread use.

When the project started in 1999, the situation with the US SiC suppliers was a little different from the one that the military faced with the US GaAs wafer industry in 1994. Cree was, and still is, the acknowledged world leader in SiC substrate production and also accounted for about 85% of the US market. The concern centered on the ability of Cree and its competitors to supply the large-area, high-quality substrates that would make the high-power devices required by the military available in volume and at a reasonable cost. The pull from the commercial semiconductor device industry that otherwise would have driven supply and quality was not great enough at the time for this to start happening.

"The semiconductor industry would not make the step of producing SiC devices unless it was viable for them to do so," said Seaford, explaining the origins of the Title III SiC project. "The substrate suppliers could not make the jump on their own of building capacity and quickly improving their products without the backing of customers." This is an example of the Catch-22 situations that Title III aims to address where it affects supply to the military.

While the Title III office recognizes the benefits of competition, it does not have a problem with a dominant domestic source (such as Cree) for any of its military needs, but the outcome of its programs must be a viable industry. "Having some competition drives improvements and increases viability," said Seaford.

Beyond substrates

By the time it closes, the SiC program will have cost about \$10.7 million, with industry adding another \$9.6 million from its own pocket and a further \$2.9 million coming from other DoD organizations taking the opportunity to link into the Title III work for their own specific purposes. So, as the project nears its conclusion, can it be considered a success? Seaford certainly thinks so, citing the moves from the 2 to 3 to 4 inch substrates and the vast improvements in material quality over the last three years (figures 1 and 2; table 1). The fruits of the Title III SiC program are now getting early insertion into DARPA programs such as the Wide Bandgap Semiconductor Technology Initiative, which is making use of improved substrates to demonstrate devices

Analysis of impurities in bulk SiC

Element	Concentration (cm ⁻³)
N [#]	4.0 E + 15
B [#]	6.2 E + 15
Al [#]	1.5 E + 14
P [*]	<6.2 E + 14
S [*]	1.2 E + 15
Ti [#]	<1.1 E + 13
V [#]	<1.8 E + 12
Cr [#]	<6.0 E + 13
Fe [#]	<1.9 E + 14
Ni [#]	<2.0 E + 14

< below detection limits

secondary ion mass spectrometry analysis

* glow discharge mass spectrometry analysis

Table 1. The level of impurities in bulk SiC material is now often below the detection limits of the various mass spectrometry techniques used for analysis.

that the DoD would like to see in its systems.

Title III is therefore building the industrial base in electronic materials (and the other technologies that it addresses) that the DoD needs to run its device-oriented programs. The Title III SiC program has successfully focused on substrates, but it is likely that its involvement will not end there. It is probable that SiC will be revisited by the Title III program in the future. Plans for a Title III wide-bandgap device initiative beginning in 2005 have been discussed, and Seaford is confident that these plans will be funded. "There are two or three companies that now know that they have a great technology and there are DoD program offices that want the technology," he said. "However, it will never become space qualified or reliability tested, and program offices don't have the funding to do it themselves. The companies are unlikely to go into mass production without guaranteed customers and so Title III may again step in to provide a way over that inertial barrier by purchasing the devices and field-testing them. Once two or three program offices accept the technology then you have the start of an industrial base."

The Title III SiC substrate program has attempted to follow the path that GaAs successfully took. Eventually the domestic commercial GaAs market took off and Title III was no longer needed. Now the DoD gets its GaAs devices and so does the commercial sector. "We consider the GaAs program a good blueprint that we intentionally tried to copy," said Seaford. "Nobody is in any doubt that GaAs changed society, and SiC has the same potential."

GaAs IC SYMPOSIUM

GaAs IC Symposium celebrates 25 years with strong program

Now in its 25th year, the GaAs IC Symposium once again promises to cover the latest advances in high-frequency and high-speed compound semiconductor circuits and technology.

As usual, this year's GaAs IC Symposium will cover all aspects of compound semiconductor technology, including papers from both commercial and newly emerging military applications. The conference focuses on describing the latest advances in high-frequency and high-speed circuits and technology using GaAs, InP, SiGe, GaN, SiC and other materials. To better reflect the scope of the conference, which covers all compound semiconductors rather than just GaAs, the organizers have decided to rename it starting next year (when it will be held in Monterey, CA). In future the event will be known as the Compound Semiconductor IC Symposium.

As well as 65 technical papers, 25 of which are invited presentations, there will be two courses and five panel sessions (see below). Participants will also enjoy various social events including a Symposium Party at San Diego's famous SeaWorld.

Technical program

The conference will open with three overview talks on the industry, followed by invited presentations from Philips on quad-band power amplifiers, from Raytheon on RF MEMS switches, and from BAE Systems on metamorphic GaAs HEMTs. A session on MMICs

Conference summary

Dates: November 9–12, 2003

Technical session: Monday–Wednesday

Exhibit: Monday evening, Tuesday

Location: Wyndham US Grant Hotel, San Diego, California, USA

Hotel reservation deadline: October 9

Sponsors: IEEE Electron Devices Society, IEEE Microwave Theory & Techniques Society, IEEE Solid State Circuits Society

Corporate benefactors: Anadigics, BAE Systems, RFMD, Sumitomo Electric

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for the handset market will include a paper on Nokia's direct conversion receiver IC for CDMA-2000, and a review of wireless communication MMIC development in Japan. A separate session on SiGe will include papers from IBM and Jazz Semiconductor on SiGe BiCMOS for power amplifier and wireless transceiver applications.

Despite the sluggish nature of the fiber-optic market, companies such as OpNext,

Infineon and Big Bear Networks continue to pursue R&D in ICs for future 40 Gbit/s systems. These companies will present papers advocating InP, CMOS and SiGe, respectively. NTT, Fujitsu and NEC are among the companies presenting papers on the use of InP-based HEMTs and HBTs for even higher-frequency digital ICs.

The wireless and millimeter-wave domains will also be well covered, with talks on the development of gigabit wireless links in Japan, design challenges for 60 GHz radios, and a session on amplifiers for S to W band applications. Both optical transmitter and receiver components will be discussed, along with reliability, simulation and modeling, high-speed signal processing and frequency conversion ICs. The technical program concludes with a look at emerging technologies, including antimonide-based devices and nitride-based HEMTs.

2002 Outstanding Paper award

The award for the Outstanding Paper of the 2002 GaAs IC Symposium will be presented to S Masuda and colleagues from Fujitsu for their paper, "An over-110 GHz InP HEMT flip-chip distributed baseband amplifier with inverted microstrip line structure for optical transmission systems."

Courses and Panel Sessions

Short Course: Emerging Technologies from Defense to Commercial

Sunday 8.00 a.m. – 4.45 p.m.

Covers DARPA-sponsored technologies, RF MEMS, SiGe technology, GaN PAs for wireless infrastructure, and InP HBT technology and circuits.

Primer course: Basics of Compound Semiconductor ICs

Sunday 5.30 p.m. – 8.30 p.m.

For professionals in the electronic industry with little or no experience in compound semiconductor IC technology.

Panel session 1: InP v SiGe v CMOS for high-speed digital applications

Monday 3.30 p.m. – 5.00 p.m.

Panel session 2: Why would I want to switch?

Monday 3.30 p.m. – 5.00 p.m.

Panel session 3: Is first pass success for complex mixed-signal design realizable?

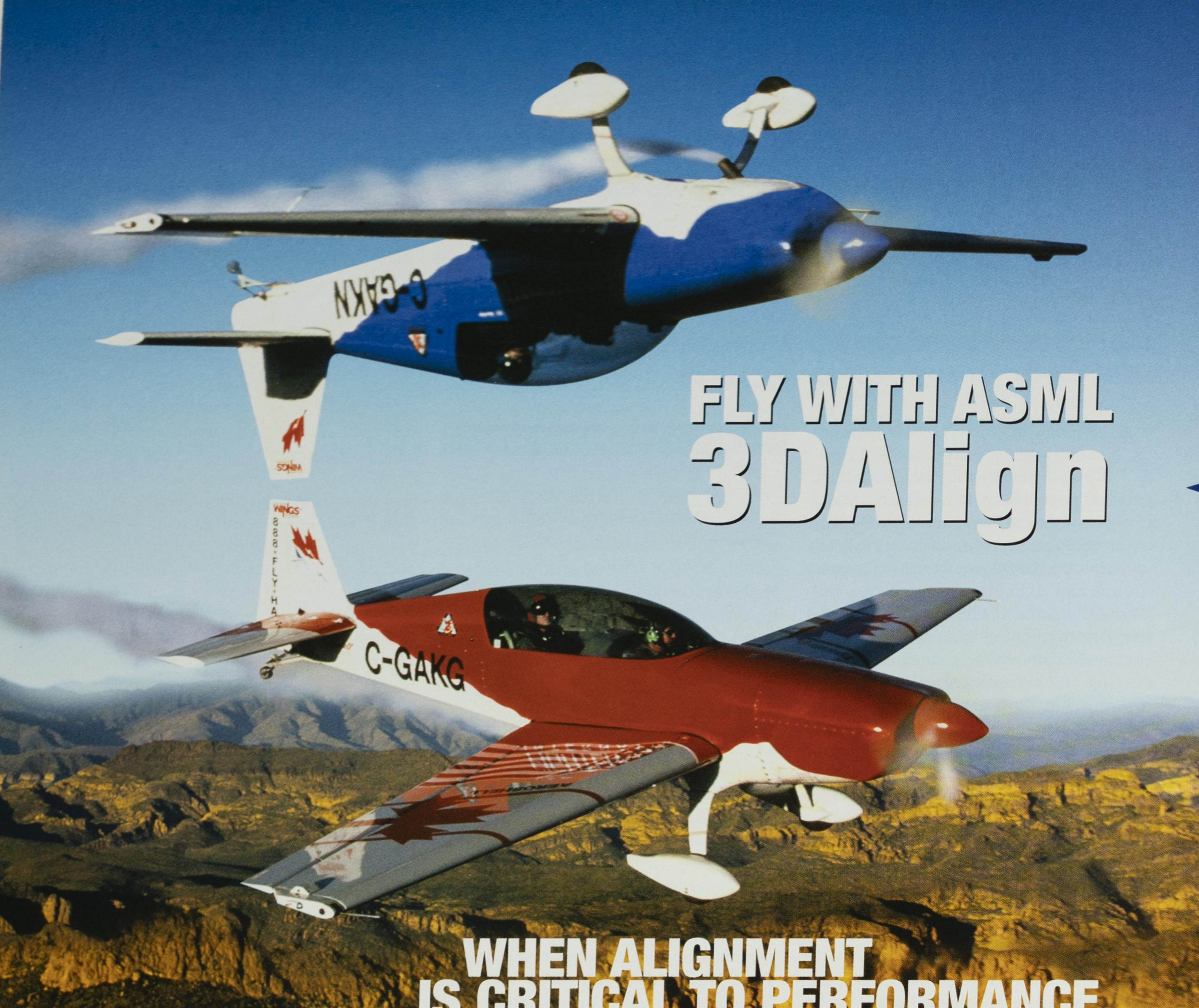
Tuesday 1.30 p.m. – 3.00 p.m.

Panel session 4: Base-station PA technology – LDMOS forever?

Wednesday 1.00 p.m. – 2.30 p.m.

Panel session 5: Module to MMIC to module – here we go again

Wednesday 1.00 p.m. – 2.30 p.m.



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The indium market and compound semiconductors

The recent drop in demand for InP-based devices means that less indium is being consumed by the semiconductor industry, yet indium prices have risen sharply. **Thomas Jansseune** explains why.

In its purest form, indium is the raw material used in the semiconductor industry for InP, InAs or InSb bulk crystal growth and the epitaxial growth of related materials such as GaInAsP. It is introduced as a metal ingot in Czochralski furnaces or vertical gradient freeze furnaces for bulk crystal growth, or as smaller pieces in MBE equipment.

The purity of the indium used for crystal growth is typically 6N or six-nines (99.9999%), which means that the total amount of impurities is less than 1000 ppb. The higher-purity 6N5 or 99.99995% indium, and even higher purities, 6N8 and 7N, are used in smaller quantities, most often in epitaxial growth or for R&D. At these low levels of impurities, maximum concentration limits are often imposed on critical elements. For epitaxial growth by MOCVD, the indium is not present as a metal ingot, but rather as a metalorganic compound, for example trimethylindium.

The high purity of the material requires accurate measurement techniques for the impurities. Typically, glow discharge mass spectrometry (GDMS) would be used to measure a full spectrum of elements, although other techniques are also used. In general, GDMS provides the ability to detect impurities below the detection limit of most other techniques. Recognized laboratories performing GDMS measurements include Shiva Technologies in the US and France, and the National Research Council of Canada.

Uses of indium

While semiconductors are undoubtedly the most demanding application in terms of indium purity, they are not the largest consumer by volume (figure 1). According to the US Geological Survey (USGS), the semiconductor industry consumed 15% of the 335,000 kg of indium produced in 2002, and given the present depressed market conditions for InP-based devices, this could be even less for 2003. However, when the potential of InP-based devices is considered, the use of high-

Indium production by country in 2002

Country	Important indium producers	Refinery production (thousand kg)
Belgium	Umicore	40
Canada	Falconbridge, Cominco	45
China	Huludao, Liuzhou China Tin, Zhuzhou Zinc	85
France	Metaleurop	65
Japan	Nippon Mining, Dowa Mining	60
Peru		5
Russia		15
others		20
total		335

Table 1. The indium production figures for 2003 will look very different as stricter mining regulations in China and a drop in French output begin to make an impact.

purity indium for semiconductors could account for a much larger share of the total consumption in the future. The purity of the indium used in alloys and in thin-film coatings such as indium tin oxide (ITO), which is primarily used in flat-panel display manufacturing, is typically limited to 2N and 4N8, respectively.

Indium production

To date, no "indium mines" have been opened as the relatively low concentrations of indium in the Earth's crust would not guarantee the economic sustainability of such operations. As a result, indium is recovered as a by-product of zinc and lead production in several different countries (table 1).

The landscape of indium production has been shaken up considerably in the last year. The severe 2001 Nandan mining accident in China and the subsequent stricter mining regulations in the indium-rich Chinese provinces of Guangxi and Hunan has caused the supply of indium concentrates to fall. As a result, Chinese production of indium in 2003 will be considerably less than before as, for example, Liuzhou Zinc stops its 20,000 kg per year indium production in the Guangxi province.

In addition to the problems in China, Metaleurop in France decided to stop producing indium in its Noyelles-Godault plant, taking 65,000 kg of indium production capac-

2002 indium market

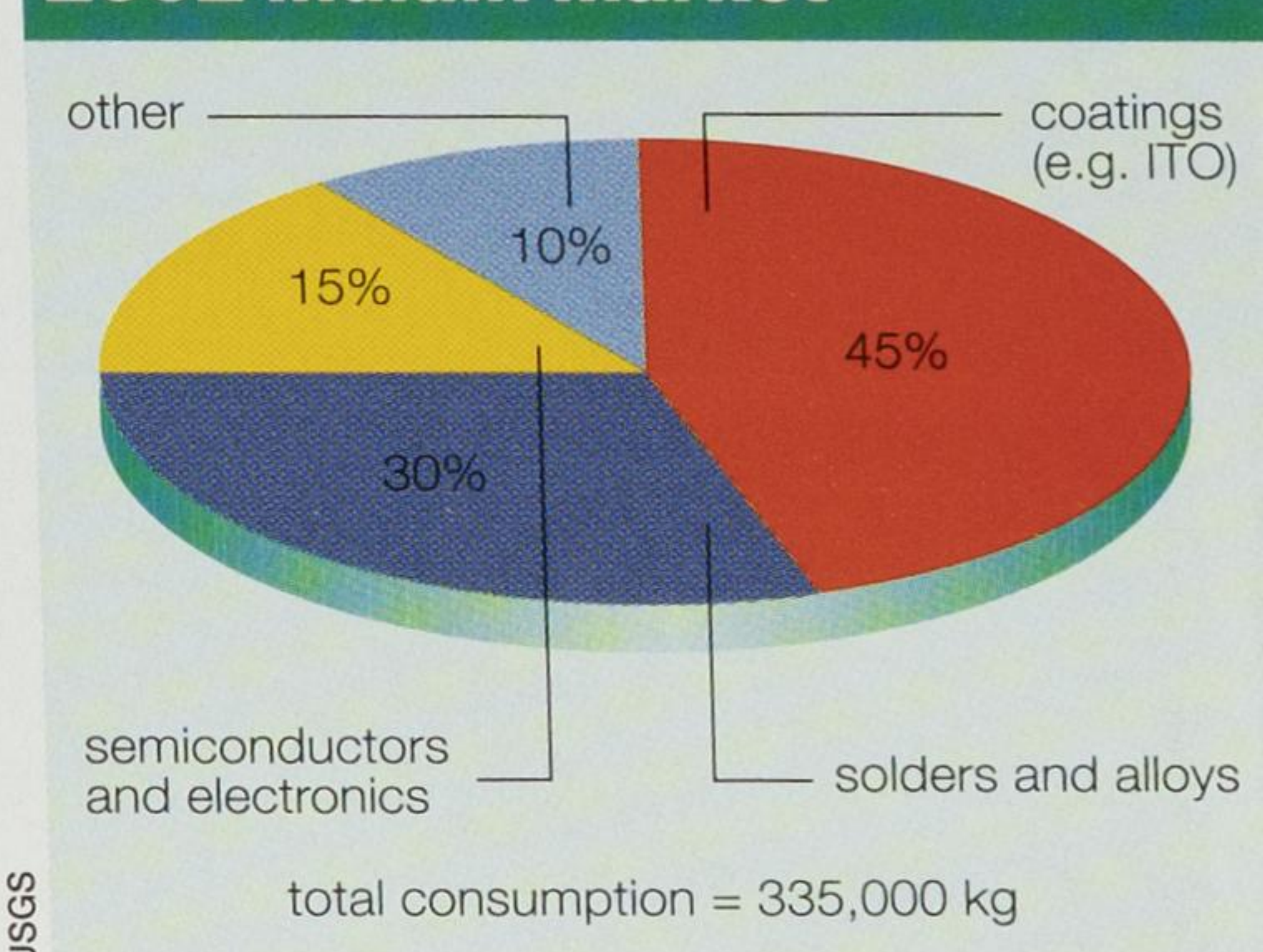


Fig. 1. In 2002, the semiconductor industry accounted for 15% of indium consumption, equivalent to around 50,000 kg.

ity out of the market. Although the USGS figures probably underestimate the Chinese production (more likely figures of 140,000 kg in 2002 and 180,000 kg in 2001 were published in *Platts Commodity News* in June, 2003), the further drop in indium availability in 2003 will be significant.

Because of the still relatively small quantities of indium used in semiconductors at present, producers of virgin indium do not necessarily refine it to semiconductor grade themselves, although some producers such as Umicore and Dowa Mining do so. In order to minimize contamination, Umicore produces

high-purity indium in a dedicated plant, Umicore Indium Products in Providence, RI, where only products such as high-purity indium and ITO are manufactured. The virgin indium is produced at a separate facility in Hoboken, Belgium. Other producers of high-purity indium include Indium Corporation of America in the US, PPM in Germany, MCP Group in the UK, and Rasa and Japan Energy in Japan, with Chinese suppliers possibly entering the market in the near future. If the demand for high-purity indium increases and the shortage of indium raw material persists, fully integrated suppliers will probably have an advantage over those who only buy and purify indium. This situation is already being seen in the market for ITO.

Indium price evolution

From the above it is clear that at present the price of indium in general is a function of two variables: the ITO consumption for displays and the indium production. Due to the recent cuts in indium production and the growth of the displays market, the indium price has risen dramatically over the last 9 months (figure 2).

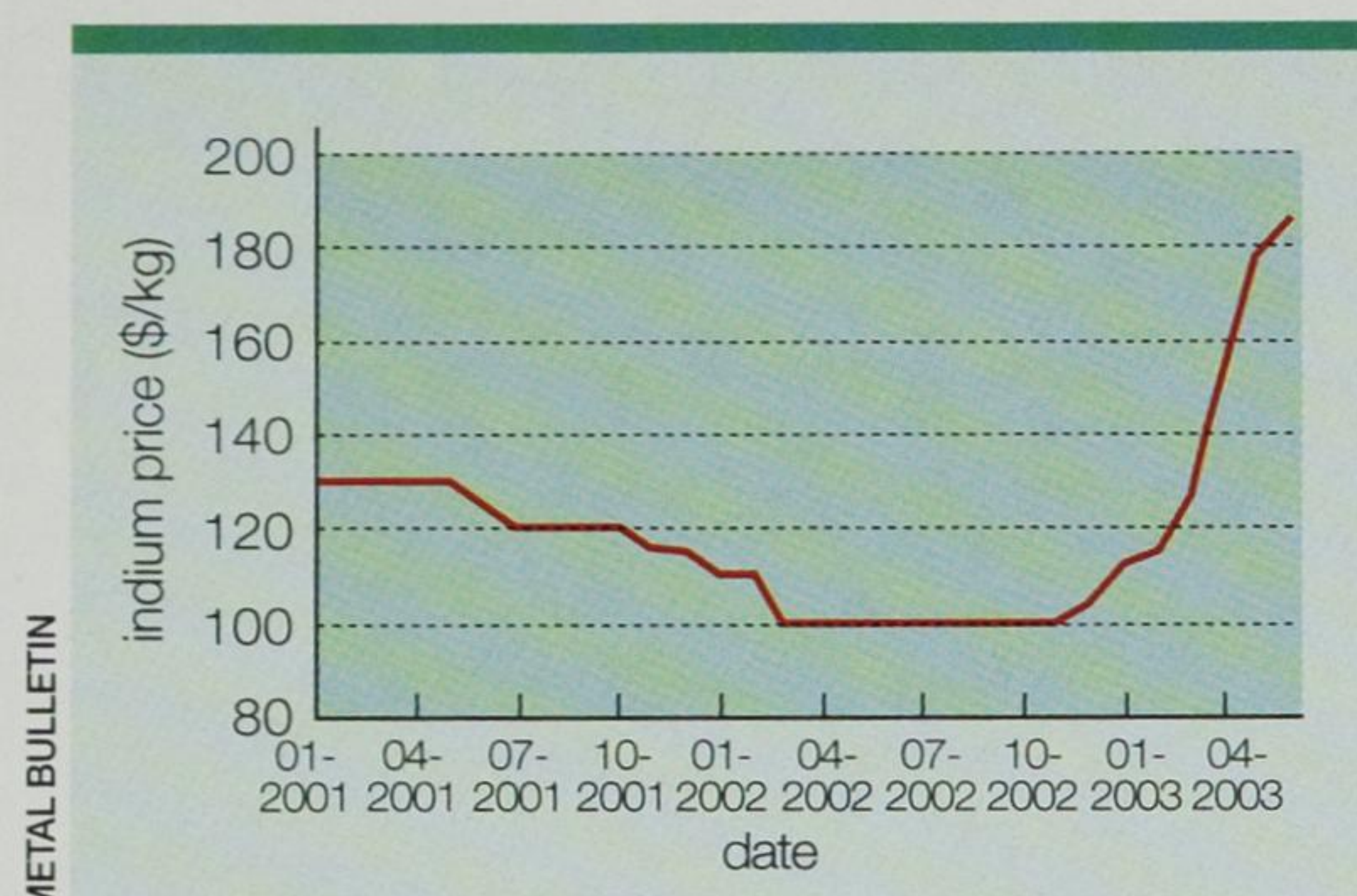


Fig. 2. The price evolution of technical quality (3N7) indium. The price of 6N indium tends to follow the same trend.

The price for 6N indium in large quantities typically follows the same trends as that of technical quality indium as shown in figure 2. For higher purities, the relationship to technical quality material tends to fade because of the high costs involved in employing cutting-edge refining technology and because these materials are often produced according to critical customer specifications.

Due to historically low indium prices, recycling of indium was a non-issue in 2002. Now

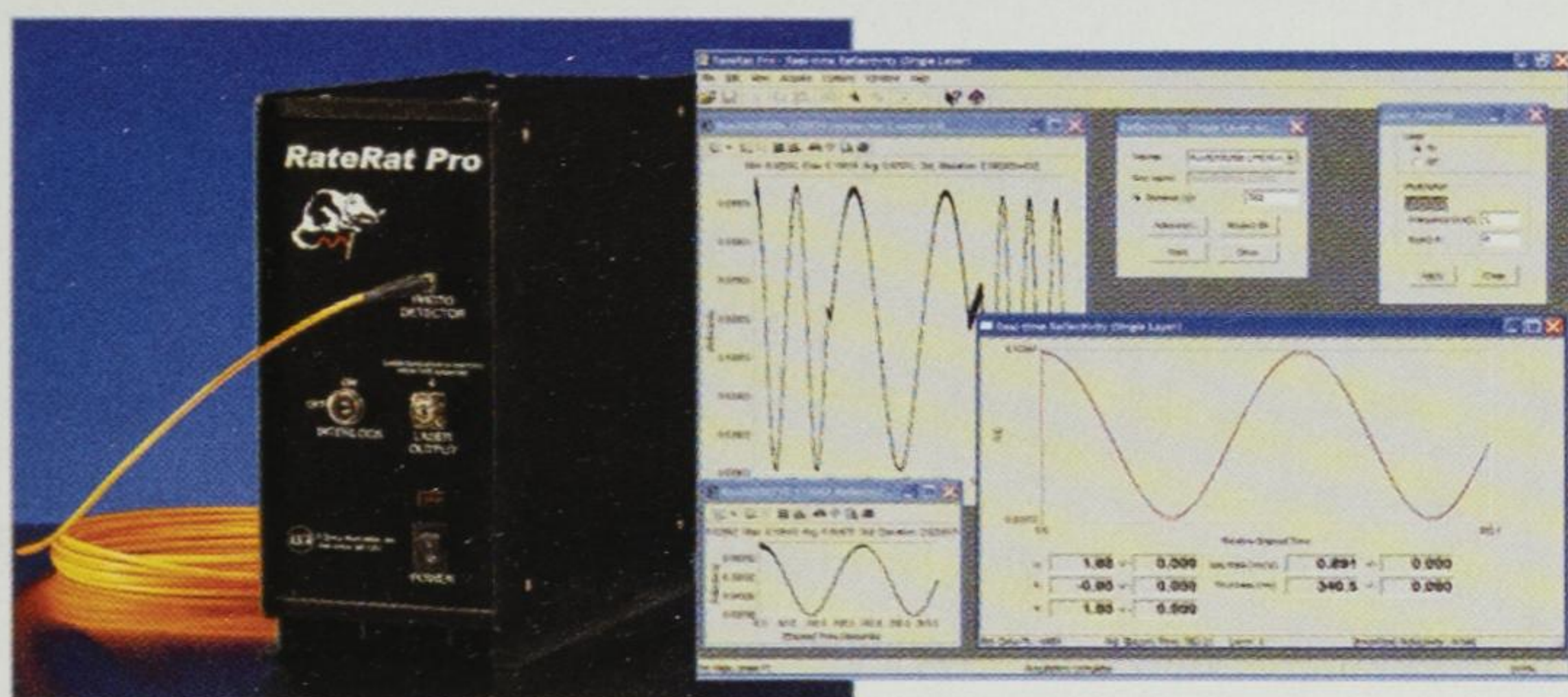
that indium prices have climbed up to the \$200/kg level, recycling starts to become viable again. In some cases, up to 70% of ITO can be recycled, generating a considerable source for secondary indium, attenuating the effect of reduced virgin indium production.

Outlook

Although at present the need for indium in InP production and epitaxial growth is modest, it could account for a considerable share of the indium production in the future. In the short and mid-term, however, no shortages of high-purity indium are foreseen, but the prices will probably continue to increase, following the price of technical quality material. In the long term, and if the consumption of InP-based devices picks up, good control over the entire supply chain will become more critical and may favor the integrated suppliers of indium products as is currently being demonstrated in the ITO market.

Thomas Jansseune is product manager for high-purity indium at Umicore. E-mail thomas.jansseune@umicore.com.

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SAES and Aeronex settle patent row

SAES and Aeronex have agreed to put an end to the recent legal wrangling over their respective technologies for ammonia and hydride gas purification (*Compound Semiconductor* September 2002 p29). According to the settlement agreement, each party will dismiss its respective patent infringement claims, and SAES will also dismiss its false advertising and unfair competition claims against Aeronex.

Mantis Deposition opens for business

A new company dedicated to the provision of accessories for MBE has begun trading in Oxford, UK. Mantis Deposition was set up by Lars Allers, the former director of Oxford Applied Research (OAR), and is supplying nanocluster deposition sources and systems, RF atom and RF ion sources, e-beam evaporators, k-cells and thermal gas crackers. Allers has been joined by former OAR sales staff in the US, Steve Rothstein and Jim Vance.

UK university opens new MBE facility

The UK National Centre for III-V Semiconductor Technologies, based at the University of Sheffield, has established a new MBE facility for optoelectronic device research.

The laboratory features a new multiwafer V90+ MBE reactor from VG Semicon, equipped with *in situ* optical monitoring from LayTec, and new digital acquisition RHEED analysis equipment from JRL. A new X-ray diffraction wafer characterization tool has been purchased from Bede.

The laboratory forms part of a program of enhancement in growth and device processing capabilities following recent record investment from the UK's Engineering and Physical Sciences Research Council.

The new facility will allow the group to build on recent successes in GaAs-based optoelectronics, such as the demonstration of room-temperature CW 1.3 μm quantum dot lasers and 1.55 μm emission from InGaAsN quantum wells.

Equipment sales

● **Arima Optoelectronics** has ordered an **Aixtron** AIX 2600G3 HT system for production of GaN-based LED epiwafers at its plant in Dashi, Taiwan.

● **Lumileds** is to expand the production capacity for its Luxeon LED products through a multiple MOCVD system

purchase agreement with Aixtron. The first system has already been ordered.

● **Riber** has sold a dual-chamber Compact 21 T system to the **University of Karlsruhe** in Germany for the deposition of GaInNAs nanostructures and for research on ZnSe-based materials.

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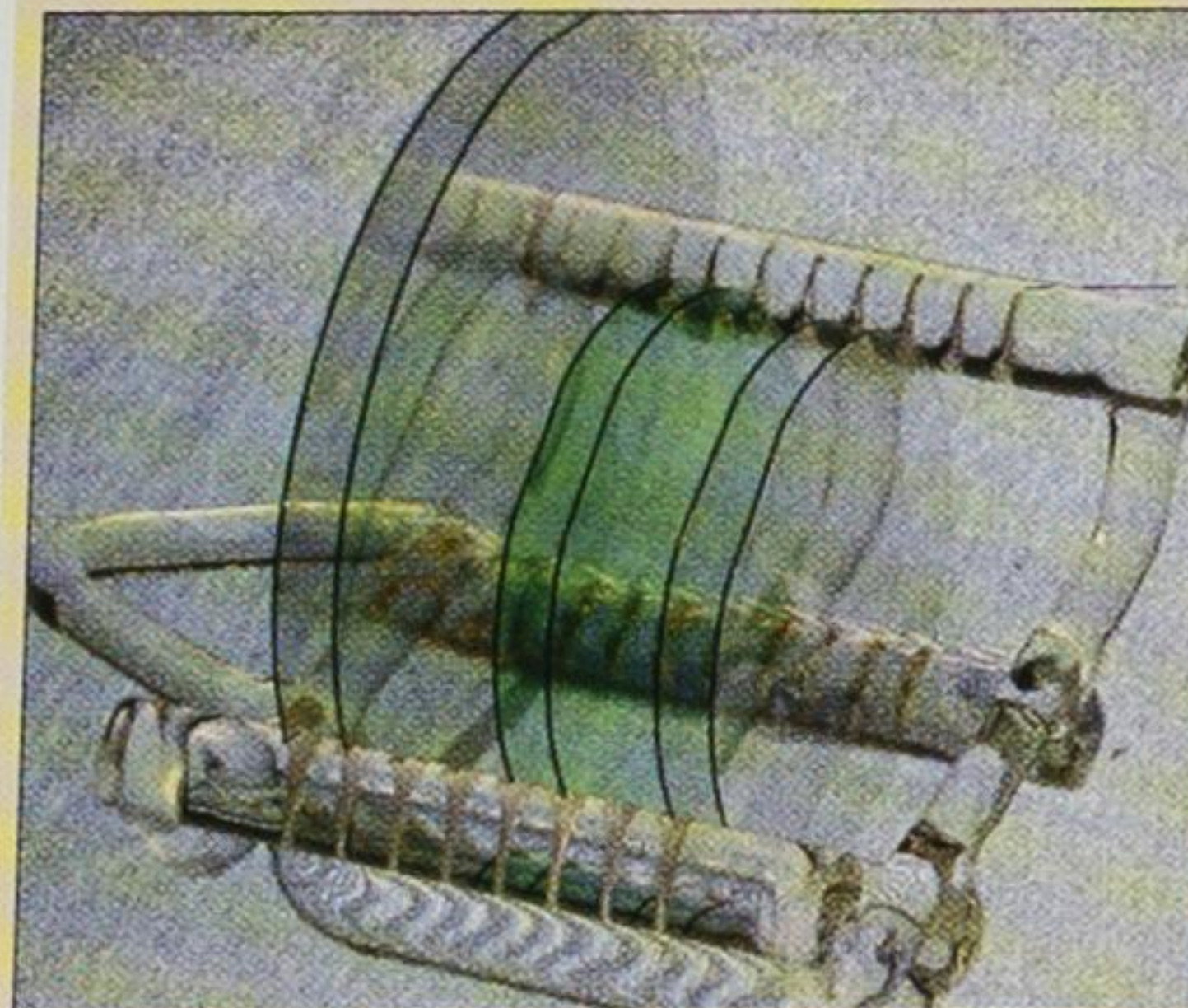
Single-crystal SiC substrates

II-VI, Incorporated

The Wide Bandgap Materials Group of II-VI, Inc currently manufactures and markets high-quality single-crystal SiC substrates for use in the solid-state lighting, wireless infrastructure, RF electronics and power switching industries. Their products include prime grade, semi-insulating and n-type 2" substrates. 3" prime grade semi-insulating substrates are also now available. All substrates come with II-VI's proprietary state-of-the-art CMP

surface polish. The Group has two facilities in Pine Brook, NJ, and Saxonburg, PA.

Contact: Dr Thomas Anderson, II-VI, Inc, Wide Bandgap Materials Group, 20 Chapin Road, PO Box 840, Pine Brook, NJ 07058, USA
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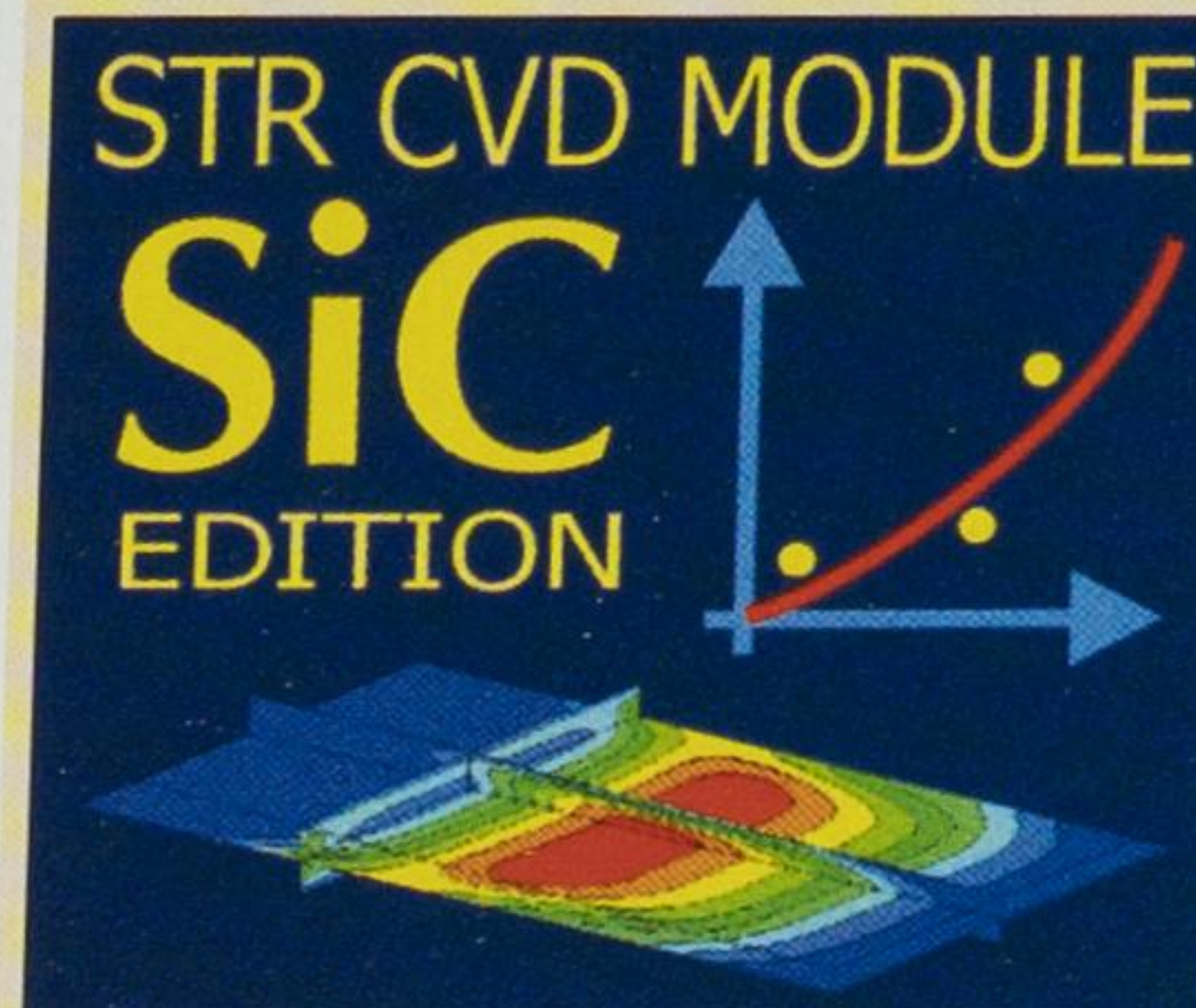
STR CVD Module – SiC Edition

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The SiC edition of the STR CVD module is a tool for modeling chemical vapor deposition of silicon carbide from silane and propane diluted in hydrogen. The growth model implemented in the software describes the basic gas-phase and surface chemical processes including the hydrogen etching effect. Material losses due to nucleation of silicon in the gas phase are also accounted for. The tool works in

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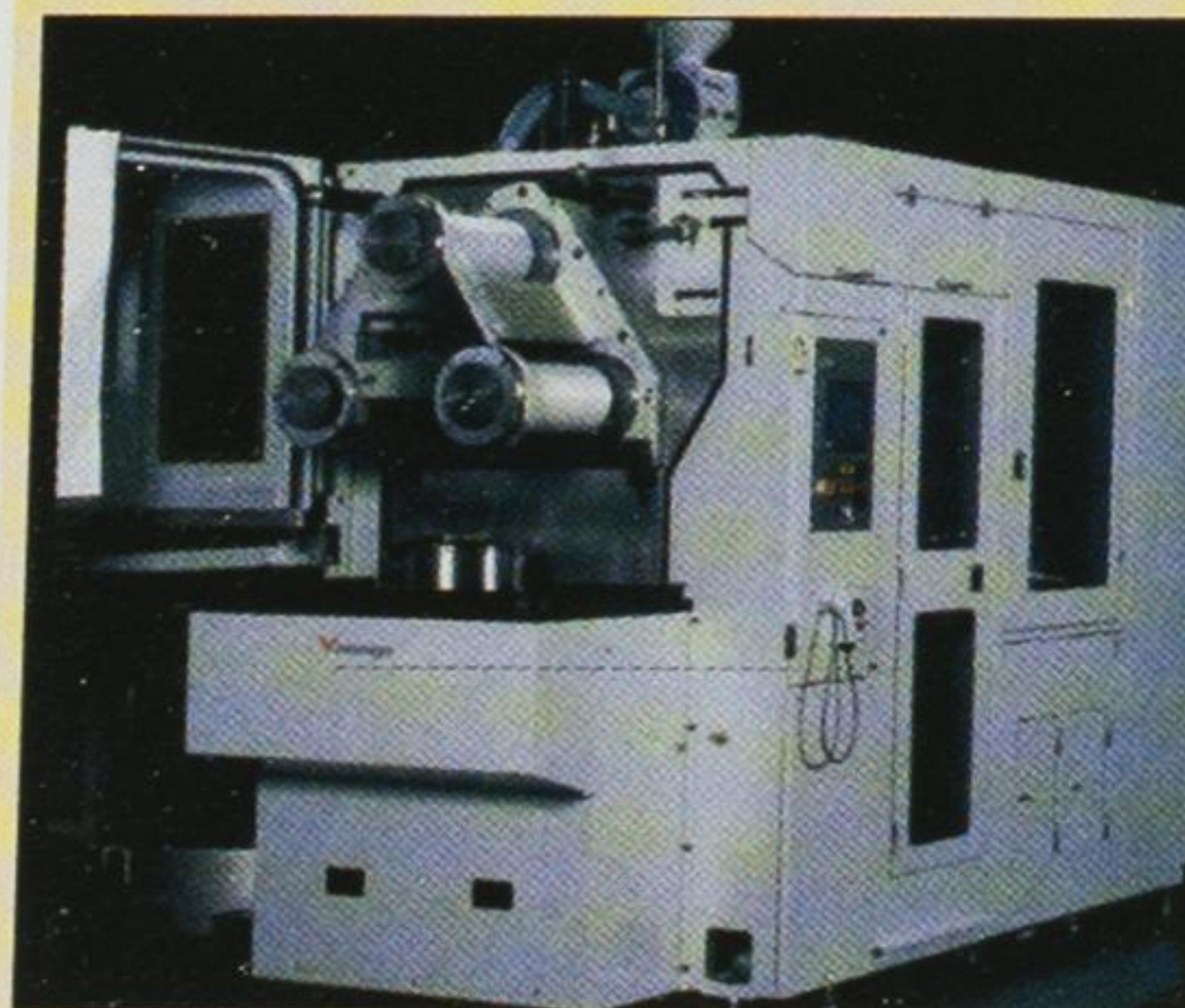
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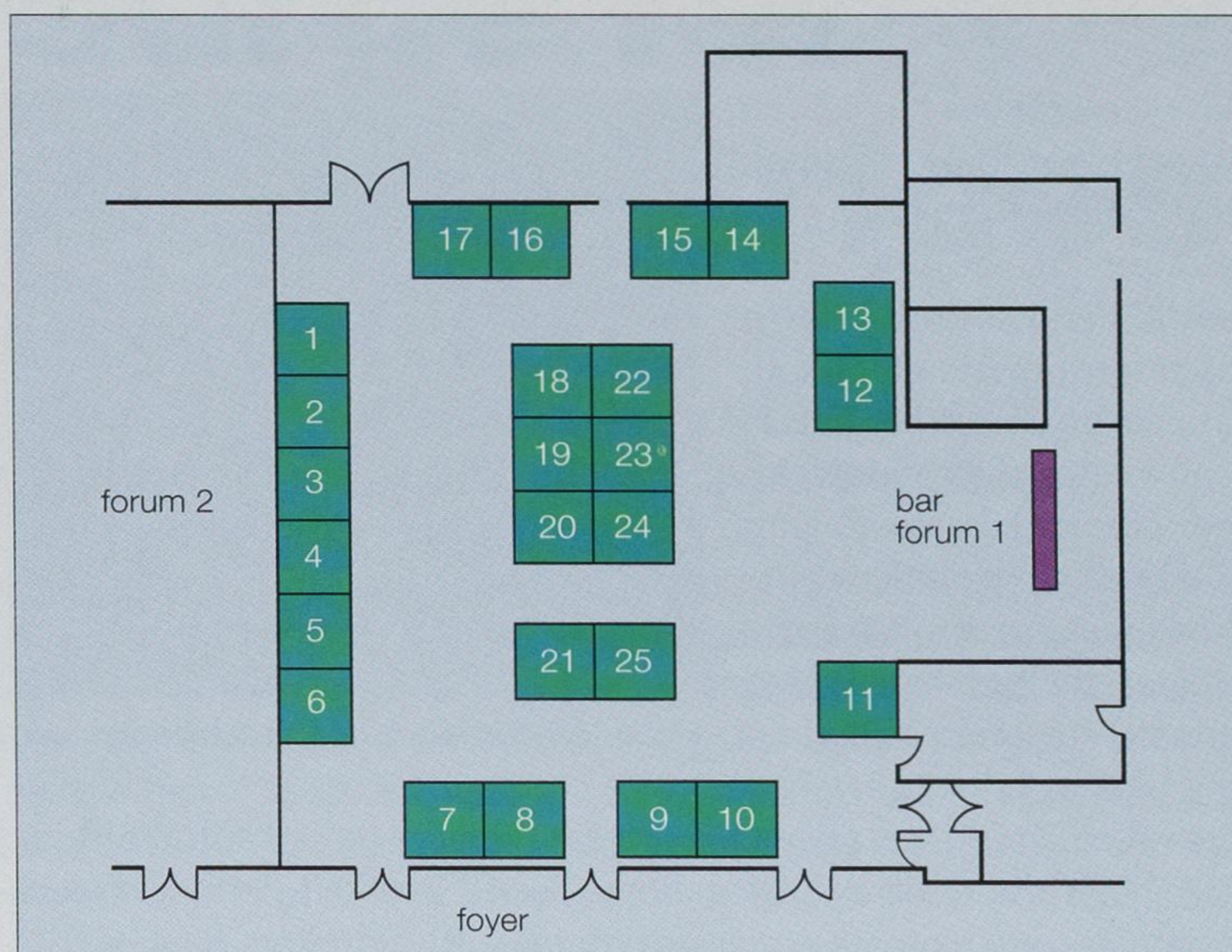
EXHIBITION GUIDE*

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The International Conference on Silicon Carbide and Related Materials (ICSCRM) takes place on October 5–10, 2003 in Lyon, France. Visit <http://icscrm2003.inpg.fr> for more information.

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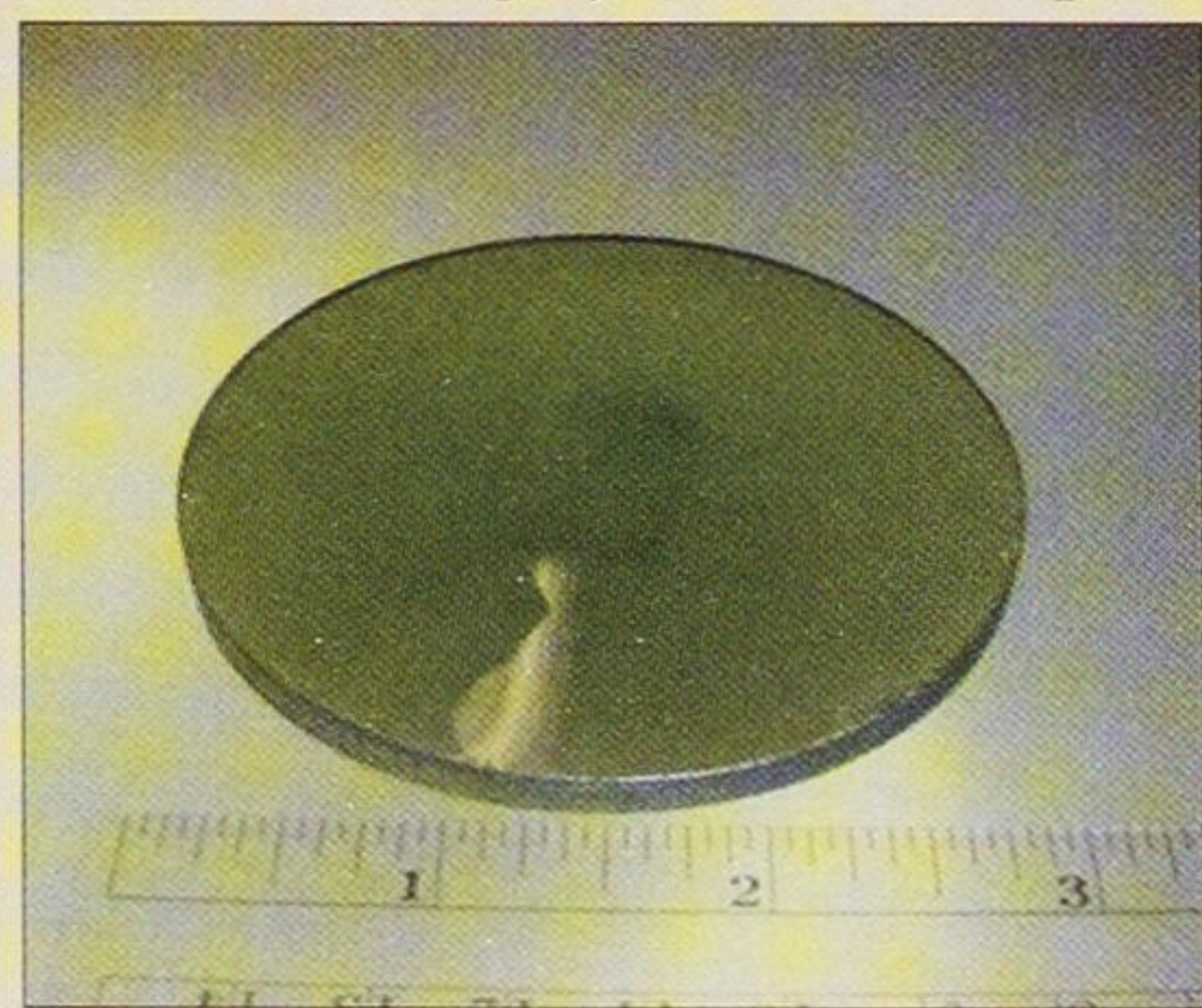
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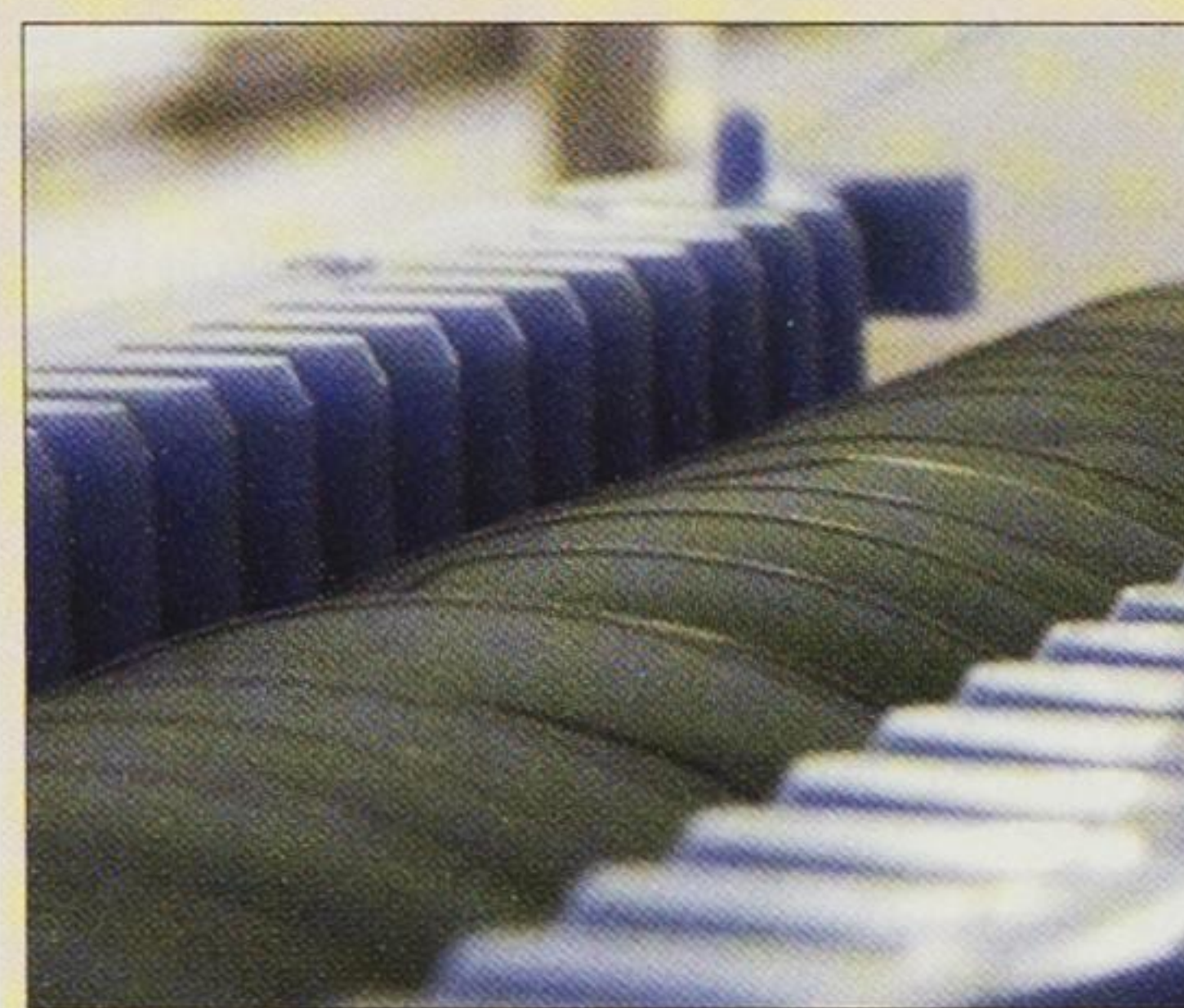
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Si/C ratio and micropipes in 6H-SiC

Great advances have been made recently in reducing the occurrence on SiC substrates of hollow core spiral dislocations, known as micropipes, which can impact on device yield. It is known that micropipes can be covered over during CVD if the growth conditions are correct, leaving a planar surface for device processing. Micropipe closing is thought to occur when

the rate of step-flow growth is greater than the rate of spiral hillock formation around screw dislocations. The C/Si ratio in particular plays a crucial role in closing over micropipes. Researchers from Kyoto University have made the first systematic study of the effect of the C/Si ratio on step-flow growth on 6H-SiC and spiral growth around screw dislocations (*Jap. J. Appl. Phys.* 2003 **42** (Pt. 2 **7B**) L846).

The C/Si ratio was found to strongly affect the shape of spiral hillocks as step-flow growth competed with the generation of steps

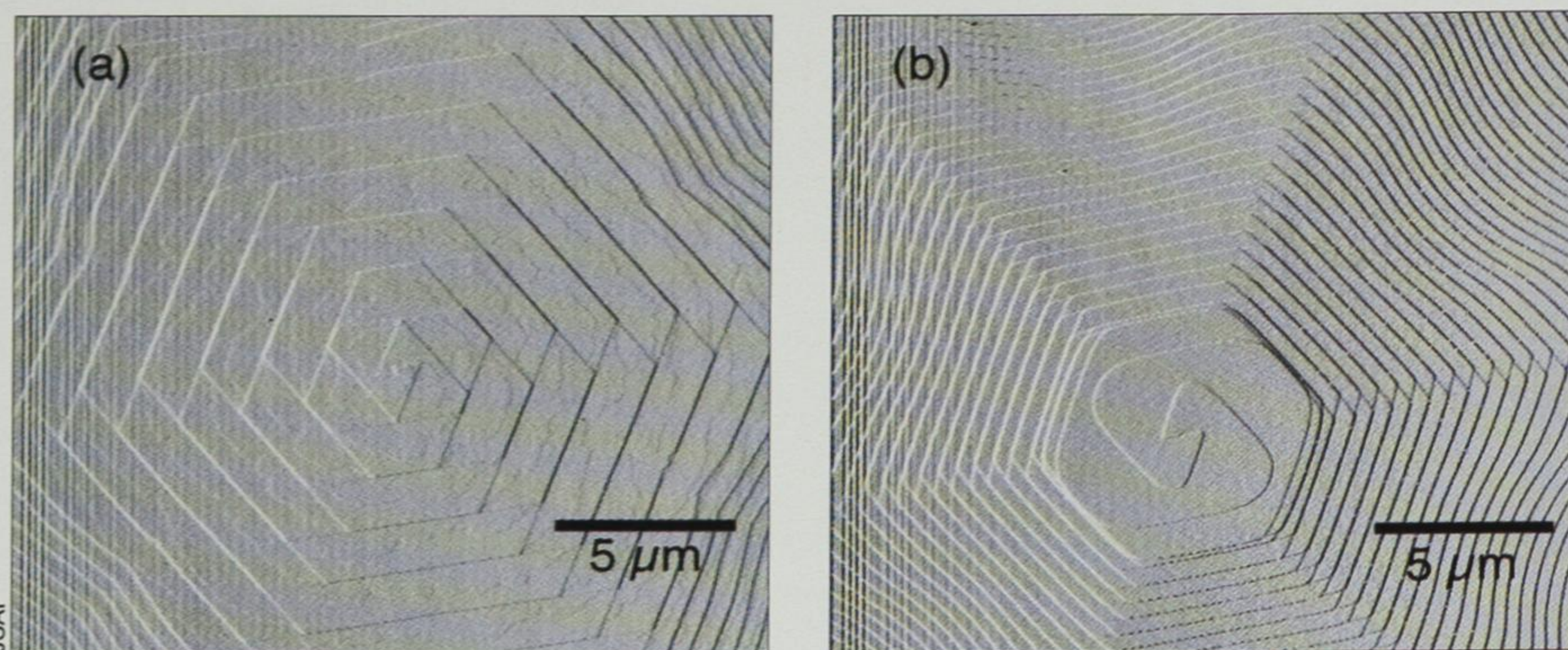


Fig. 1. AFM images of spiral hillocks formed under C/Si ratios of (a) 1 and (b) 4.

by spiral growth around screw dislocations. With a high C/Si ratio the steps formed pillar-like bunches around screw dislocations, while low C/Si ratios produced mounds of interlacing steps with a more gentle gradient around screw dislocations (figure 1).

The authors attributed the difference in the shape of the formations around the screw dislocations to the difference

in the ratio of the generation of steps by spiral growth around the dislocations to the advance rate of steps by normal step-flow growth. A high C/Si ratio enhances the rate of spiral growth, resulting in the more pillar-like formations around the screw dislocations. A low C/Si ratio promotes step-flow growth, which hinders the formation of spiral pillars, producing broader spiral hillocks around screw dislocations. These observations lend weight to previous observations that micropipe closing can be enhanced with low C/Si ratios during CVD.

First 10 kV 4H-SiC Schottky diodes demonstrated

The blocking voltage of SiC Schottky diodes has risen steadily since the first 1000 V devices were reported in 1994 using a 10 μm drift layer of nitrogen-doped 6H-SiC and Pd as the contact metal. Since then 4H-SiC has become available with higher electron mobility than 6H material, and the use of Ni and Pt as higher barrier contacts has helped to increase the achievable blocking voltages. A joint effort by Rutgers University and United Silicon Carbide, NY, has resulted in the first 4H-SiC Schottky diode using Ni contacts to pass the 10 kV mark (*Elec. Dev. Lett.* 2003 **24**(6) 396).

The SiC wafer, supplied by Cree, consisted of a thick 115 μm n-type drift layer, followed by a 0.4 μm n-type buffer and a 0.8 μm p-type

layer. Ni was used as the ohmic contact (cathode) on the substrate side and also as the topside Schottky metal. The Schottky contact was circular with a 300 μm diameter.

The device was tested at the chip level and conducted an anode current density (J) of 20 A/cm² at a forward voltage of 3.15 V. The turn-on voltage was determined to be 1.2 V from extrapolation of the J-V plot. At forward voltages of 11.75 and 17.6 V, the current densities were 100 and 140 A/cm².

In blocking mode, the device showed sub-nA currents corresponding to a leakage current density of 1.4×10^{-6} A/cm² for voltages up to 3400 V. At 10 kV the leakage current was 10^{-5} A (1.4×10^{-2} A/cm²).

Characteristics of SiC MOSFETs on cubic 3C-SiC

MOSFETs fabricated using 3C-SiC as opposed to the more common 4H and 6H-SiC have attracted interest because of their potential for producing devices with higher channel mobilities and higher breakdown voltages. The 3C-SiC devices reported to date have mostly been processed on material deposited on a silicon substrate. Such devices have suffered from high leakage currents, probably as a result of poor crystalline quality, and researchers have been hampered by the limited range of temperatures available during processing because of silicon's low melting point relative to SiC. The recent availability of freestanding 3C-SiC substrates means that high-quality thick SiC epilayers can now be grown and the full potential of 3C-SiC devices explored (*Compound Semiconductor* June 2003 p9).

Researchers at the Atomic Energy Research Institute in Japan have studied the characteristics of 3C-SiC MOSFETs fabricated on free-standing (001) 3C-SiC wafers supplied by Hoya Advanced Semiconductor Technologies (*Jpn. J. Appl. Phys.* 2003 **Pt. 2**(6B) L625). The

devices consisted of an epitaxially grown 5 μm thick SiC layer and a 27 nm gate oxide. No post-oxidation oxide annealing, which has been observed to increase channel mobility in 4H- and 6H-SiC devices, was performed on reported devices. Curiously, although the devices were designed as enhancement mode FETs, at a V_{ds} of 10 V the gate threshold voltage was -5 V. Negative threshold voltages have not been observed in similar devices made using 6H-SiC. The leakage current at a V_g of -2 V was about 10^{-8} A, comparable to 6H-SiC devices, but two orders of magnitude lower than previously reported 3C devices. Channel mobility of up to 260 cm²/Vs was observed, another record for 3C-SiC devices. The gate oxide showed a rapid increase in leakage current at an electric field of 8.5 MV/cm, similar to the values reported for 4H- and 6H-SiC, and twice those seen previously in 3C-SiC. As the breakdown electric field is a function of SiC surface defects, the authors attribute the performance of their devices to the high quality of the epitaxial 3C-SiC.

Summertime surge for revenues and stock prices

Recent upbeat forecasts for the silicon-dominated semiconductor industry have had a positive effect on compound semiconductor companies, and hopefully point to a sustainable recovery.



The flurry of June quarter earnings announcements is now behind us, with most of the companies in the portfolio having reported and justified their results, both good and bad, to investors. A quick glance at the new-look table shows that the June quarter revenue figures generally exceeded those of the March quarter. Most companies have also seen their share prices rise steadily since late May, partly because they are tracking the recent upward trend in the global

equity markets, and partly due to a number of positive forecasts for the semiconductor industry as a whole.

One set of results that generated much discussion came from epiwafer supplier IQE. Its revenue showed a 3% increase to £5.1 m (\$8.1 m) and its operating loss for the June quarter, before exceptional items, improved to £2.9 m compared with £3.4 m in the March quarter and £19.9 m in the year-ago period. It was not the actual figures that generated the interest, but comments from the company that accompanied them. These seemed to indicate that IQE was seeing the end of its decline and was now looking towards a period of steady revenue growth. The company said that it had seen a rise in the number of customers sampling new products and that it anticipates that this will begin to add to sales in the December quarter as those products become qualified for customers' production processes. This prompted a buying spree in IQE's stock that saw it rise by about 20% to £0.13 on the day of the results announcement, with it climbing steadily to stand at £0.20 on August 29.

Although the company is well advanced with its project to radically cut costs and reshape its business, profitability will be some way off if its quarterly revenue growth does not accelerate considerably past the 3% mark. By IQE's own admission visibility may be improving, but it is still not good, and while having more products in qualification with customers is encouraging, turning those into regular orders is not a fast process.

Another epiwafer vendor that has seen its losses fall recently is Kopin. It reported a revenue rise of \$1.9 m to \$19.9 m for the June quarter, driven by its improving LCD display business. A little help came from its ramping production of CyberLite blue LEDs, the revenue from which exceeded \$2 m. Sales of Kopin's HBT epiwafers suffered from a build-up of finished goods inventory in Asia which reduced demand from chip-makers, resulting in a 9% fall in quarterly HBT revenue to \$8.7 m.

Equipment vendors see orders grow

Semiconductor equipment manufacturers were another interesting group releasing results for the June quarter. Trikon reported its highest quarterly order levels since 2000 for its etching and deposition tools. New orders totaled \$11.4 m, giving it a book-to-bill ratio of 1.9:1. The company's revenues for the June quarter were

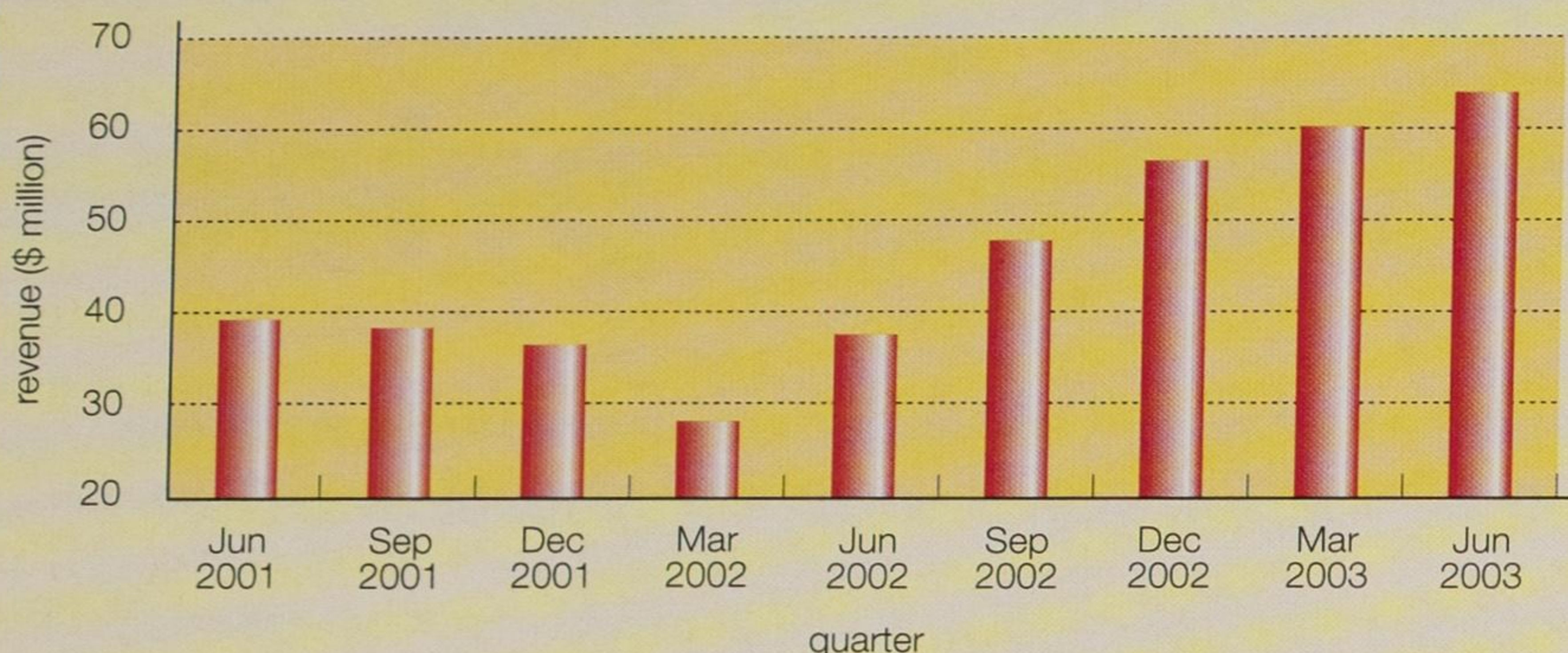
Market overview

Company	Symbol	Closing price on Aug 29	% change since May 23	June quarter revenue (\$m)	% change over March quarter revenue
GaAs IC companies					
Anadigics	ANAD	4.98	74.1	18.0	11.8
Celeritek	CLTK	7.77	-2.6	6.6	-18.5
Endwave	ENWV	4.45	140.5	8.5	10.4
RF Micro Devices	RFMD	8.83	73.1	131.5	-4.9
Sirenza Microdevices	SMDI	4.47	179.4	9.1	56.9
Skyworks Solutions	SWKS	11.36	64.9	150.2	-4.6
TriQuint	TQNT	5.52	38.7	72.8	1.5
Vitesse	VTSS	6.82	53.6	35.2	-12.9
Opto companies					
Agilent	A	24.32	49.6	1502.0*	3.9
Cree	CREE	15.82	-24.8	60.2	6.2
JDS Uniphase	JDSU	3.45	8.8	165.7	5.8
Semiconductor materials and equipment companies					
ATMI	ATMI	27.95	36.5	57.5	6.9
AXT	AXTI	2.68	104.6	8.5	-32.7
Emcore	EMKR	2.93	27.4	32.2	16.2
Kopin	KOPN	8.71	72.1	19.9	10.6
Tegal	TGAL	1.06	71.0	3.9	-2.5
Trikon	TRKN	6.29	87.2	6.0	17.6
Veeco	VECO	21.35	18.2	73.4	11.6
European companies (share prices and revenues in €)					
Aixtron	AIXG.F	4.99	76.3	22.3	19.3
Bede	BED.L	0.41	141.2	x	x
Bookham	BHM.L	1.13	13.0	30.2	0.0
IQE	IQE.L	0.29	314.3	7.3	4.1
Riber	RIBE.LN	1.21	42.4	2.6	13.0
Soitec	SOIT.LN	5.75	13.0	19.4	-27.6
STS	SRTS.L	0.16	33.3	x	x
Unaxis	UNAXZN.VX	144	101.4	x	x

*Quarter ended July 31

x figures not available

Cree's rising revenue



The biggest GaAs IC companies, RF Micro Devices and Skyworks, both reported revenues declining by a little under 5% to \$131.5 m and \$150.2 m, respectively.

\$6.0 m, an increase of 18% sequentially, but a decrease of 29% on the year-ago quarter. Operating loss was \$8.5 m, compared with \$4.4 m for the second quarter of 2002, and included one-time items of about \$4 m. The news resulted in Trikon's share price, which had been rising steadily for some weeks, taking a sudden jump from \$4.70 to \$5.15 before settling again. However, in late August the stock price crested \$5 once again on a wave of optimism over the prospects for the semiconductor industry, and continued rising to close at \$6.29 before the Labor Day weekend.

Other equipment companies with a stock price riding the upsurge in enthusiasm for "chip stocks" included X-ray diffractometer manufacturer Bede. Bede has yet to comment on its June quarter financial performance, but has reported a number of orders for its new line of diffractometers aimed at metrology in high-throughput silicon fabs. These tools are used to characterize the new materials, such as SiGe, strained Si and high-k dielectrics, which are finding their way into mainstream silicon processing. The company has also invested heavily to make its tools more applicable to other industries such as pharmaceutical manufacturing, reducing its exposure to the often crippling cycles of the semiconductor business.

Riber, the French manufacturer of MBE systems reported a slight revenue increase to €2.6 m in the June quarter, compared with €2.3 m in the March quarter. This brought sales for the first half of 2003, which included six Compact 21 research reactors, to €4.9 m, 64% down on the year-ago period. Its order book for 2003 stands at about €14.4 m, and includes two more Compact 21 and one MBE49 production reactor ordered in July. However, as if to underline the continued uncertainty in this business, Riber noted that it had seen the withdrawal of an order for a production reactor earlier this year, unwelcome news for a business selling low volumes of high-value products.

Hardly a week goes by without Aixtron announcing another order for an MOCVD tool, mostly for LED manufacturing in Asia. However, its trading situation is very different to the one it had a couple of years ago, when another order barely warranted a mention. Its June quar-

ter revenues were €22.3 m, €3.6 m higher sequentially, but for the half year ending June 30, Aixtron reported revenues of €41 m, half the level for the same period in 2002. The company now expects revenue for the year ending December 31 to be €90–95 m compared with €150.7 m in 2002. Like Bede, Aixtron is also branching out, applying its expertise developed for compound semiconductors to the new materials being introduced for future generations of CMOS devices.

Revenue growth slows at Cree

It's been a pleasure to watch Cree turning out results each quarter that beat the previous quarter's figures and take its earnings record to a new level. The June quarter results continued this trend, but the figures did not meet with universal approval from Cree-watchers on Wall Street. The revenue of \$64 m was a \$3.9 m rise on the March quarter and a 69% increase over the year-ago period. However, this represents a continuing deceleration in earnings growth and was below the expectations of some. The June quarter is also the end of Cree's fiscal year and it recorded revenue of \$229.8 m, an increase of 48% on the previous fiscal year's figure. The company has consistently made a profit this year with net income for FY2003 of \$34.9 m, compared with a net loss of \$101.7 m in FY2002. Cree is one of the few companies in the table to show a drop in share price since May 23. This fall began in early June when the various lawsuits that it is now disputing were announced, and continued as the results were revealed, at one point taking the share price below \$12.

Popularity of GaAs IC companies soars

As a group, the GaAs IC companies are currently the stars of the portfolio where share price is concerned. All except Celeritek have shown impressive rises with Sirenza leaping by nearly 180% over three months. However, the group's share price performance is not matched by its revenue growth, with half of the companies showing sequential declines in the June quarter. Sirenza showed the largest revenue increase, rising 57% to \$9.1 m, as revenues flowed in from its Vari-L acquisition, which was completed in May. Endwave's share price took a leap when it raised revenue guidance for the June quarter from \$6.5–7.5 m to \$8.2–8.5 m. A couple of weeks later it duly delivered a revenue figure of \$8.5 m compared with \$7.7 m in the March quarter.

The biggest GaAs IC companies, RF Micro Devices and Skyworks, both reported revenues declining by a little under 5% to \$131.5 m and \$150.2 m, respectively. RFMD's revenue represented an increase of 25% on the year ago period, but it still lost \$8.1 m compared with a profit of \$2.3 m in the June 2002 quarter. The SARS outbreak and the build-up and subsequent correction to wireless handset inventories in Asia were partly to blame for the figures. RFMD's guidance for the September quarter was for a similar revenue and loss to the June figures.

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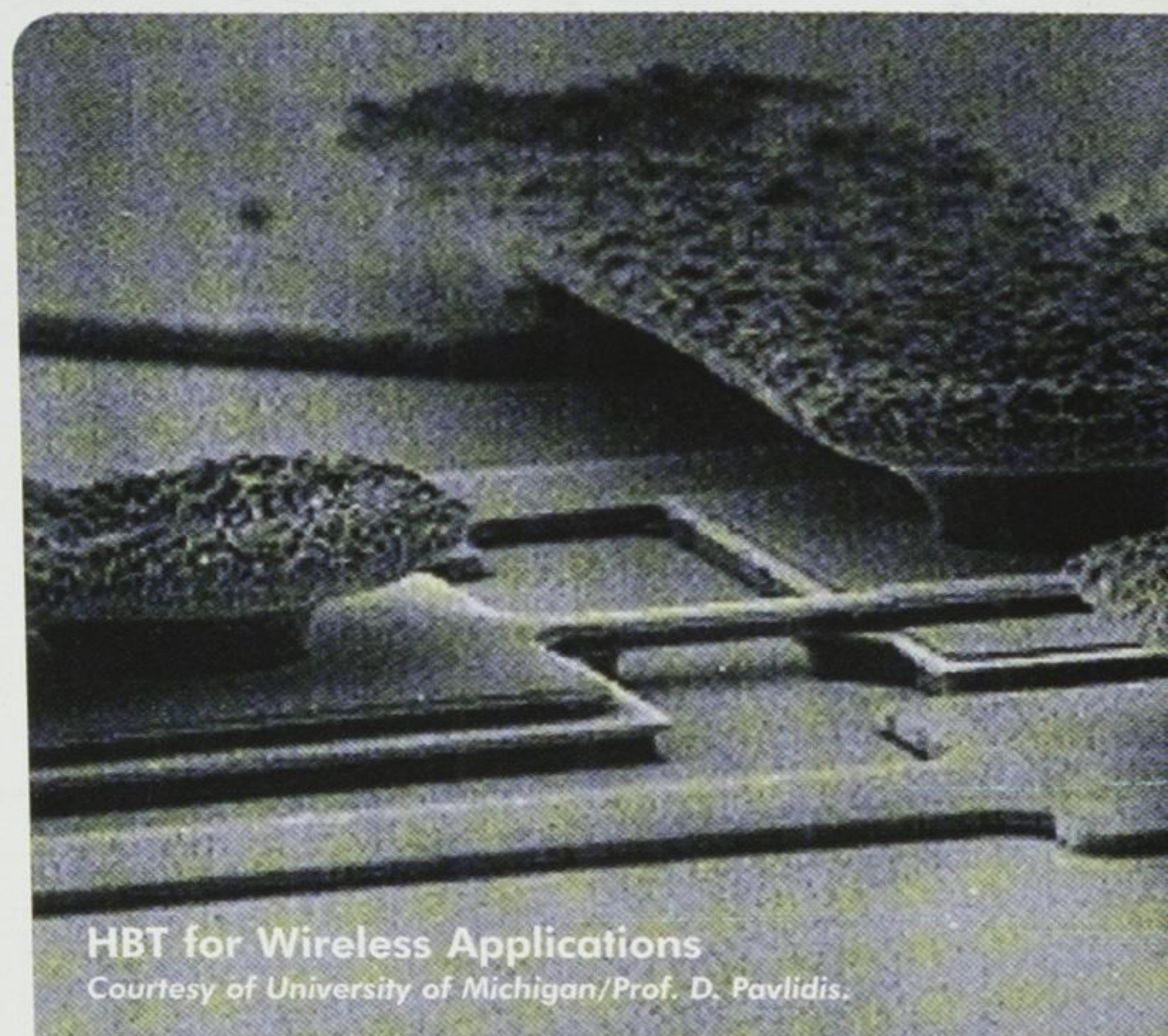
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