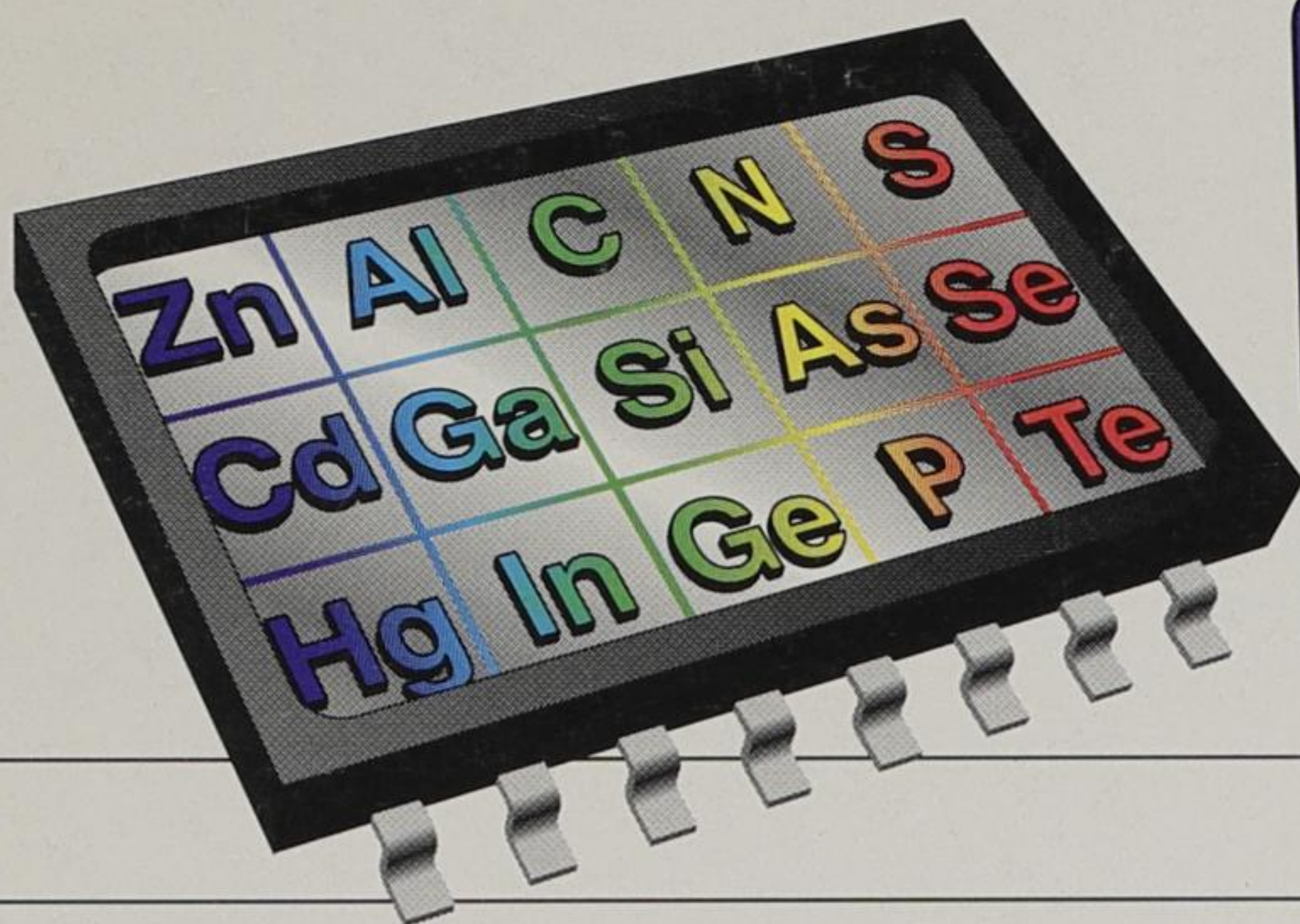




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March 2000

Volume 6 Number 2

LEDs

- Strategies in Light conference
- Toyoda Gosei profile
- Proposed LED lighting program
- Engineering with LEDs

Building a bridge to
21st century lighting

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Siemens on mm-wave modules...ONR's Roadmap...

Samsung on SOAs...Discovery's high-speed detectors...and more.



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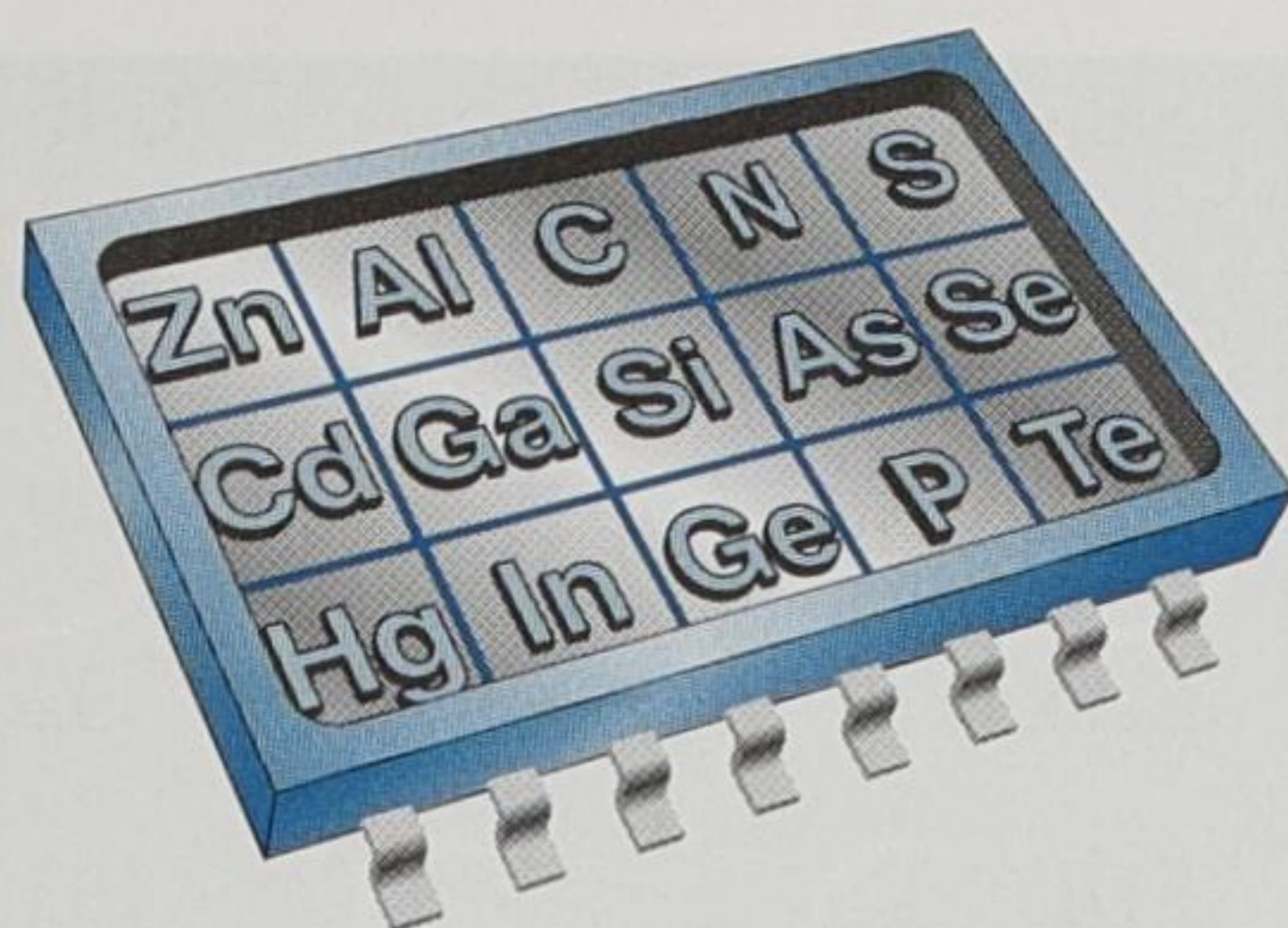
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COVER STORY – LEDs

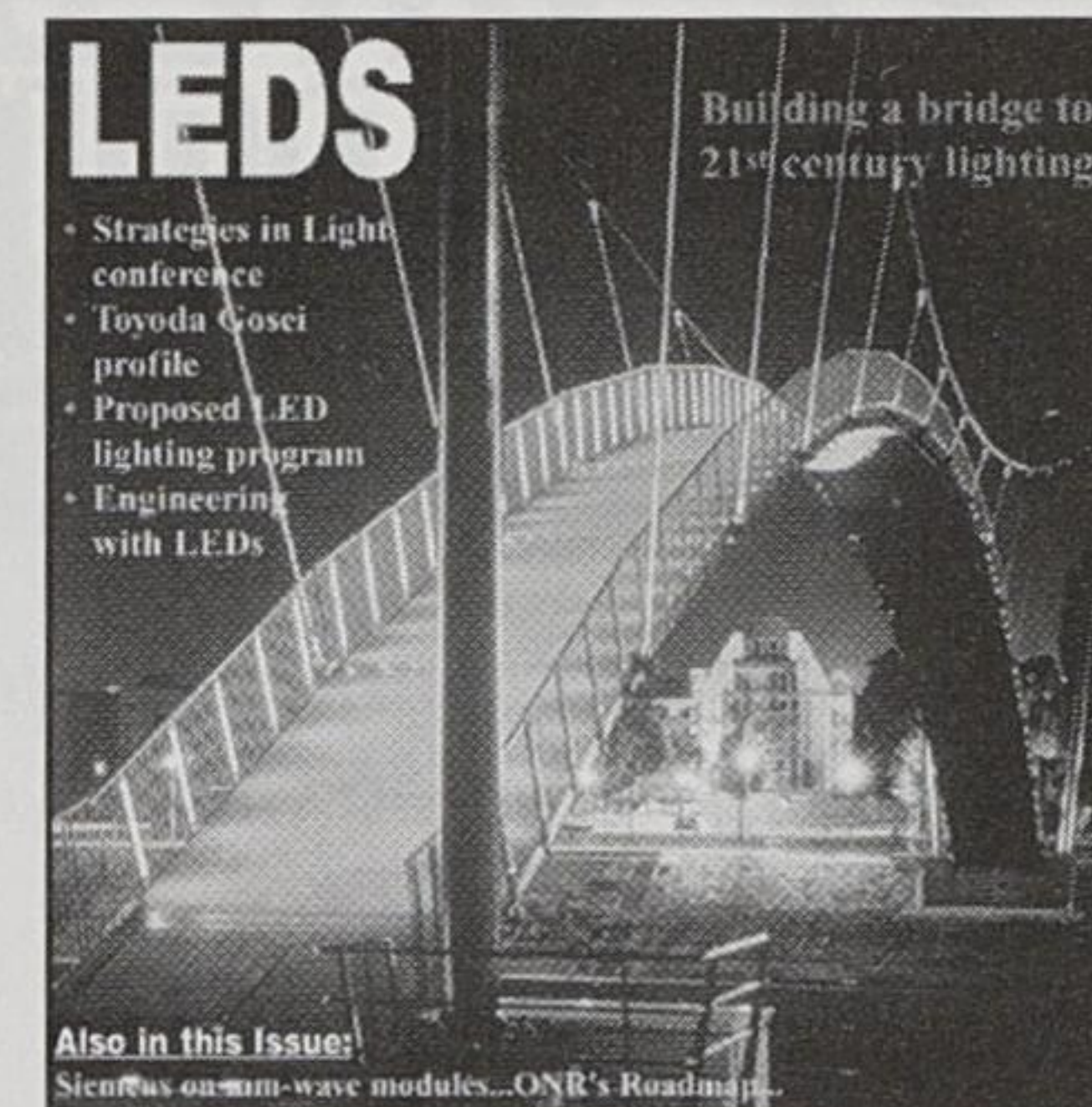
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The availability of high brightness LEDs is opening up a wide range of applications in automobiles, architecture, displays and signs, and general illumination. In this example, vertical strips of white LEDs have been used to illuminate this footbridge in Duisburg, Germany. Our coverage of this area begins on page 26.

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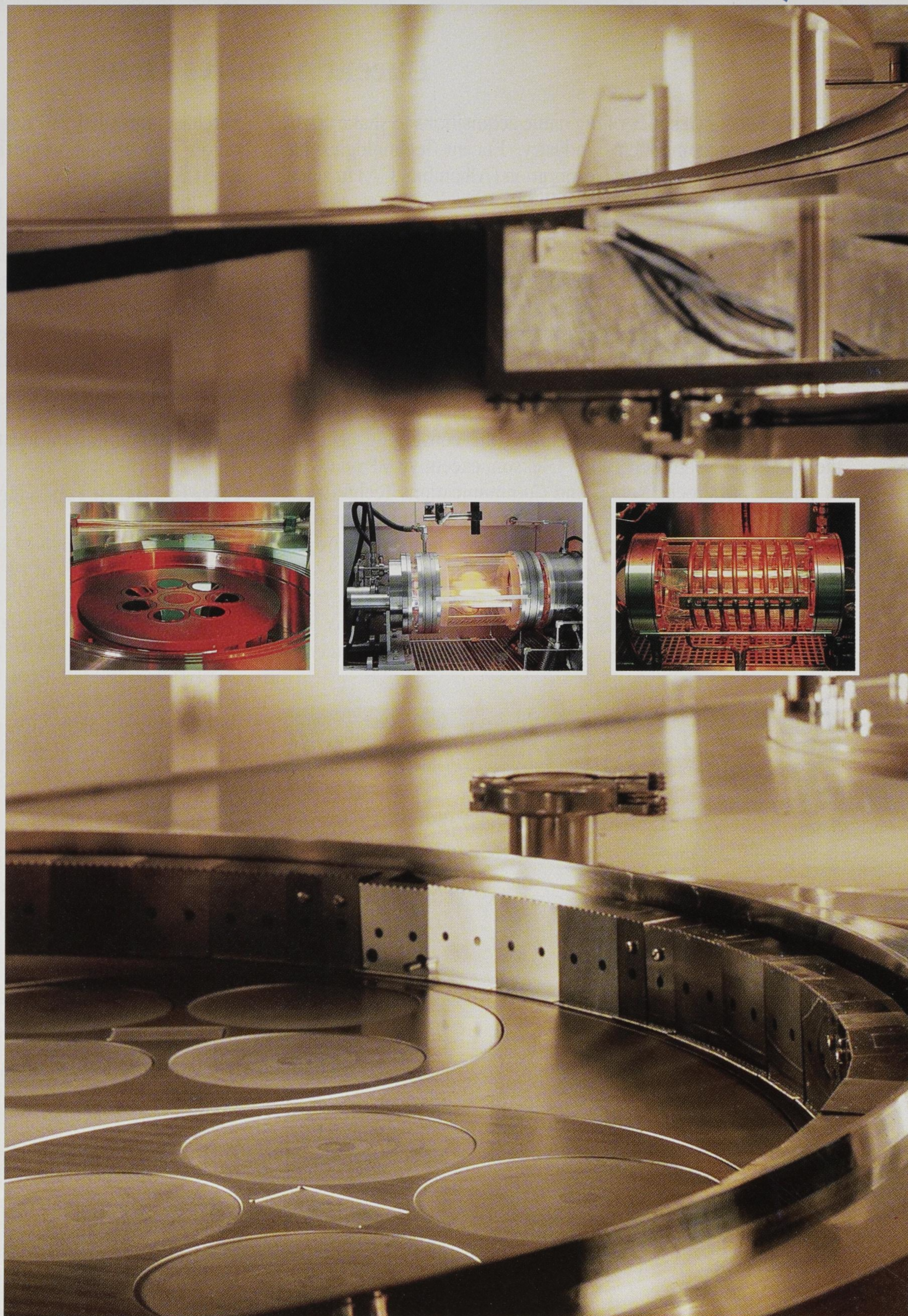
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Lucent Acquires Ortel

In the latest in a series of big name acquisitions to shake up the fiber-optic components industry, Lucent Technologies has agreed to acquire Ortel Corporation (Alhambra, CA) in a deal valued at approximately \$2.95 billion.

Ortel is a leading developer of optoelectronic components for cable TV (CATV) systems, and is a supplier to General Instrument, Antec and other major CATV manufacturers. Ortel's technology enables CATV system suppliers to build high-capacity networks to meet the increasing demand for next-generation services to the home, such as Internet telephony and access.

"This acquisition marries our leadership optoelectronics for communications with Ortel's expertise in optoelectronics for cable TV, and positions us to support the converging needs of these markets," comments John Dickson, executive VP and CEO of Lucent's Microelectronics and Communications Technologies unit. "We expect the injection of Ortel's wealth of talent and technology to further fuel the momentum of our fast-growing optoelectronics business."

Ortel also augments Lucent's programs for 10 Gb/s transmitter/receiver components for optical communications networks. In our last issue, we reported that Lucent had agreed to

purchase uncooled 980 nm pump lasers from Ortel for incorporation into optical amplifiers for metro fiber-optic networks [see CS 6(1), p. 9].

"In addition to its rich product portfolio, Lucent provides us with access to its leading edge technologies, including its industry-leading automated packaging processes," says Stephen Rizzone, Ortel's president and CEO. "The significant increase in output we can achieve by employing such a process can help us more readily meet the increasing demand for our products." Lucent expects the acquisition to be completed during the quarter ending June 30, 2000. Ortel will become part of Lucent's optoelectronics component division, and its 550 employees will remain at their current locations.

Ortel Sells 10 Gb/s Receivers to Kestrel Solutions

Ortel has announced a multi-million dollar agreement for immediate shipment of its 10 Gb/s receiver product to Kestrel Solutions of Mountain View, CA, for integration into Kestrel's Optical Frequency Division Multiplexing (Optical FDM) backbone technology for metro networks.

Ortel's 2860 family of 10 Gb/s optical receivers incorporates a high-speed planar PIN diode and transimpedance amplifier to deliver exceptionally high performance for a wide range of 10 Gb/s applications, including short, intermediate and long haul systems, DWDM systems, SONET/SDH equipment and datacom equipment.

"Kestrel selected Ortel because of their proven ability to immediately deliver the gain, sensitivity and noise performance that we demand for our optical FDM metro solutions," says Dawn Hogh, Kestrel's VP of marketing.

Lucent Quadruples Component Output

In related news, Lucent's Microelectronics Group has announced that the \$30 million expansion of its optoelectronics components operations will lead to a quadrupling of its output in 2000 [see CS 5(7), p. 6]. In addition, Lucent says it will invest approximately \$1 billion in optoelectronics R&D over the next 3 years. The expansion includes a new 143,000 sq. ft. (12,900 m²) optoelectronics facility at Lucent's 200-acre site in Breinigsville, Pennsylvania, as well as a \$6 million renovation of its nearby Reading facility. This is being driven by the growing market demand for components used in high-speed optical communications networks, says Lucent, which revealed that its optoelectronics business grew 83% in 1999.

"Our expansion program will dramatically boost our ability to meet the increasing demand for optical networking components," said Dan DiLeo, president of the optoelectronics division of Lucent's Microelectronics Group. "Coupled with our industry-leading automated processes, this expansion will better position us to meet our customer's needs in a capacity-constrained market."



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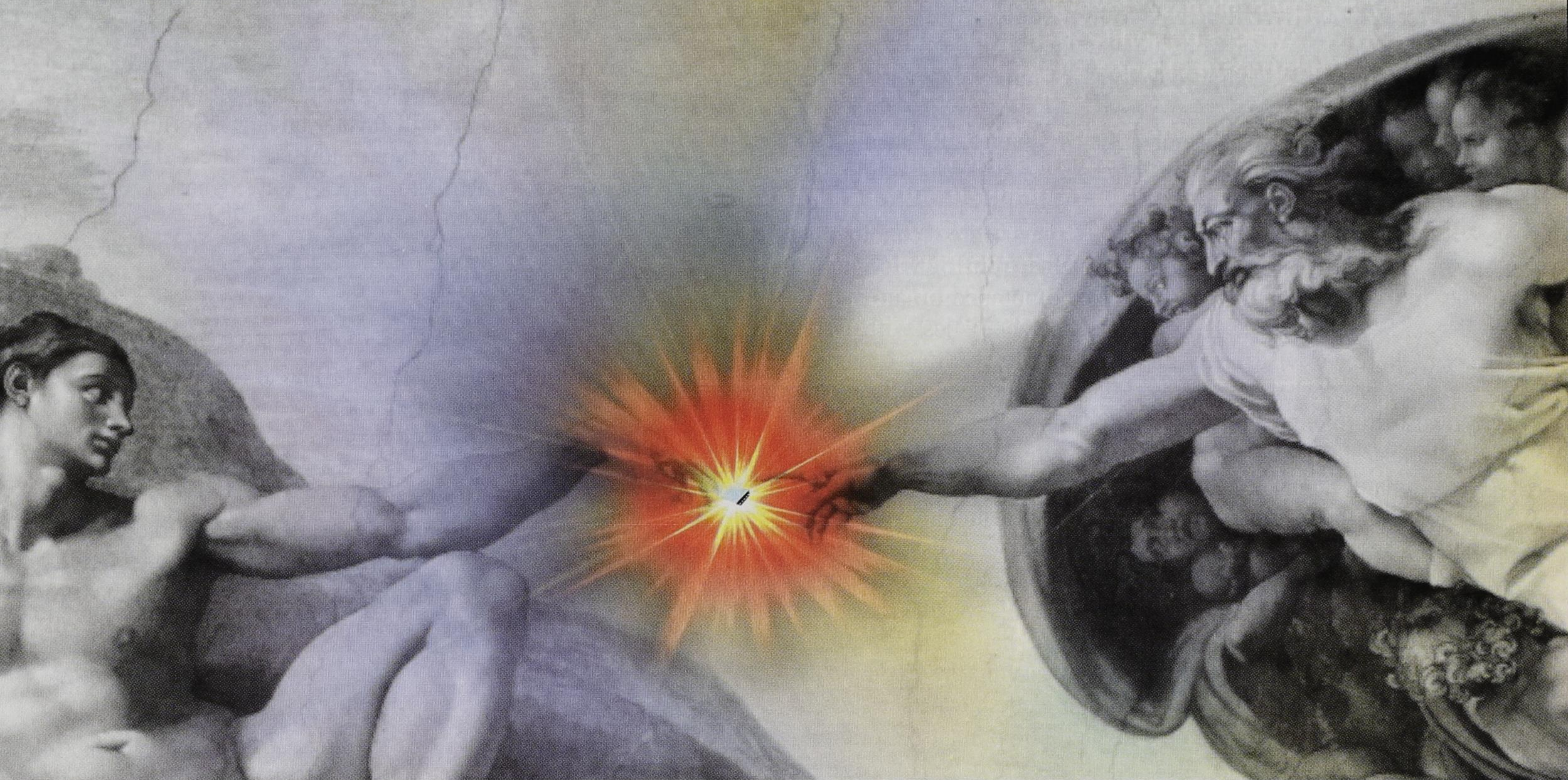
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Altitun Expands, Lucent Launches Tunable Laser

Altitun is expanding its manufacturing facilities following the receipt of a second round of financing, which yielded \$10 million. The tunable laser specialist based in Stockholm, Sweden, announced plans to open a new combined manufacturing and headquarters facility in Stockholm, leased from Mitel. The company says that, beginning in the second quarter of 2000, it will be able to turn out tens of thousands of tunable lasers per year from the new facility.

Altitun is the leading developer of tunable semiconductor lasers, which are seen as a key technology for the future of WDM networks. Last November the company announced that it had reached an agreement with Infineon for the marketing and distribution of the devices.

Altitun AB was founded in 1997. Their core technology is a InGaAsP/InP laser chip that is tunable from 1525-1565nm - the entire wavelength band that can be pumped by an EDFA. The chip shares some features and characteristics with DBR lasers, however DBR lasers are only tunable over much smaller ranges. The technology was originally developed at Sweden's Royal Institute of Technology and its contract research affiliate, the Industrial Microelectronics Center, situated near Stockholm.

In late January Altitun, Norway's Telenor and Marconi announced the results of a two-year project which they claimed had successfully demonstrated a tunable laser driven, all-optical, 100 channel DWDM network. Bjorn Broberg, VP of engineering at Altitun, said the group believed this was the first time such a passive reconfigurable architecture had been developed where switching was accomplished by varying the frequencies of the transmitter lasers. The trial had also shown that such a system could be built with off-the-shelf components from three different manufacturers.

In related news, Lucent Technologies recently announced what it describes as "the first field-deployable, wavelength-stabilized tunable transmitter module for DWDM systems". Based on electroabsorptive modulated laser (EML) technology pioneered at Bell Labs, the new C488 transmitter is intended for extended-reach applications in the 200-640 km range. The module operates at 2.5 Gb/s, and Lucent says it is the first to combine functions such as multiple channel selection, wavelength locking, output power adjustment and remote monitoring and programming.

"This is the first mainstream tunable product to be available in the industry," says Tom Hausken, optical communications senior analyst with Strategies Unlimited. "Lucent's new tunable transmitter marks a milestone much anticipated by systems manufacturers. It promises to ease inventory management as well as introduce new system architectures, reducing the number of primary and spare source components needed in transmission systems."

Corning to Acquire Photonics Technology Research Center from British Telecommunications

Corning Inc. has announced that it will work with British Telecommunications (BT) as a research partner in photonics technology, and that it has acquired BT's Photonics Technology Research Center (PTRC), for approximately \$66 million. The PTRC is located at BT's Adastral Park, in Martlesham, Suffolk, UK.

"The synergy derived from the work being conducted at the PTRC with that at Corning Lasertron, an industry leader in laser manufacturing, will further advance Corning's rapid development and manufacture of low cost lasers and packaging for use in optical amplifiers," says Charles Deneka, Corning's Chief Technology Officer. "The research and development of planar integrated optics, semiconductor optical amplifiers (SOAs), electro-absorption modulators (EAMs) and optical networking devices (ONDs) underway at the Center offer excellent opportunities for us to deliver new products to our current businesses, and at the same time augment our other internal product development efforts. Additionally, we are pleased that we have been able establish a working presence at BT's world-renowned research and development center."

Corning's acquisition of the PTRC furthers the company's global strategy of becoming a leading integrated supplier of a broad range of optical and photonic products that are critical to the development and eventual deployment of the all optical network.

Over the past 15 years BT has invested more than \$300 million in optical component technology and optical systems research, and in the process has amassed a significant intellectual property portfolio. As part of the acquisition Corning and BT have agreed to leverage this research technology and advance it toward commercial viability. In addition to the PTRC's team of researchers and its physical assets, Corning is also acquiring licenses to 20 patent "families" covering photonic networking technologies, including modulators, amplifiers and lasers.

Corning and Samsung Electronics have formed a new equity-venture company, Samsung Corning Micro-Optics, to package thin film filters for DWDM components. Located in an existing Samsung facility near Seoul in Suwon, South Korea, the company will use advanced automation to perform key manufacturing steps currently done manually. As a result, the company expects enormous benefits in capacity, reproducibility, unit cost and reduced cycle time. Volume manufacturing is expected by mid-2000.

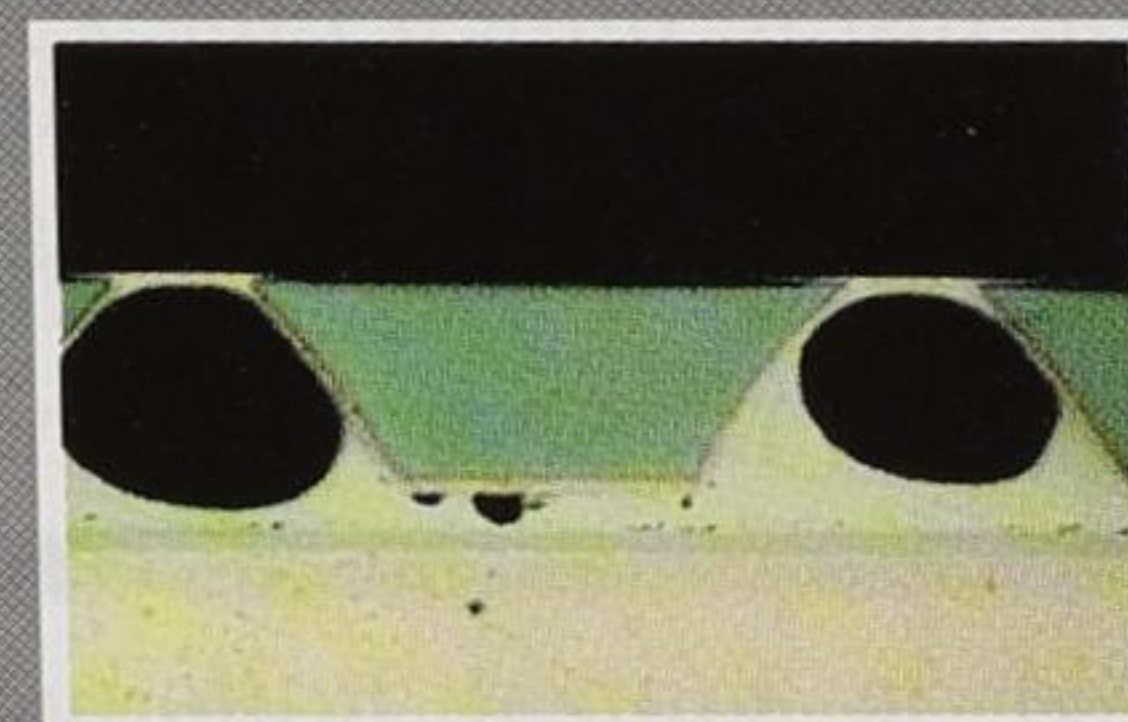
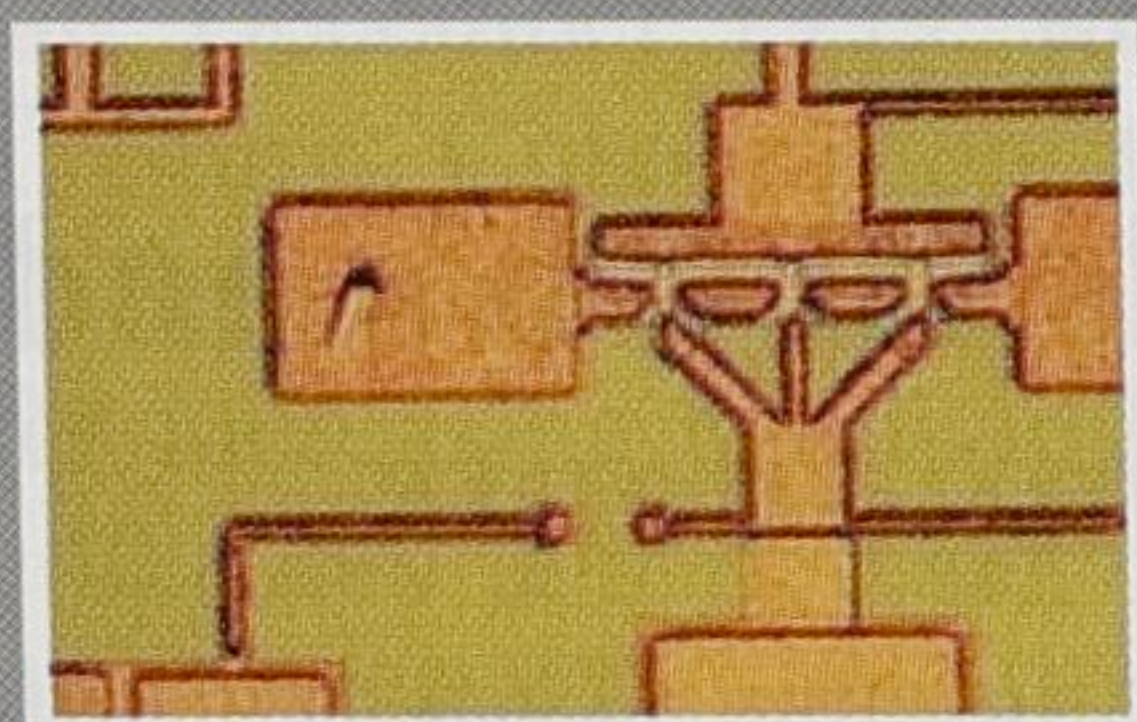
In related news, Corning has agreed to acquire NetOptix Corp. (Sturbridge, MA) a manufacturer of thin film filters for DWDM components, for \$2 billion in stock.

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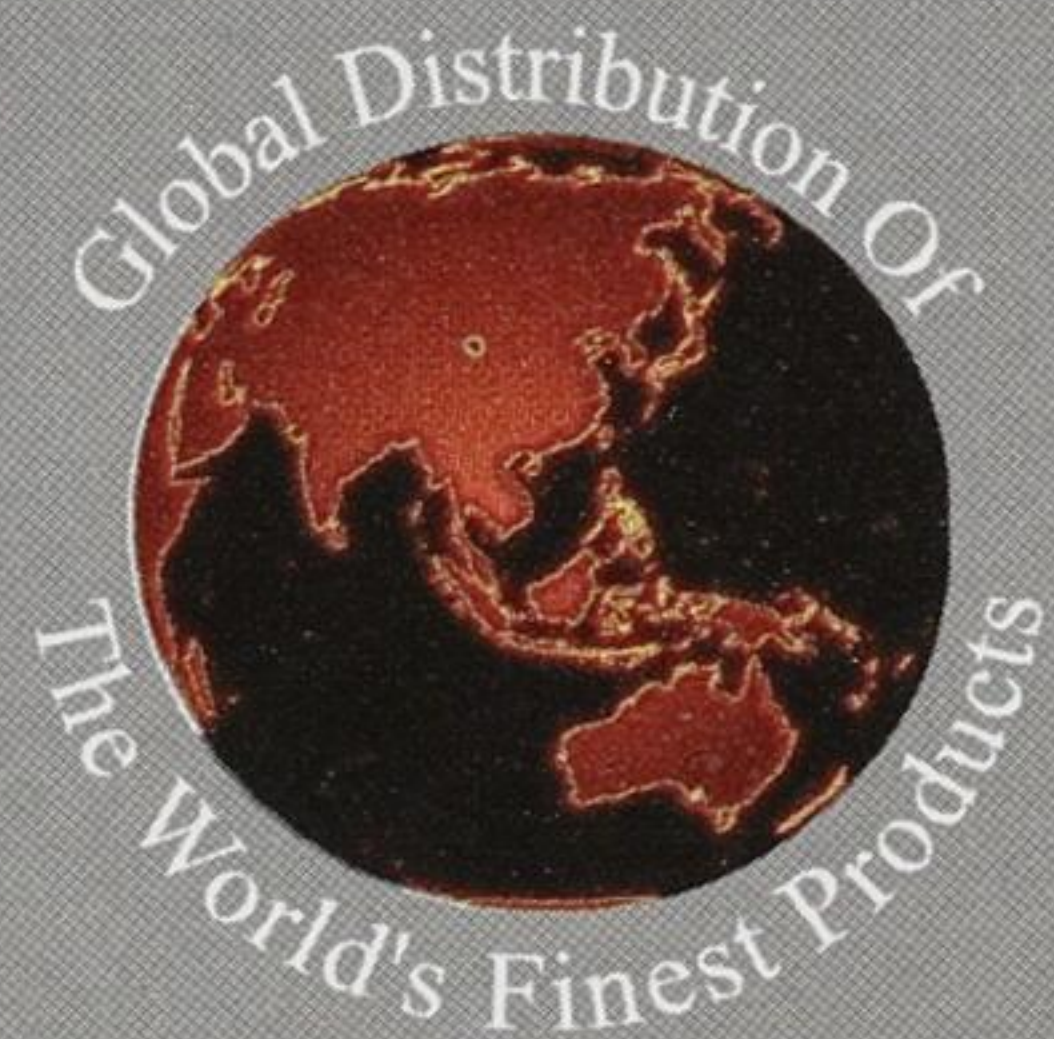
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Agilent Acquires Research Center from Telecom Italia

Agilent Technologies is to acquire the Optical Technology Center (OTC) from Telecom Italia's central research laboratory, CSELT (Centro Studi e Laboratori Telecomunicazioni). Agilent will acquire around 50 research employees from OTC along with its modern facilities in Turin, Italy, including advanced laboratory equipment and the research center's patent portfolio. The 40,000 sq. ft. OTC facility contains a clean room for epitaxy and processing, as well as characterization and packaging laboratories.

OTC will become part of Agilent's Fiber Optics Communications Division (FOCD) and will be closely linked to the Ipswich Components Operation (ICO). Located in Ipswich, England, ICO carries out high volume manufacturing of single-mode, fiber-optic components. OTC's advanced technology and research facilities are expected to accelerate the delivery by Agilent of 10 Gb/s and DWDM technologies to the telecom and datacom markets. Agilent claims to be the world's largest manufacturer of optoelectronics and fiber-optic modules for the networking industry. "We plan to make today's more exotic technologies, such as 10 Gb/s and DWDM, as common as fast Ethernet by marrying OTC's leading-edge research with our high-volume manufacturing capability," says David Parker, ICO's general manager.

The sale of OTC allows Telecom Italia to focus on its core business activities while at the same time enabling commercialization of technologies developed within its research group. Agilent intends establish a collaboration agreement with CSELT and Telecom Italia. "The agreement acknowledges the high level of competence reached by the OTC research group over the years," says Cesare Mossotto, general manager of CSELT. "Moving this knowledge from a research lab to a commercial environment is the best way to apply it successfully all around the world."

In related news, Agilent has announced plans to expand its central research organization with a new facility in Scotland. Agilent Laboratories Scotland, located at South Queensferry, will undertake research into next-generation communication technologies, including improving the performance and management of the Internet, optical networks and other high-bandwidth technologies.

CyOptics Unveils 10 Gb/s and 40 Gb/s Components

CyOptics, a venture-backed startup company founded in January 1999, will be demonstrating its InP-based components for high speed optical networking at this year's Optical Fiber Conference (OFC 2000) in Baltimore. The company is targeting the ultra-long-haul (ULH - defined as over 2,500 km without regeneration) 10 Gb/s and 40 Gb/s transmission markets. "The nominal speed of optical transmission channels doubles itself every 18 months," said Eran Yarkoni, president of CyOptics. "While today's commercial systems operate at speeds of 2.5 and 10 Gb/s, the first commercial deployments of 40 and 80 Gb/s systems are already expected in 2001."

CyOptics is headquartered in Los Angeles and maintains research and development facilities in northern Israel. The company has full optoelectronic component manufacturing capability, including InP wafer fabrication, regrowth and characterization, as well as microelectronic packaging, test and qualification facilities.

CyOptics' patented Pulse Generating Laser (PGL) technology enables very high-speed and long-haul DWDM transmission by generating high power, short laser pulses. The technology is suitable for the integration of multiple functions (such as signal generation, modulation and power monitoring) into one component, and is ideal for implementation of RZ (Return to Zero) and OTDM (Optical Time Domain Multiplexing) transmission systems. Recent experiments have demonstrated successful transmission of 40 Gb/s optical channels over conventional optical fiber at distances of more than 400 kilometers, as well as transmission of 6.4 Tb/s over a single fiber.



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Methode Plans Optoelectronics Spin-Off

Methode Electronics (Chicago, IL), which recently acquired the optoelectronics unit of Spire Corporation, has announced plans to spin-off its optical products business to form a new independent publicly traded company. The move will take advantage of the 120% increase in shipments and profits generated by Methode's optoelectronic transceiver business during the year ending January 31, 2000. Methode operates a number of separate business units, with the largest being optoelectronic devices for the company's Optical segment, and automotive controls for the Electronics segment.

"Over the last two years, we have enjoyed strong growth in sales from our optoelectronics division, which produces high performance optoelectronic transceiver sub-systems," says Methode president James McGinley. "These transceivers, operating in excess of 1 Gb/s, employ the Gigabit Ethernet and Fiber Channel protocols for data communications and storage area network applications. In April of 1999, we acquired Methode Communication Modules, another designer and manufacturer of optoelectronic transceiver sub-systems, to target the mid-range of data communications operating at 10-200 Mb/s.

"In late December 1999, we acquired the optoelectronics business assets of Spire Corporation through a newly created subsidiary Bandwidth Semiconductor, LLC," continues McGinley. "Anticipating the demand for increasing bandwidth to extend to new products operable at 10 Gb/s, 40 Gb/s and beyond, Bandwidth Semiconductor provides us with established R&D capabilities including MOCVD growth for the fabrication of active optoelectronic devices."

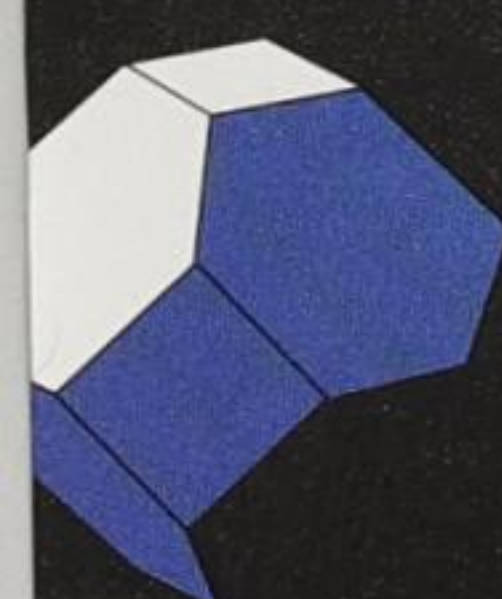
The new optical products company will consist of Methode's optoelectronics division, together with the subsidiaries Methode Communications Modules, Inc. and Bandwidth Semiconductor, LLC, in addition to certain other assets. Methode states that it expects the new company to offer 15% of its common stock in an initial public offering later this year.

Emcore Ships Record Breaking Solar Cells

Emcore has announced the shipment of the world's highest efficiency dual-junction solar cell for satellite applications. Based on satellite industry metrics, the company has achieved an efficiency of 25.3% - the highest in the world for large-area (27.5 cm²) dual-junction flight solar cells. The devices are produced at Emcore's PhotoVoltaics Division in Albuquerque, New Mexico.

"Our cells reach far beyond the capability of silicon-based solar cells, which have a theoretical maximum efficiency of approximately 19% and degrade quite rapidly during orbit," says Reuben Richards, Emcore's president and CEO. "The use of compound semiconductor cells equates to fewer devices being needed, resulting in smaller, lighter satellites with longer lifetimes, while providing more power."

The dual-junction InGaP/GaAs solar cells are grown on Ge substrates, and feature a minimum average efficiency of 23% measured at air mass zero (AM0) and 28°C. Emcore says it has also produced triple-junction cells with a minimum average of efficiency of 26% in pilot runs at the Albuquerque facility. In preliminary radiation testing at NASA's Jet Propulsion Labs (JPL), these triple-junction cells demonstrated enhanced radiation stability with a power degradation of only 8% for an equivalent life of 15 years in geo-stationary orbit. Emcore's triple junction solar cells will begin a full qualification program in spring 2000 and are expected to begin in-flight production in summer 2000.



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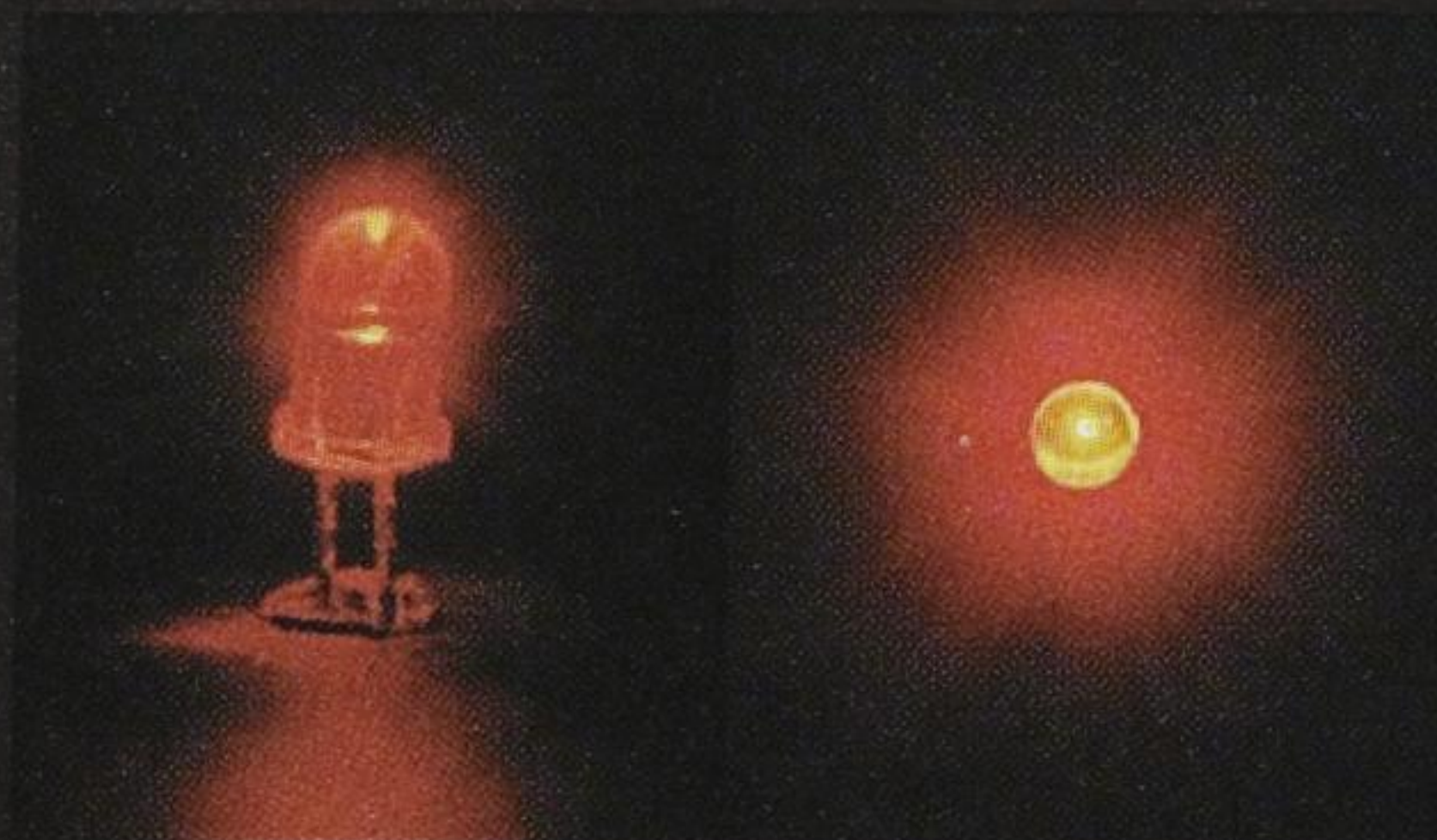
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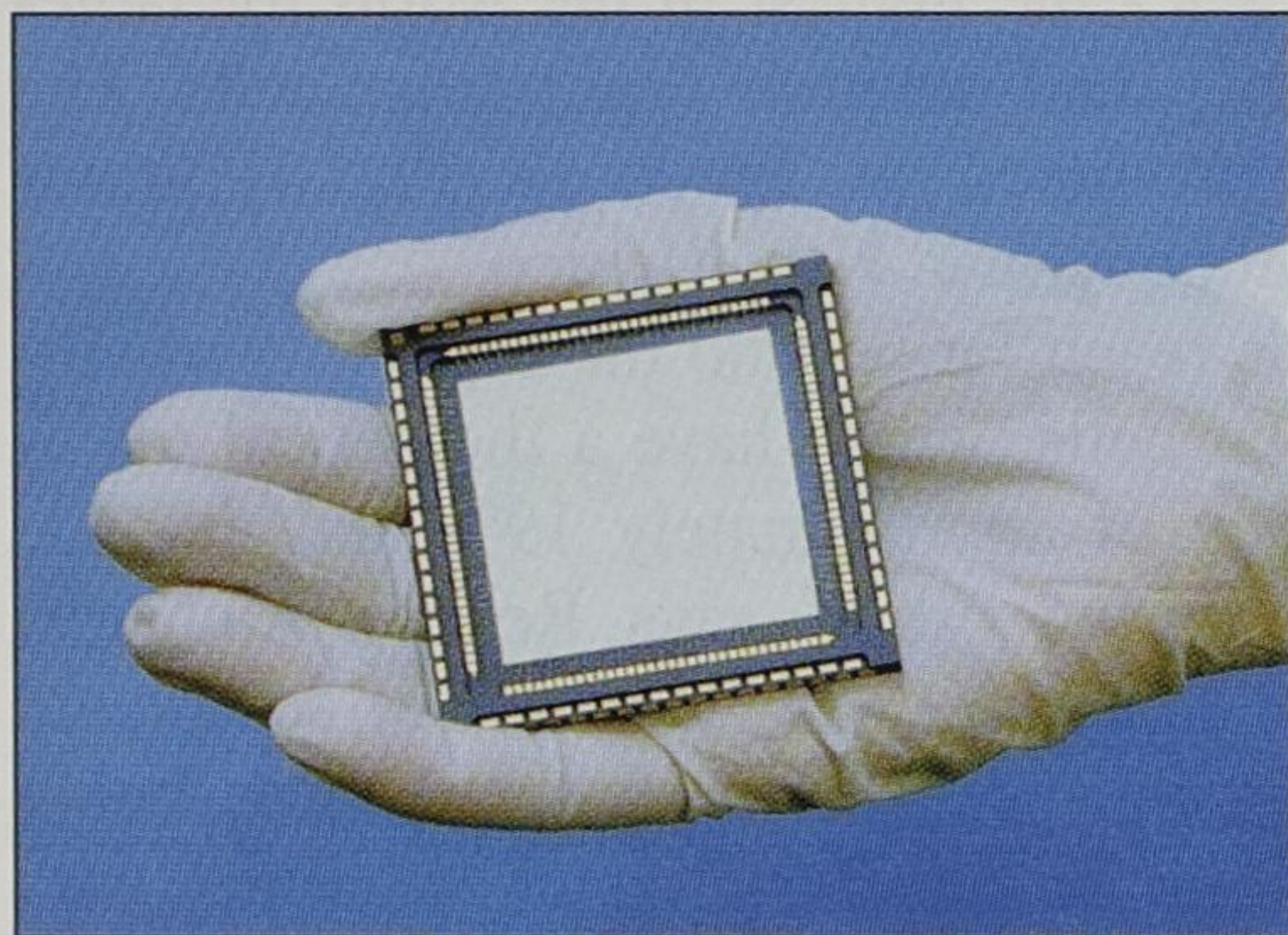
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Rockwell Develops 2048 x 2048 HgCdTe Array

Rockwell Science Center has developed what it describes as the world's largest infrared image sensor – a mercury cadmium telluride (HgCdTe or MCT) focal plane array



Rockwell Science Center

containing nearly 4.2 million pixels. The sensor, which can record images lower than one billionth the level of typical room light, was developed for deep-space astronomy as part of a two-year program funded by a consortium of observatories led by the University of Hawaii. By detecting small amounts of heat radiated from distant celestial bodies, the imaging array will enable the detection of faint galaxies from the beginning of the Universe. "This is a breakthrough development that will enable astronomers to explore the farthest reaches of space," said Derek Cheung, Rockwell's VP for Research and director of the Science Center.

The infrared image sensor is fabricated from a 2048 x 2048 HgCdTe focal plane array containing nearly 4.2 million pixels, which operate in the 0.9-2.5 μm wavelength range. Rockwell says that the imager is unique in having a very high percentage of working pixels – a total of 99.98% are operational in the device. The array is bump-bonded to a CMOS readout IC containing over 13 million transistors, exceeding the number found on today's computer chips. The 4 x 4 cm CMOS chip, fabricated by Conexant Systems, is said to be the largest in the world. Rockwell Science Center is also planning to build a 4096 x 4096 infrared sensor.

Optoelectronics Thriving in Taiwan

Taiwan is known as a center of rapid growth for LED manufacturing, but the country is also home to manufacturers of other opto-electronic devices, including VCSELs and DVD lasers. Here we profile a selection of these companies.

Optronics International Corp. (OIC)

Optronics International Corporation (OIC) is an advanced laser diode company founded in 1996 with investment from several publicly traded companies in Taiwan. The company specializes in mass production of high quality and low cost lasers, LEDs, detectors, modules and transceivers for a range of applications. Based in Hsinchu's Science-Based Industrial Park, OIC is fully vertically integrated, with in-house MOCVD capability as well as complete facilities for chip fabrication, packaging and module assembly.

The company began mass production of 5 mW red (650 nm) lasers in January 1997, and by the 2nd quarter of 1998 had reached a production volume of 1 million TO-18 packages per month. In line with the rapid expansion in the fiber optic communication market, the company made a transition during the second half of 1999 to concentrate on the production of devices for this market.

The company now manufactures a range of MQW lasers at 1310 nm and 1550 nm, as well as InGaAs PIN photodiodes for telecommunications applications. Related products include pig-tailed and receptacle modules incorporating the above devices,

and transceivers operating at OC-3 (155 Mb/s), OC-12 (622 Mb/s) and OC-24 (1.25 Gb/s).

At the start of 2000, the company began production of a series of data communication products such as 1310 nm LEDs, 850 nm VCSELs and GaAs PIN photodiodes and transceivers for use in Fast Ethernet (100 Mb/s) and Gigabit Ethernet (1.25 Gb/s) applications.

The company also packages OIC's PIN photodiode with a transimpedance amplifier (TIA) in a TO-46 package; this PIN-TIA is used as a front-end receiver. Depending on the characteristics of the TIA, the PIN-TIA can be used at different data rates.

The current OIC transceiver has an industry standard 1 x 9 footprint, while the company is in the process of developing small form factor (SFF) transceivers. In addition, the company is developing low cost DFB lasers for WDM applications: these devices will be available in the second half of 2000. [Web: www.oic.com.tw]

United Epitaxy Company Ltd (UEC)

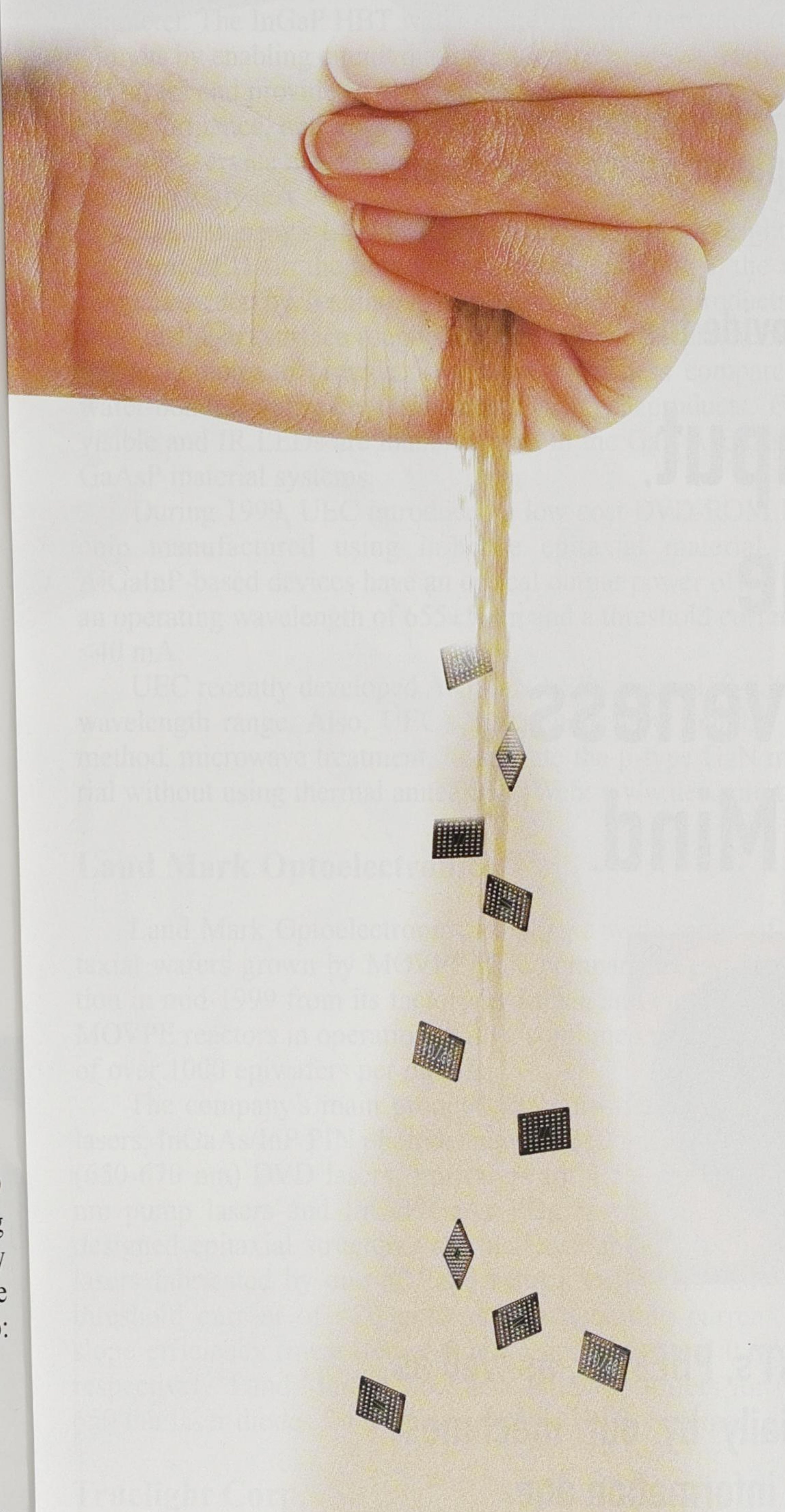
United Epitaxy Company Ltd (UEC) was the third company in the world (after Hewlett-Packard and Toshiba) to begin mass production of high brightness AlGaInP LEDs. The company, established in September 1993, currently occupies two sites at the Science-based Industrial Park in Hsinchu and has around 400 employees.



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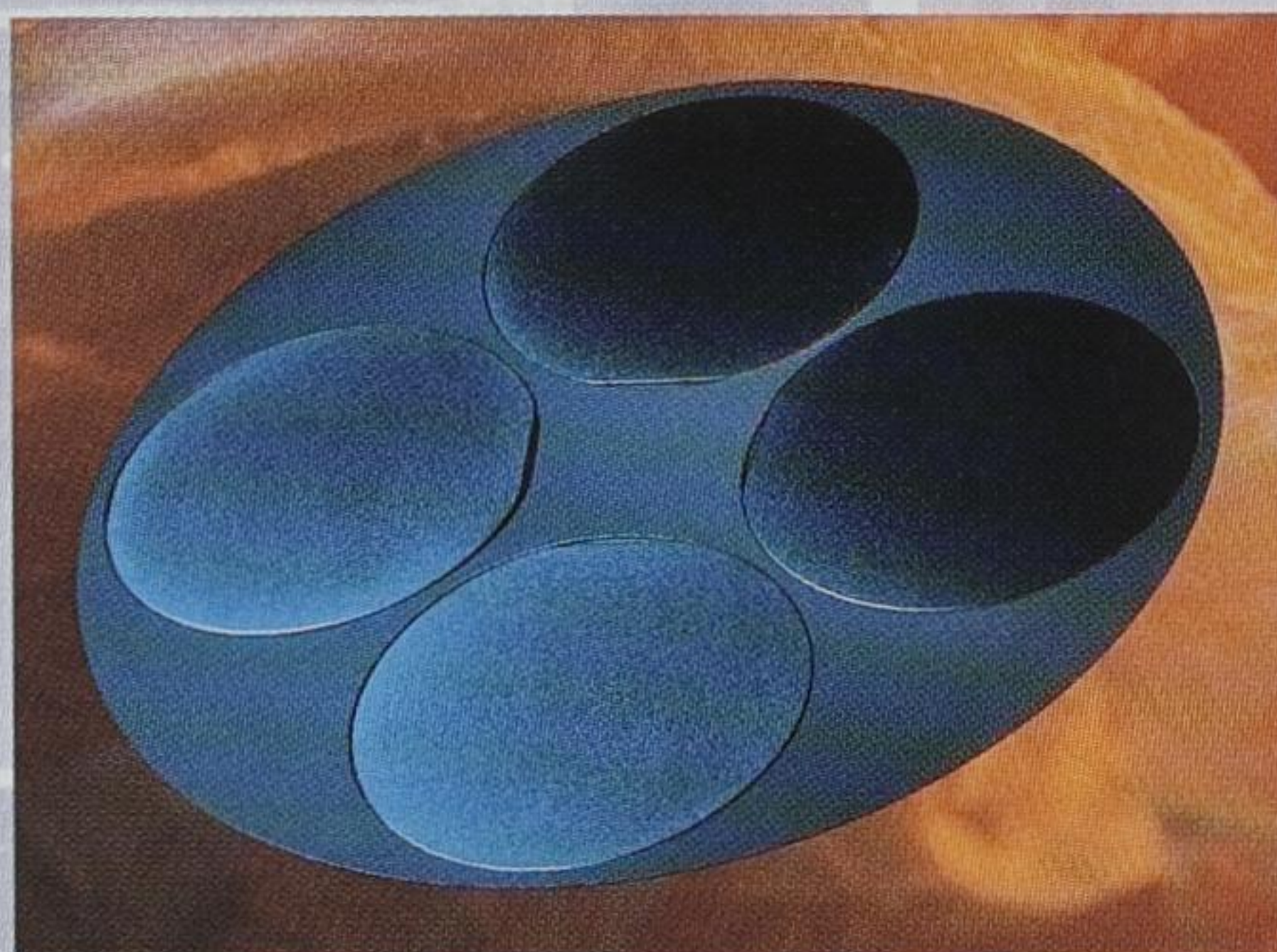
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UEC supplies a large variety of epitaxial wafer and device chip products, particularly visible and IR LEDs and lasers. The company's facilities support MOVPE growth, chip fabrication, testing of optical and electrical characteristics, and reliability analysis. UEC also recently began to supply epitaxial wafers for MMIC applications. These are InGaP-emitter HBTs and PHEMTs grown by MOVPE on substrates up to 6 inches in diameter. The InGaP HBT wafer simplifies the formation of the circuits by enabling circuit manufacturers to precisely etch emitter layers and provides a platform to develop more robust, higher performance, and very reliable HBT circuits. UEC's MMIC epiwafer service also includes epiwafer design, device probing and reliability test.

The company's LED products include ultra-high brightness AlGaInP LEDs in the 560-650 nm wavelength range, the wide range provided by Toshiba. According to UEC, the products use state-of-the-art surface roughening and oxidation current blocking technology to provide 50% more brightness compared to wafer-bonded transparent substrate (TS) type products. Other visible and IR LEDs are manufactured in the GaP, AlGaAs and GaAsP material systems.

During 1999, UEC introduced a low cost DVD-ROM laser chip manufactured using in-house epitaxial material. The AlGaInP-based devices have an optical output power of >5 mW, an operating wavelength of 655 ± 5 nm and a threshold current of <40 mA.

UEC recently developed AlGaInN LEDs in the 450-530 nm wavelength range. Also, UEC's researchers have found a new method, microwave treatment, to activate the p-type GaN material without using thermal annealing. [Web: www.uec.com.tw]

Land Mark Optoelectronics

Land Mark Optoelectronics supplies a wide range of epitaxial wafers grown by MOVPE. The company began production in mid-1999 from its factory in Tainan and currently has 6 MOVPE reactors in operation, with a combined monthly output of over 1000 epiwafers per month.

The company's main products are epiwafers for 1300 nm lasers, InGaAs/InP PIN photodetectors, 1310 nm LEDs and red (650-670 nm) DVD lasers. Epiwafers for 1.55 μ m lasers, 980 nm pump lasers and InGaP/GaAs PDs as well as customer-designed epitaxial structures are also available. 650 nm DVD lasers fabricated by one of Land Mark's customers showed a threshold current of <20 mA, and an operating current and slope efficiency (measured at 5 mW) of 30 mA and 0.6 W/A respectively. Land Mark is now developing epiwafers for 635-650 nm laser diodes for use in rewritable DVD systems.

Truelight Corp.

TrueLight, located in the Science-based Industrial Park in Hsinchu, is a VCSEL manufacturer established in September 1997 by a technical team that emerged from the National Chiao-Tung University. The company currently occupies a 2,400 m² manufacturing facility and has over 60 employees: a spokesperson states that the company is currently going through a phase

of expanding its facilities and increasing its capital. TrueLight manufactures VCSELs and GaAs and InGaAs photodiodes for a variety of communications applications including Gigabit Ethernet, Fiber Channel, ATM and local area networks (LANs). These devices also have a number of industrial applications including optical sensors, optical switches, optical storage, printers, bar code scanners and free-space data links.

TrueLight offers 850 nm VCSEL chips and arrays, packaged components, and transmitter and receiver optical sub-assemblies in high volume or engineering sample quantities. The company's key product lines are VCSELs in a TO-46 package with a cap and/or a monitoring photodiode assembly. The VCSEL has a typical threshold current of 3 mA, a typical 1.9 V bias voltage, a typical output power of 2 mW, and a slope efficiency of 0.25 mW/mA. These devices have also demonstrated superior reliability and 3- and 5-V Gigabit Ethernet performance under numerous verification programs. [Web: www.true-light.com.tw]

Sirus Technology Corp.

Sirus Technology's main products at present are 650 nm lasers for DVD applications, which the company supplies in chip, packaged or module form. The 5 mW devices have a threshold current of 40 mA and operate up to 50°C. Sirus is located in Yang-Mei, Taiwan. [Web: www.sirustech.com]

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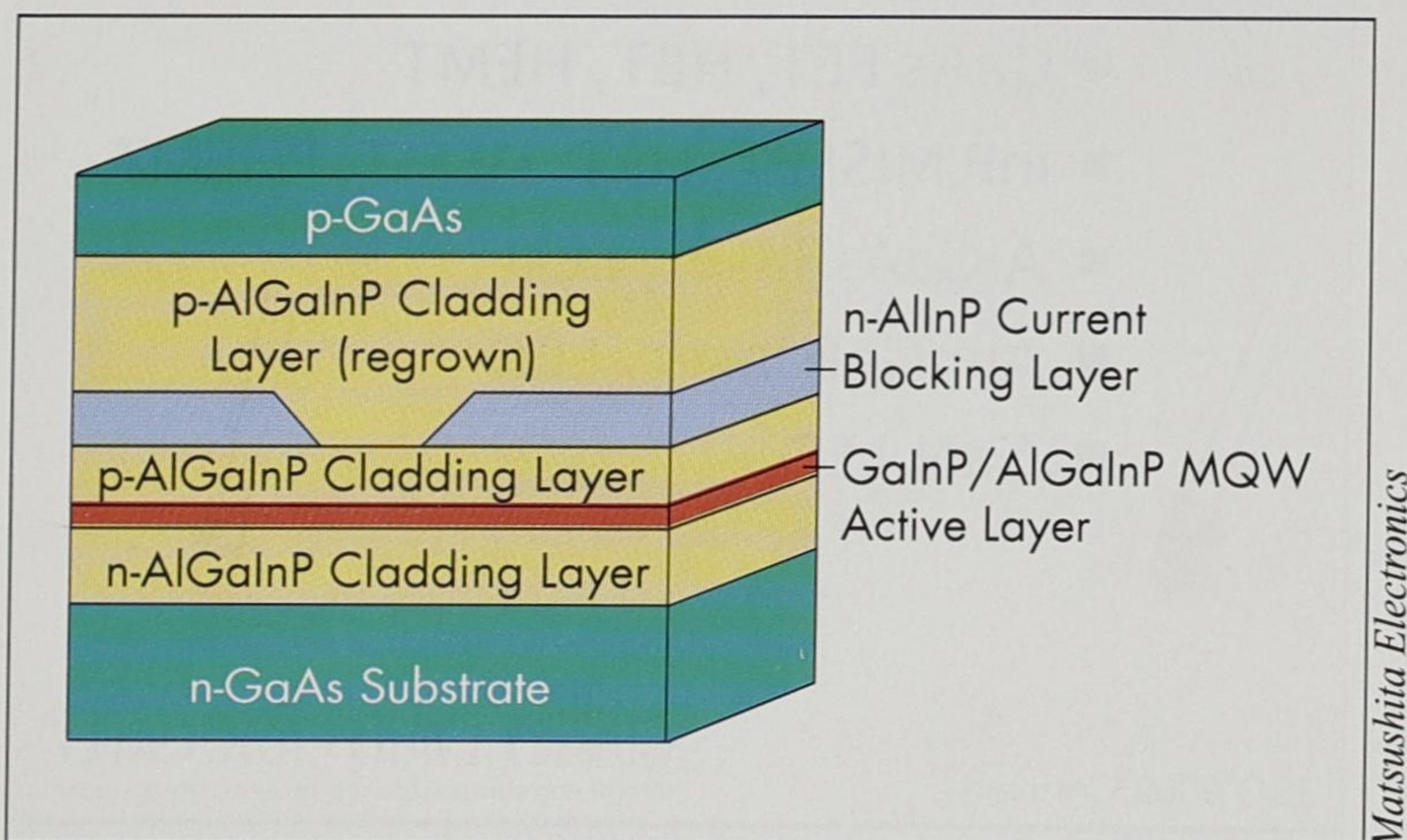
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Matsushita Introduces Industry's First Low Noise, Monolithic Dual-Wavelength Laser for CD/DVD Pickups

Matsushita Electronics Corp. has developed a low noise, monolithic, dual-wavelength laser source for use in optical pickups supporting both CD and DVD playback. The component combines a 650-nm AlGaInP laser (for DVD playback) and a 780-nm AlGaAs-based diode (for CD playback). The two lasers are monolithically integrated side by side on the same GaAs substrate, an arrangement that provides a ten-fold improvement in pointing accuracy compared to hybrid solutions. For the first time, the lasers at both wavelengths operate by self-pulsation, resulting in very low noise characteristics. Sample shipments of the component were scheduled to begin in February.

In optical data storage systems, optical feedback noise in the laser is caused by light reflected from the optical disk. Noise reduction in conventional systems requires the use of additional components such as quarter-wavelength plates (an optical element that reduces optical interference and noise by rotating the polarization direction of light) or external high frequency circuits. The elimination of such components using low noise laser sources can reduce the cost, size and power consumption of DVD/CD drives.

Matsushita has developed self-pulsating lasers with low noise characteristics for both visible and IR wavelengths. Self-pulsation is an oscillation condition in which the laser exhibits pulsed emission in spite of being provided with a direct current. Multimode oscillation occurs under these conditions because the refractive index of the active layer in the laser changes during the pulse period. The result is that laser emission occurs across a range of wavelengths. This means that the interference caused by light reflected back from the optical disk is significantly reduced compared to a system in which the light is all emitted at the same wavelength.



Schematic showing a 650 nm AlGaInP-based laser with the RISA structure.

RISA Structure

Self-pulsation has been achieved in structures that employ a saturable absorption layer for optical confinement, however the inherent power loss makes it difficult to realize low current operation in such a device. Matsushita has developed a proprietary RISA (Real refractive Index-guided Self-Aligned) structure, which enables both self-pulsation and low-current operation. The AlGaInP-based RISA structure (see Figure) employs an $\text{Al}_{0.5}\text{In}_{0.5}\text{P}$ current blocking layer which is transparent to the laser light, hence the absorption loss is reduced.

The RISA structure has been previously used for AlGaAs-based infrared lasers for CDs and MiniDiscs. The structural design values for InGaAlP-based red lasers were obtained using a two-dimensional laser simulation developed in collaboration with Stanford University. An exact estimation of semiconductor laser characteristics needs to take into account the interaction between injected carriers and the stimulated emission, as well as the spatial expanse of the generated beams. The simulation performs laser operation calculations with high accuracy, even in the case where a generated beam penetrates deep into the optical confinement layer and has a large spatial distribution.

A relative intensity noise of less than -130 dB/Hz was achieved for both lasers without adding external circuits or optical elements, such as quarter-wavelength plates. The RISA structure also enables a reduction in operating current of about 33% compared to conventional self-pulsating lasers. This is a crucial feature in order to avoid heating problems caused by the proximity of the monolithically integrated lasers. At a power of 5 mW, the operating current is 47 mA for the IR laser and 62 mA for the red laser.

Device Fabrication

The dual-wavelength laser is fabricated in a multi-step process. First, the epilayers for the AlGaInP-based red laser are grown in two MOCVD steps, and then the AlGaAs-based laser is grown, also in a two-step growth process. Growth is optimized to control dopant migration and to prevent degradation of characteristics during deposition of the second layer sequence.

Because the spacing between the two lasers in the monolithic structure is determined by lithography, the point of light emission is positioned with an accuracy of $\pm 1 \mu\text{m}$. That value is around $\pm 10 \mu\text{m}$ in conventional hybrid structures in which red and infrared lasers are formed on separate substrates and assembled side by side using die bonding. This greatly facilitates optical fine-tuning of the objective lens, the beam splitter, and other elements.

Northrop Grumman to Build SiC-Based Radar Transmitter

Northrop Grumman's Electronic Sensors and Systems Sector (ES3) has been awarded a 24-month, \$3.5 million US Navy contract for the development of a 540 kW radar transmitter that uses SiC-based transistors. SiC is capable of functioning under high temperature, high power and high frequency conditions, making it a strong candidate for a variety of electronic devices and applications, including radar.

"Northrop Grumman has been involved in the development of SiC microwave devices for more than a decade," says Kelly Overman, VP and general manager of the Baltimore-based Systems Development and Technology business unit at ES3. "Winning this contract keeps us at the forefront of this important technology." Northrop Grumman's ES3 sector designs and manufactures electronics systems for defense airspace management, marine, precision weapons, space, and automation and information management.

GE, Sanders and Cornell to Collaborate on Bulk GaN Growth

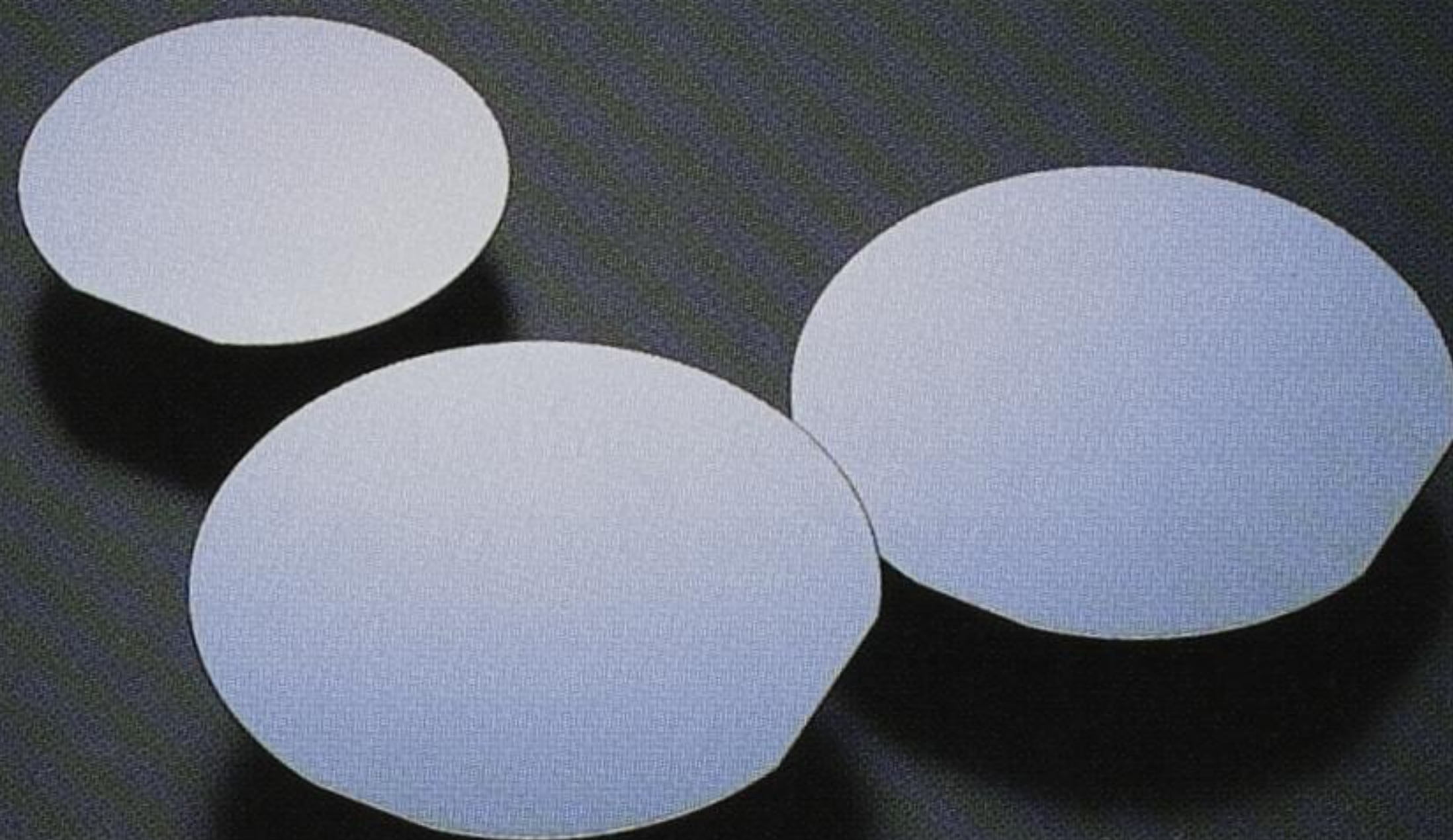
General Electric's Corporate R&D department (Schenectady, NY) will lead a project with Sanders (a Lockheed Martin Company, based in Nashua, NH) and Cornell University to develop a commercially viable process for producing low cost, large-area crystals of GaN for use as epitaxial substrates. GaN substrates offer the ability to grow low dislocation density GaN epitaxial layers to enable high-quality optoelectronic and microelectronic devices.

The 3-year project is valued at approximately \$4.6 million, with additional Advanced Technology Program (ATP) funds of \$2,254,000 available. Researchers at GE and Sanders will use high pressure, high temperature apparatus similar to that used by GE to make synthetic diamond around 10 years ago.

SVTA Introduces GaN-Based UV Photodetectors

SVT Associates (Eden Prairie, MN) has introduced a range of MBE-grown GaN p-i-n photodiodes for use as UV photodetectors in UV curing, combustion monitoring, spectroscopy and phototherapy control applications. Offering a typical quantum efficiency of 40% at 360 nm, the 0.5 mm² active-area photodetectors offer a high rejection to visible and infrared wavelengths. Available in TO-46, TO-8 and SMT packages, they deliver a frequency response of DC to >18 MHz with -3 dB of noise, and a responsivity of 0.1 A/W and 0.05 A/W at 360 and 250 nm, respectively.

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High Temperature Electronics – a Market Forecast

The world market for high temperature electronic (HTE) components will grow from \$177.2 million in 1998 to \$376.8 million in 2003, according to recent estimates published by the High Temperature Electronics Network (HITEN – see box). By 2008, the market will have grown to \$887.1 million, with components based on III-V materials and wide bandgap semiconductors such as SiC, diamond and GaN accounting for 25% of the total (see Table 1). The main driving force for this growth is the elimination of expensive and bulky cooling systems that are currently required to protect electronics from extreme environments, particularly in energy-intensive sectors such as the aerospace, automotive and industrial process industries.

The HTE component industry is currently dominated by discrete devices, e.g. diodes, transistors and sensors, with only a limited number of ICs on the commercial market. Few commercially available components are specified for operation above 125°C, and these are mostly silicon or SOI analog ICs and sensors. Currently 97% of the market is for operation up to 200°C.

The largest HTE application for III-V devices is in the automotive industry (see Table 2). Hall sensors based on GaAs, InAs and InSb are now widely used for position and rotation detection in engine management, anti-lock brakes and power steering, at temperatures up to 180°C.

Wide bandgap semiconductors are seen as crucial for the development of components operating up to and above 300°C. SiC is the most promising such material, and has the potential to operate up to 600-700°C, although its development is roughly where GaAs was 25 years ago. HITEN expects that SiC electronic devices could be designed into systems for niche HTE applications above 300°C in the next 3-4 years. In contrast, nitride devices are likely to play only a minor commercial role over the next 10 years. SiC devices are currently used in niche applications such as UV flame detectors based on SiC photodiodes that assist with turbine engine combustion control in aircraft.

Specialized systems called sondes that contain sensors and data acquisition electronics are used to log the environment around drilling heads in oil, gas and geothermal wells. Such environments are among the most extreme and demanding of any HTE application. Sondes are starting to take advantage of the HTE properties of SiC-based devices, and this market should grow as deeper and hotter wells are explored. Other potential applications for SiC-based devices are satellite electronics, and HDTV distribution systems.

HITEN - the High Temperature Electronics Network - is one of the networks of excellence supported by the European Commission under the Esprit programme. The bulk of the funding to run the service comes from membership subscriptions, either in individual or corporate form. Access to the network is via the worldwide web at <http://www.hiten.com>. For further information, contact Richard Sharp at hiten@aeat.co.uk.

Device Type	Market (\$ million)		
	1998	2003	2008
Silicon/ Silicon-on-insulator (SOI)	155.7	308.8	667.2
III-V Devices (GaAs, InAs, InSb)	20.6	60.8	183.2
Wide Bandgap Devices (SiC, diamond, GaN)	0.9	7.2	36.2
Total	177.2	376.8	887.1

Table 1. World market for HTE components by semiconductor type.

Application	III-V Devices		Wide Bandgap Devices	
	1998	2003	1998	2003
Automotive	20.4	57.3	0.0	2.1
Aerospace	0.15	0.9	0.1	1.4
Well Logging	0.0	2.2	0.8	3.2
Other	0.0	0.4	0.0	0.5

Table 2. World market for HTE components based on III-V or wide bandgap devices, by application.

Nitronex Lands Venture Capital, Expands Facilities

Nitronex will receive \$500,000 in venture capital from a fund started by the state of North Carolina to help launch new companies affiliated with North Carolina State University (NCSU). The funding will allow the Raleigh-based company to begin scaling up its proprietary "Pendeo" epitaxial growth technique, particularly for the integration of GaN onto Si substrates.

According to Nitres' CEO Mark Johnson, epitaxial growth of GaN on Si represents an opportunity to integrate the digital circuit functionality of Si with the power amplification capability of GaN devices. "The Pendeo process provides a dramatic reduction in the defect density of GaN epilayers, thus enabling a wide variety of new electronic or optoelectronic devices," says Johnson, one of the four NCSU graduates who founded Nitronex in 1998. "Nitronex has a family of device products under development, and we expect the first product releases this year."

Nitres also recently announced the expansion of its headquarters in Raleigh. "Work on our new clean room has started, and the expansion will also allow us to put our R&D, fabrication, and sales and marketing under one roof," says Johnson. "After addressing the R&D issues we can now rapidly transfer into production at our new facility."

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HRL Labs Reports High Performance MBE-Grown Nitride MODFETs

HRL Laboratories (Malibu, CA) has made "a major breakthrough" in GaN microwave transistor technology, enabling the demonstration of 6.3 W of output power at 10 GHz from a 1-mm-wide MODFET device. This is the highest output power density reported for a power device with a width of 1 mm or larger. More importantly, the power density remains nearly constant as the device size is scaled upward from a width of 0.1 mm (where the device exhibits 6.5 W/mm) to 1.0 mm. These results clearly show that GaN MODFET (modulation doped field effect transistor) technology is ready for the next step, the development of monolithic microwave integrated circuits.

According to HRL, the key to its success is its pioneering work in both epitaxial growth and device processing. These record-setting transistors were fabricated from AlGaIn/GaN heterostructures grown on semi-insulating SiC substrates. HRL has developed a proprietary MBE growth process that has virtually eliminated material defects common to other reported GaN devices, thereby enabling the observed scaling. MBE growth also produces device characteristics with less than 5% standard deviation over the 2-inch diameter SiC substrate, a six-fold improvement over previously reported results.

This technology, targeting near term applications in military hardware such as radars, missiles, and satellites, is expected to draw widespread interest for commercial applications such as wireless base stations. GaN, with its capabilities for both high frequency (beyond X-Band) and high temperature operation is the next generation technology for low noise- and power amplifiers replacing today's commercial GaAs PHEMT. HRL Laboratories is the jointly owned central research laboratory for Hughes Electronics and Raytheon.

Correction: Nitres

In our last issue, we described the performance of AlGaIn/GaN HEMTs fabricated by Nitres Inc. The width of a device providing a record output power of 9.1 W/mm was incorrectly stated as 100 mm – the correct value for the device width is 100 μ m.

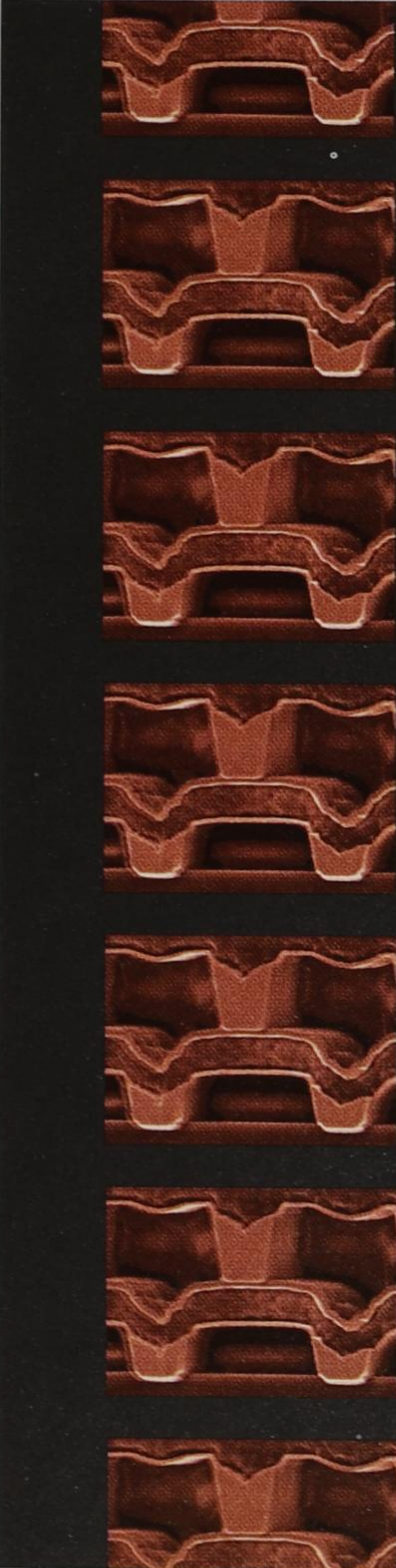
Isonics and ATMI Aim to Improve Thermal Conductivity of SiC

Isonics (Golden, CO) is to collaborate with ATMI (Danbury, CT) to develop isotopically pure SiC epitaxial material in an effort to reduce the epilayer's thermal conductivity. According to Isonics' Dr. Stephen Burden, the proportion of isotopes (chemical species that possess the same number of protons and differing number of neutrons) has a substantial effect on the thermal conductivity of semiconductor materials because heat is conducted primarily by phonons, not electrons as in metals.

Using ^{28}Si -silane supplied by Isonics, ATMI will attempt to determine if the thermal conductivity improvements found in silicon and diamond will hold true for compound semiconductors. Studies of diamond by General Electric in the early 1990's found that removing the 1% ^{13}C in diamond increased the room temperature thermal conductivity by 50%. "The use of isotopically pure epitaxial layers is a natural extension of this technology and could also greatly increase the heat spreading in high-power semiconductor devices," says Burden. "Device performance and chip yields, which are adversely affected by 'hot spots' in the electronic device, can be improved with better thermal conductivity."

Single crystal SiC has a large thermal conductivity (3 times that of silicon), leading to more efficient removal of heat from the active region of a power device. Typically, a mixture of five isotopes will be present in a SiC film. However, isotopically pure SiC can be grown by using isotopically purified silicon (^{28}Si) and carbon (^{12}C) gaseous precursors during the SiC epitaxial growth process.

The collaboration is funded by a 12-month Office of Naval Research (ONR) contract, with ATMI as the main contractor. Thermal conductivity measurements will be performed at Brooklyn College, City University of New York (CUNY).



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Sumitomo Electric Announces Plans for Volume Production of ZnSe-Based White LEDs

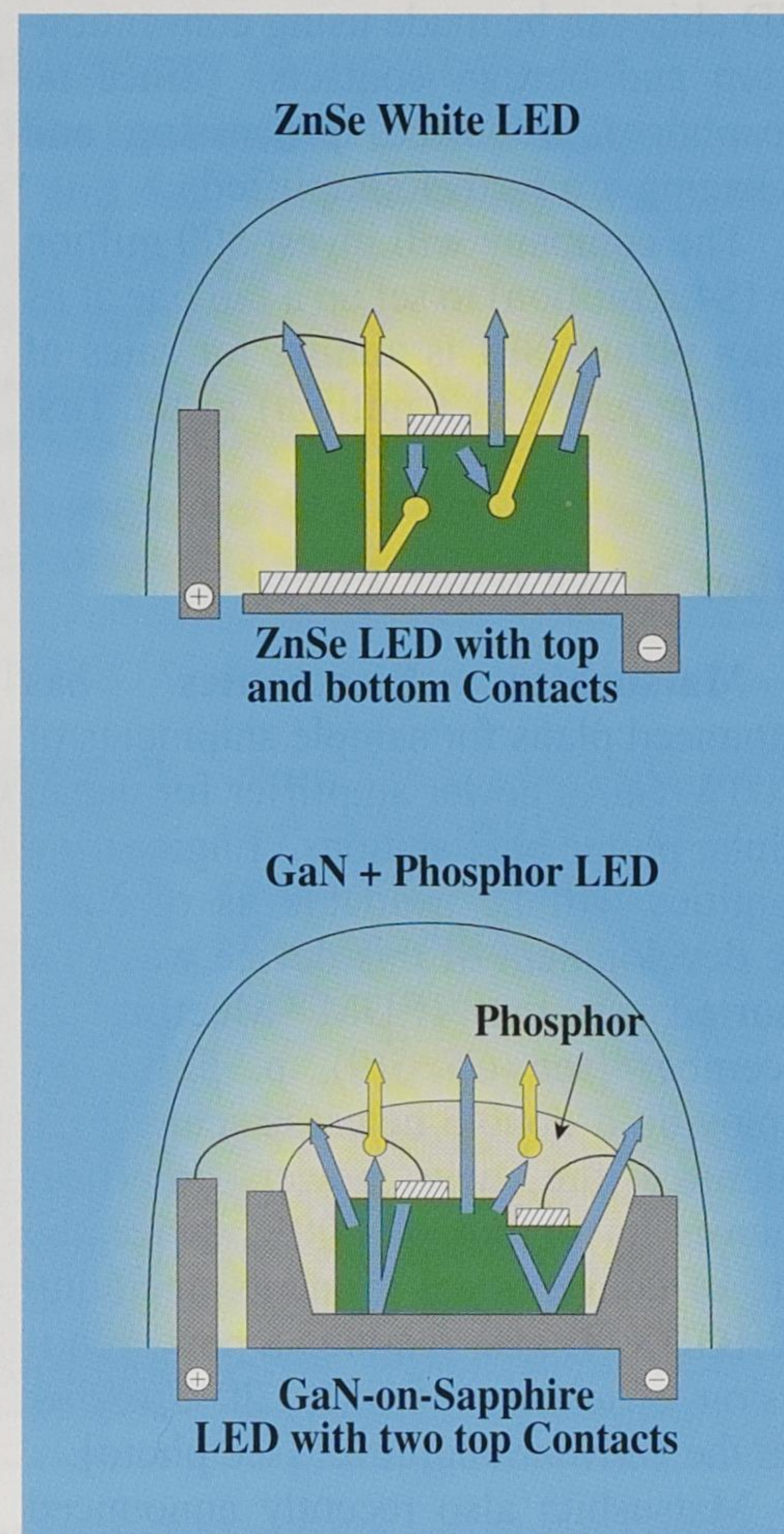
On February 29 Sumitomo Electric announced its plans for launching volume production of the world's first white light LED based on the ZnSe material system. Production will begin this fall, with initial volumes of 5 million units per month. The first target market is cellular handset LCD backlights.

Sumitomo first announced the development of the device last year. [see CS 5(1), p. 32.] It is based on a homoepitaxial ZnSe blue LED, made using ZnSe substrates developed at Sumitomo. The LED simultaneously produces blue light from the active layer and a broader based emission, centered on yellow, from the substrate. The end result is a white light emission, but one which is achieved without the use of a phosphor.

The Sumitomo approach is quite

novel, in part because of their captive ZnSe substrate manufacturing capacity. The other white light LEDs that are currently available are based on the use of a GaN-based blue LED coated with a phosphor. This field has been restricted to just a few companies. A patent battle being fought between two of the participants, Nichia Chemical and Toyoda Gosei, appears to have deterred other companies from entering the market using GaN-on-Sapphire blue LEDs. The rest of the business has, therefore been left to Cree and its customers, such as Osram Opto, because Cree is unique in that its blue LED technology is based on the use of SiC substrates.

Sumitomo believes that their approach also has very strong intellectual property protection. It potentially offers



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other advantages as well. The ZnSe substrate is semi-conducting; therefore the LED chip can be made using conventional top and bottom contacts. Since no phosphor is required, processing and packaging are further simplified.

The company will invest 500 million yen (\$4.6 million) to set up a fab line at its Osaka plant. SEI is aiming for sales of 2 billion yen (\$18.3 million) in the first year.

Other News from Japan

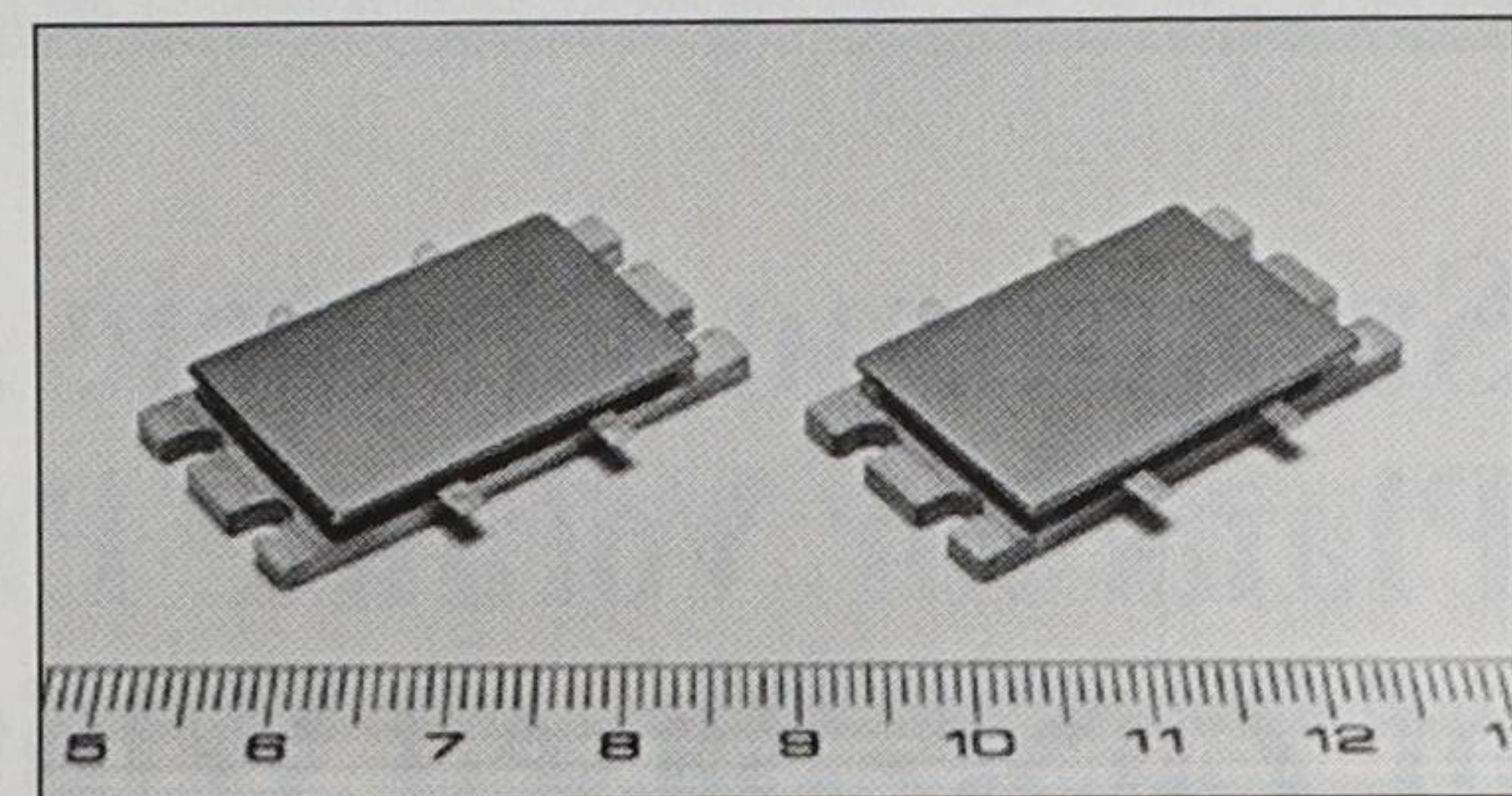
Matsushita Electronics has announced plans for sample shipments of a 200W GaAs power amplifier for use in cellular phone base stations. Engineering quantities will be available as of June. The development of this device was first reported at the IEDM Meeting in December [see CS 5(9), p. 52]. By employing a double heterostructure FET structure, the new power amplifier achieves an output of 200W, twice the level of conventional products operating at 2.1GHz. It also features a power conversion efficiency of 55%, 20% higher than the conventional level [see photo].

Matsushita also recently announced that they had developed the industry's smallest GaAs power amplifier for use in digital cellular phone handsets. The new

device has a footprint of 38 mm², which the company says is 33% less than the smallest product on the market. Its power consumption is said to be 6% less than that of its predecessor. Samples were made available in December for 2,000 yen (\$19.05), and volume production is scheduled to in March at 1 million units per month.

On February 25 **Furukawa Electric** announced that it would increase capacity for manufacturing pump laser diode modules for WDM systems from the current 20,000 to 50,000 units monthly within fiscal 2000. Furukawa is one of the leading producer of pump laser diodes, and the company says it is now operating its 1.48-micron laser diode facility at full capacity. With strong demand from European communications equipment makers, Furukawa expects its WDM-related sales to double year-on-year to 25 billion yen (\$225.2 million) in fiscal 1999 and continue to grow substantially in fiscal 2000.

Furukawa also announced in February that it was terminating its compound semiconductor materials business, which has remained unprofitable ever since the outset. Furukawa had sold S.I. GaAs substrates and high purity elemental chemicals. Sales have halved



Matsushita's 200 W GaAs base station power amplifier.

from the peak of 200 million yen (\$1.8 million) monthly, largely as a result of declining price competitiveness. To relieve itself of the heavy burden of related R&D expenditure, Furukawa discontinued production of silicon wafers at its Chiba plant at the end of 1999 and will close its semiconductor department by the end of 2000. Most of the resources, including 50 personnel, will be transferred to the optical device section.

Sharp has begun sample shipments of a hybrid dual-wavelength laser that can be used to read CD and DVD data. A 780nm and a 650nm laser are separately embedded on a silicon substrate which is housed in a 3mm-thick package. The device is sample-priced at 1,000 yen (\$9.71). The company will launch volume production at 500,000 units per month in April.

SILICON UPDATE

Silicon Phase Shifters

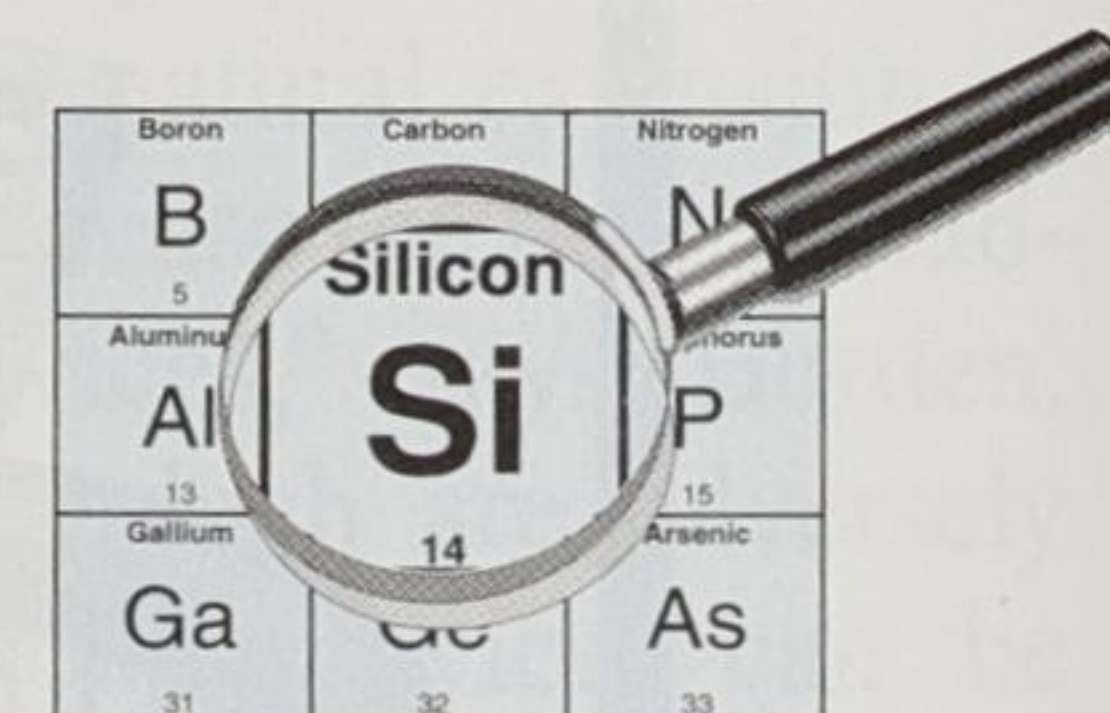
ROBERT A. METZGER

Traditional electronic phase shifters generally rely on GaAs-based MESFETs or PHEMTs - these devices switch between different line lengths, or between high- and low pass- filters to obtain a desired phase shift. A key application for phase shifting is that of phased array radars, in which different elements within the radar array use the phase shifters to delay localized signal elements which can then be compared to signals from other array elements. The major drawback of using a FET for this application is that because a FET does not make a perfect switch (on/off), there can be high insertion losses due to the finite

resistance of the FET channel when the device is biased in the on state. This results in increased power requirements to drive the device. In a phased array radar with thousands of elements, biasing all these FETs consumes a great deal of power.

What can one do?

Silicon offers a potential solution, one which relies on RF MEMS (Microelectromechanical Systems) technology. Rather than using the on/off characteristics of a FET to approximate the behavior of an ideal switch, why not simply build a switch - one small enough to easily integrate with conventional circuitry?



That is just what the MEMS community is doing.

Researchers at Raytheon Systems Company in Dallas, Texas have used Si-based MEMS techniques to fabricate a metal membrane capacitive switch which is compatible with conventional Si processing. The process starts off by growing a 1 μm thick SiO_2 layer on a high resistivity Si substrate ($> 10 \text{ k}\Omega\cdot\text{cm}$), upon which is deposited a 0.4 μm thick layer of refractory metal that is patterned to define the switch electrodes. A layer of PECVD silicon nitride is then deposited and patterned to form the switch dielectric. This is followed by a 4 μm layer of aluminum alloy, which is evaporated and patterned to define the metal transmission lines and the mechanical support posts for the switch. At this point, a polymer sacrificial layer is spin coated and patterned. The thickness of this polymer will determine the air cap thickness of the capacitor. Then, an aluminum membrane layer less than 0.5 μm thick is deposited and patterned to define the switch membrane. The sacrificial polymer layer is then removed by a plasma etch to release the membrane.

With no applied actuation potential, the residual tensile stress keeps the membrane suspended above the RF path, and the capacitive reactance in this open state is 20-50 fF. Application of an electrostatic field between the membrane and the lower electrode induces charges on the conductor surfaces and the suspended membrane snaps down onto the lower electrode and dielectric surface, forming a low-impedance RF path to ground, with typical capacitance in this closed state of 3-4 pF.

These switches have now been used in the fabrication of X- and Ka-band phase shifters [1-2]. An X-Band 4-bit phase shifter based on a reflection topology using 3 dB Lange couplers has been implemented with these RF MEMS capacitors. The average insertion loss of the circuit is only 1.4 dB with a return loss of less than 8 dB for 8 GHz operation, which represents the lowest reported loss for an X-band phase shifter at this frequency. Decreasing the insertion loss for an array of phase shifters will greatly reduce cost, weight, and heat dissipation problems by requiring fewer amplifiers to drive the shifters.

For even higher frequency operation, a switched transmission line 4-bit resonant phase shifter was constructed. Operating at 34 GHz, the 4-bit phase shifter exhibited an average insertion loss of 2.25 dB with better than 15 dB return loss. A similar 3-bit phase shifter offered an insertion loss of 1.7 dB with better than 13 dB return loss.

Once again, these devices represent the lowest loss Ka-band phase shifters reported to date. And remember, these state-of-the-art results, operating in a frequency regime normally reserved for GaAs-based devices, were achieved with a high resistivity Si substrate.

[1] A. Malczewski et al, "X-Band RF MEMS Phase Shifters for Phased Array Applications," *IEEE Microwave and Guided Wave Letters*, Vol 9(12), December 1999, pg. 517.

[2] B. Pillans et al, "Ka-Band RF MEMS Phase Shifters," *IEEE Microwave and Guided Wave Letters*, Vol 9(12), December 1999, pg. 520.



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Riber Doubles MBE6000 Production Capacity

Riber has completed the first phase of an expansion program that has upgraded and increased the available clean room space at its fabrication facility in Rueil-Malmaison, 15 km west of Paris. New assembly and test equipment will allow the company to double its MBE6000 production capacity compared to 1999. President and CEO Michel Picault stated; "This expansion project was initiated in October 1999 to match our production capacity with the strong demand for Riber's MBE production systems from GaAs merchant suppliers and foundries, and has been completed on schedule."

Cascade Microtech Receives Funding, Licenses Technology

Cascade Microtech (Beaverton, OR) has received \$10 million in financing to accelerate the company's marketing and manufacturing capabilities in support of its Pyramid Probe technology. The funding has been received from the Teachers Insurance and Annuity Association of America. Cascade's Pyramid Probe production probe cards are used to test a variety of digital and analog ICs, including the final test for high-bandwidth communication chips. "We expect our Pyramid Probe sales to more than double this year," says Bruce McFadden, president and COO. "Our Pyramid probe is the only commercially available technology that can meet the advanced testing requirements of today's high performance semiconductors."

Another supplier of wafer probers, Electroglas, is to license essential measurement technology from Cascade Microtech. "Our license agreement with Cascade will enable us to reduce noise and substantially cut measurement settling times in probers for wafer production, permitting more accurate, faster measurements in-line," says Curt Wozniak, chairman and CEO of Electroglas. "Such improvements anticipate the measurement accuracy and throughput that new fabrication processes will necessitate."

QED and RFMD Order Multiwafer MBE Reactors from EPI MBE Products

EPI MBE Products Group has received orders for several of its new GEN2000 multiwafer production MBE systems. Quantum Epitaxial Designs (QED) of Bethlehem, PA, part of the IQE plc group, has ordered two of the new systems, while a third has been ordered by RF Micro Devices (Greensboro, NC).

The GEN2000 has been designed specifically for production applications, and is being produced at EPI's new 65,000 sq. ft. manufacturing facility at St. Paul (MN). The system is the first to utilize the cluster tool wafer-handling concept that is widely used throughout the silicon semiconductor industry.

"The GEN2000 is the first MBE system specifically designed for mass production of GaAs epiwafers using the cluster tool concept," says QED's President, Tom Hierl. "This technology reduces the per wafer cost by increasing the throughput and uptime."

Epichem Expands

Epichem has completed the second phase of a three-part expansion of its production facility at Bromborough in the United Kingdom. A new laboratory was completed in January 2000: this houses a wide range of characterization instruments for techniques including ICP optical emission spectroscopy, ICP mass spectrometry, NMR spectroscopy and gas chromatography atomic emission detection. Phase 3 – the installation of a new multi-ton plant for the production of trimethyl gallium (TMG) – is scheduled for completion by the end of 2000.

Meanwhile, the company has installed a new stainless steel plant for the production of multi-kilogram quantities of trimethyl aluminum (TMA) at its US facility in Haverhill, MA. "The multi-kilogram TMA plant will add value to customers in production as it will greatly reduce product variability, provide batch-to-batch consistency, and meet future demand forecasts," says production manager David Houlton.

Epichem reports that it has seen a great deal of demand over the past year, particularly from Japan, for its trimethyl indium (TMI) precursor, Solution TMI™. The company claims that this product offers advantages over solid TMI including consistent run-to-run pick-up, essentially 100% product usage, reduced oxygen incorporation, and accurate and reproducible compositional control. "Solution TMI has such pronounced advantages that solid TMI could be obsolete in less than two years," states Craig Farley of Emcore Electronic Materials, a leading producer of MOCVD epitaxial material. "Emcore's internal epi operations are now almost exclusively using Solution TMI in the manufacture of epitaxial material for wireless applications."

KDF Electronic & Vacuum Services Inc. has unveiled an in-line batch sputtering system developed to provide increased volume capacity by enabling multiple substrate material processing of GaAs and other compound semiconductors.

Tegal has announced several orders from unnamed customers, including a follow-on order for a 6500 series etch system from a "leading North American supplier of high performance broadband networks".

Veeco Instruments and CVC to Merge

Veeco Instruments Inc. and CVC, Inc., two companies that supply process and metrology equipment for data storage, optical telecommunications and semiconductor applications, have agreed to merge. The deal is expected to close in the second quarter of this year, and CVC will become a wholly-owned subsidiary of Veeco.

Veeco Instruments Inc., headquartered in Plainview, NY, manufactures metrology tools for the data storage, semiconductor and research markets, and process etch and deposition tools for the data storage and optical telecommunications industry.

CVC, Inc. provides cluster tool manufacturing equipment for Physical Vapor Deposition (PVD), Ion Beam Etch (IBE), Diamond-Like Carbon (DLC) and MOCVD used in the production of optical components, passive components, bump metallization, and a number of other applications.

GEO Gallium Expands Extraction Plant

GEO Gallium S.A., a wholly-owned subsidiary of GEO Specialty Chemicals, Inc., is expanding the capacity of its gallium plant in Stade, Germany by more than 50%. GEO is the world's leading producer of virgin gallium metal, and is experiencing growing demand from the compound semiconductor and optoelectronics industries. GEO expects this expansion to be on stream by the summer of 2000. A GEO spokesman said they are also considering additional expansion options to meet the future needs of these growing industries.

Since being acquired in September from Rhodia, GEO Gallium has already increased its gallium purification production at Salindres, France by over 30%. This facility purifies gallium to 6N, 7N and MBE grades and produces both generic and custom ingots of gallium. Additional purification and packaging capacity is planned to meet the growing needs of the aforementioned industries.

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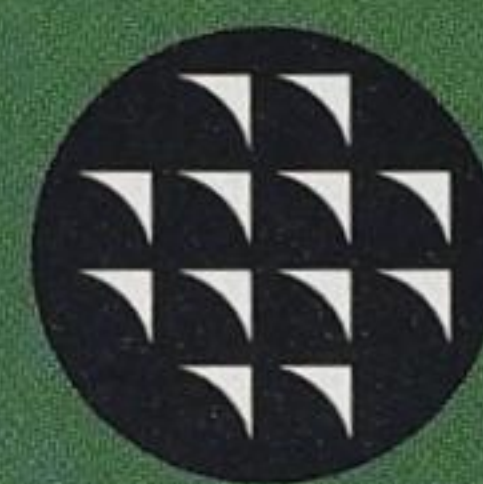


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“Craford’s Law” and the Evolution of the LED Industry

Constant progress has put the LED industry into a whole new light.

MARIE MEYER

The evolution of the computer industry was summed up neatly many years ago by Moore’s Law.¹ The evolution of LED technology has also been neatly summed up, by George Craford, who was recently appointed Chief Technology Officer of LumiLeds, the solid-state lighting joint venture between Agilent and Philips. In his previous role as head of LED development at Hewlett-Packard, he drafted what has become one of one of the most recognizable visuals in our industry – the chart plotting the progress in the performance of visible LEDs, measured in terms of lumens per watt (lm/W). The most up-to-date version of that chart is shown in Figure 1. It illustrates that LED performance has improved at a rate of 10x per

decade. Craford notes that “we just made the goal for the decade of the 1990’s” – his group published a paper on the first-ever 100 lm/W LED in November of last year. And he freely acknowledges that there is a mixture of both “R&D only” plus real product specifications in the chart. Still, it illustrates nicely how far we have come.

When it was put into use in the late 1980’s, this chart had a predictive quality. Thus this author is in favor of recognizing it (somewhat belatedly) as “Craford’s Law”. But, just as Moore’s Law had to be modified to reflect a slowing rate of progress, it is clear that “Craford’s Law” can’t be projected forward. The dictates of physics, not technological challenges, are the problem. To predict another 10x improvement in the current decade would

mean we’d have samples of 1,000 lumen per watt chips by 2010. But the theoretical limit for “perfect” devices peaks at 673 lm/W for green, and at lower levels for other colors. “We can’t go up 10x in this decade, because Mother Nature won’t let us,” says Craford. “But doubling the output of the best LEDs within the next 10 years seems like a pretty good goal.”

The Strategies in Light Conference

Food for thought of this nature was abundant at the “Strategies in Light” Conference, which was hosted by Strategies Unlimited in San Francisco in early February. 250 attendees got a unique chance to hear Craford and others describe the rosy outlook for LEDs. In fact, if it wasn’t such an apt description, the repetition of the phrase “a very ‘bright’ outlook” would have become unbearable (as most puns do, eventually).

Bob Steele, the LED expert at Strategies Unlimited, set the stage by summarizing the market. Worldwide LED sales are currently around \$2.5 billion per year, and the industry has been enjoying double-digit growth rates for the past sev-

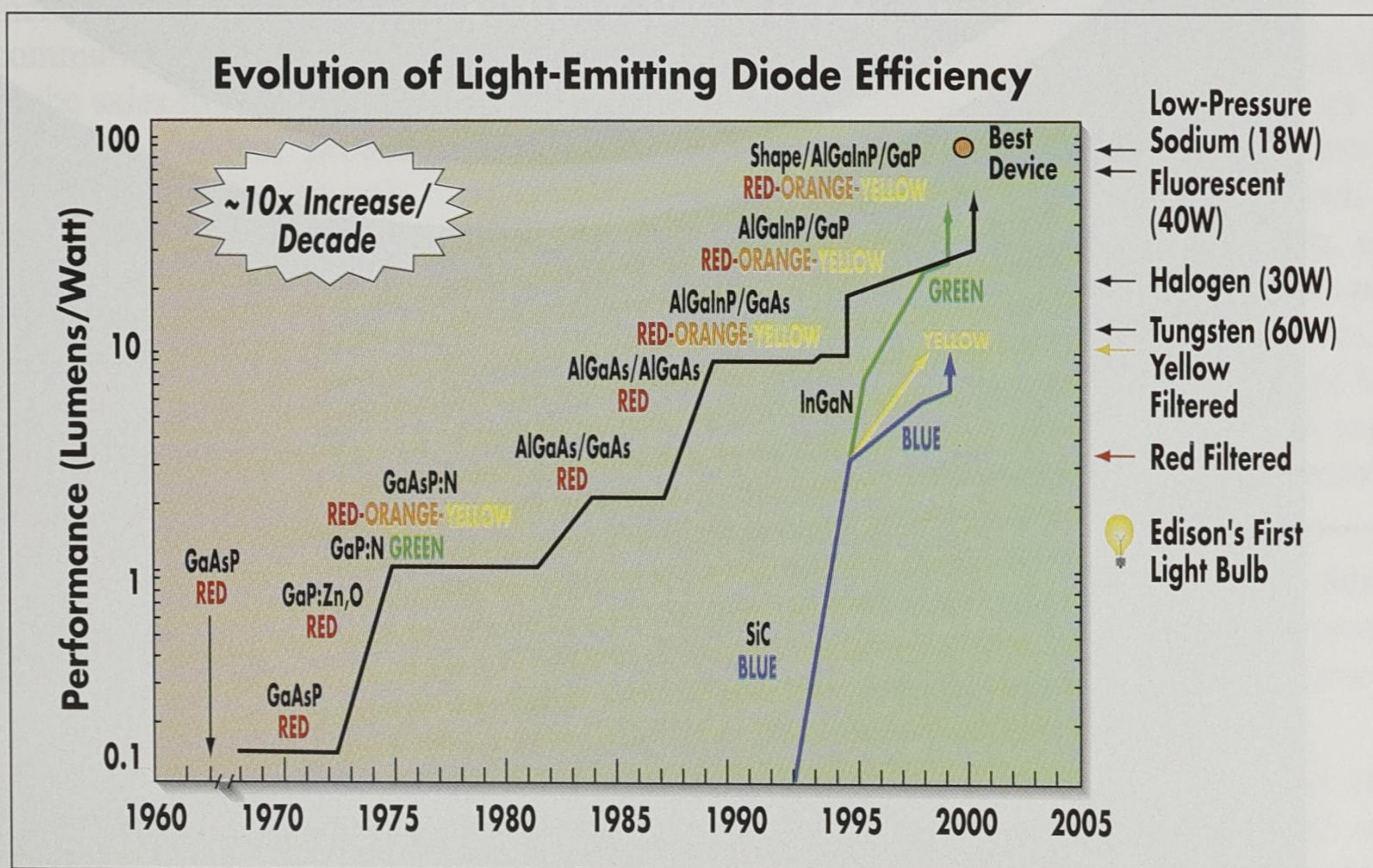


Figure 1. Chart illustrating “Craford’s Law”.

¹ “Moore’s Law” describes the observation made in 1965 by Gordon Moore, co-founder of Intel, that the number of transistors per square inch had doubled every year since the integrated circuit was invented. Moore predicted that this trend would continue for the foreseeable future. In subsequent years, the pace slowed down a bit, but data density has doubled approximately every 18 months, and this is the current definition of Moore’s Law.

eral years. High brightness LEDs now comprise around one-quarter of all LED sales. For these purposes, "high brightness" can be taken to mean all blue and green LEDs and AlInGaP red and yellow LEDs. The development of this market segment has been phenomenal, given that it barely existed before 1994. Over the past five years the overall growth rate for the LED industry has been 10 - 12%, while the high-brightness sector has grown at more than 50% per year.

The majority of the LED devices produced come from companies that are headquartered in Japan. But the U.S. and Germany each also have a respectable market share, largely because of their "national champions" - Agilent and Osram Opto. Schiu Sche of gave a remarkable presentation on behalf of the Taiwan Electric & Electronic Manufacturer's Association, illustrating that country's commitment to breaking into the top ranks of supplier countries. Sche said that "most of the world's leading optoelectronic companies are taking Taiwan as a strategic partner." To illustrate his point, he showed the results of a survey of Taiwanese optoelectronic companies that indicated that LED production in Taiwan will top \$1 billion this year, [See Figure 2.] Sche said that Taiwanese companies have more than 100 MOCVD reactors in use or on order for high brightness LED production. He also delivered a pointed criticism of "certain companies" that, in his opinion, were holding back the market as a whole with patent litigation. "The world market of full color & white LED devices could be significantly increased, if the current IP issues can be resolved," he said.

Display and Automotive Applications

Much of the discussion was marketing-related, including a great deal of coverage of the major application areas. Thus Saco Smartvision discussed large LED videos screens, such as the outer skin of the Nasdaq building in New York (see page 45). LEDs have all but replaced CRTs for large video presentations, especially outdoors - this despite the fact that they provide slightly less of a "true color" image. It came as somewhat of a surprise

to hear that Sony no longer makes large CRT systems - a representative of the famous "JumboTron" Division told the attendees that their eponymous products are now 100% LED based.

In the automotive area, the audience was introduced to the word "chimsel" - CHMSL, which stands for center high mounted stop light. General Motors demonstrated their enthusiasm by bringing an entire Cadillac into the conference room. Cadillacs were the first GM car to use the CHMSL, in 1992. Now the entire tail light section of the car is executed in LEDs. Ron Steen, speaking on behalf of GM, explained that HP/Agilent's transparent substrate AlInGaP technology was key, as its efficiency allowed the number of LEDs needed to be reduced to practical levels. There are now 60 different car models from 20 different manufacturers using LumiLed LEDs in CHMSLs.

Acceptance of LEDs for automotive applications is increasing rapidly, for several reasons. The most familiar is their long lifetime and ruggedness. But there are other factors in their favor as well. LEDs enable styling changes that can help to reduce the overall weight/mass of the vehicle, which produces savings in fuel economy. Their efficiency also means they require less power - "Depending on the bulb configuration, an LED lamp can save up to 8 amps in stop mode," Steen said. This means that more power is left over for other electrical components of the car, which in turns means that the generator can be smaller. This feature alone,

according to Steen, can justify up to one-half of the additional cost of an LED lamp over an incandescent.

Norbert Hiller of Osram Opto Semiconductor focused on interior applications, and pointed out a fascinating movement among car manufacturers - or at least the German ones. Each company is adopting a signature wavelength. Hiller described it as "a sort of color/brand recognition". So whereas all BMWs use 605nm LEDs in their instrument panels,

It came as somewhat of a surprise to hear that Sony no longer makes large CRT systems - a representative of the famous "JumboTron" Division told the attendees that their eponymous products are now 100% LED based.

all Audis use 630nm, and Volkswagen has chosen yet another different point in the blue/green spectrum. He showed an example of an Audi model that already uses 300 - 350 LEDs for various types of interior illumination, and noted that studies suggest that this figure could rise to as high as 850 LEDs in just the interior. For this to happen, the LED would have to capture every spot in the car - not just the dashboard, but also the overhead lights, mirror lights, glovebox, locks, trunk, etc. But interior plus exterior use could result in as many as 1,000 LEDs being used in each car - and there are around 60 million cars produced each year.

"White Light" Applications

The biggest potential application for LEDs is in general lighting. This is variously described as "solid-state lighting" or "general lighting" or sometimes just

LED Production in Taiwan US\$ Millions					
	1996	1997	1998	1999	2000
Chips/Epi Wafers	\$120	\$182	\$215	\$254	\$296
Devices*	\$371	\$439	\$514	\$592	\$683
Display Screens**	\$49	\$52	\$65	\$81	\$91
Total	\$540	\$673	\$793	\$926	\$1,069

*Sometimes defined as "lamps"

**Sometimes defined as "displays"

Figure 2. The results of a survey of Taiwanese optoelectronics producers, estimating the total LED-related production in Taiwan.

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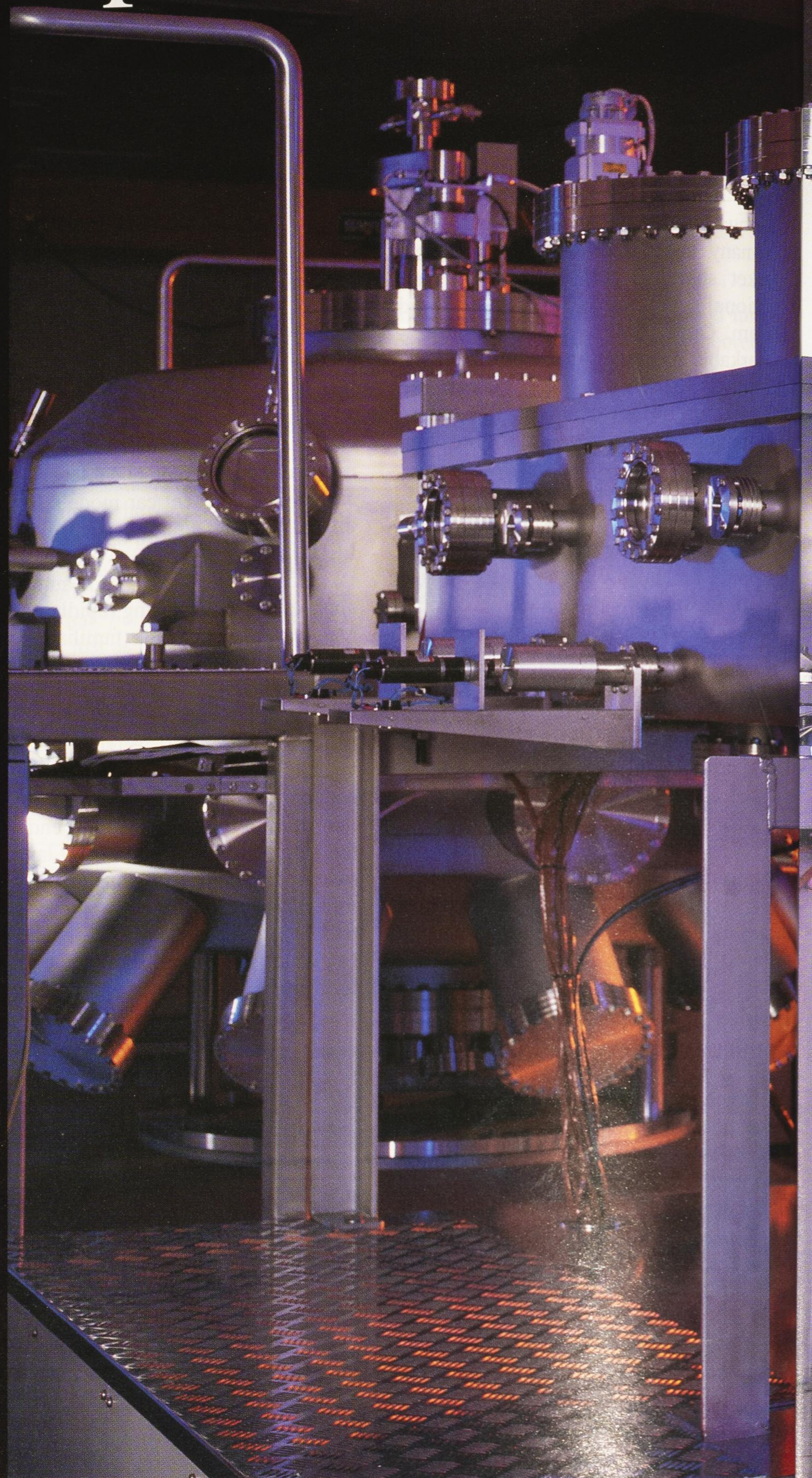
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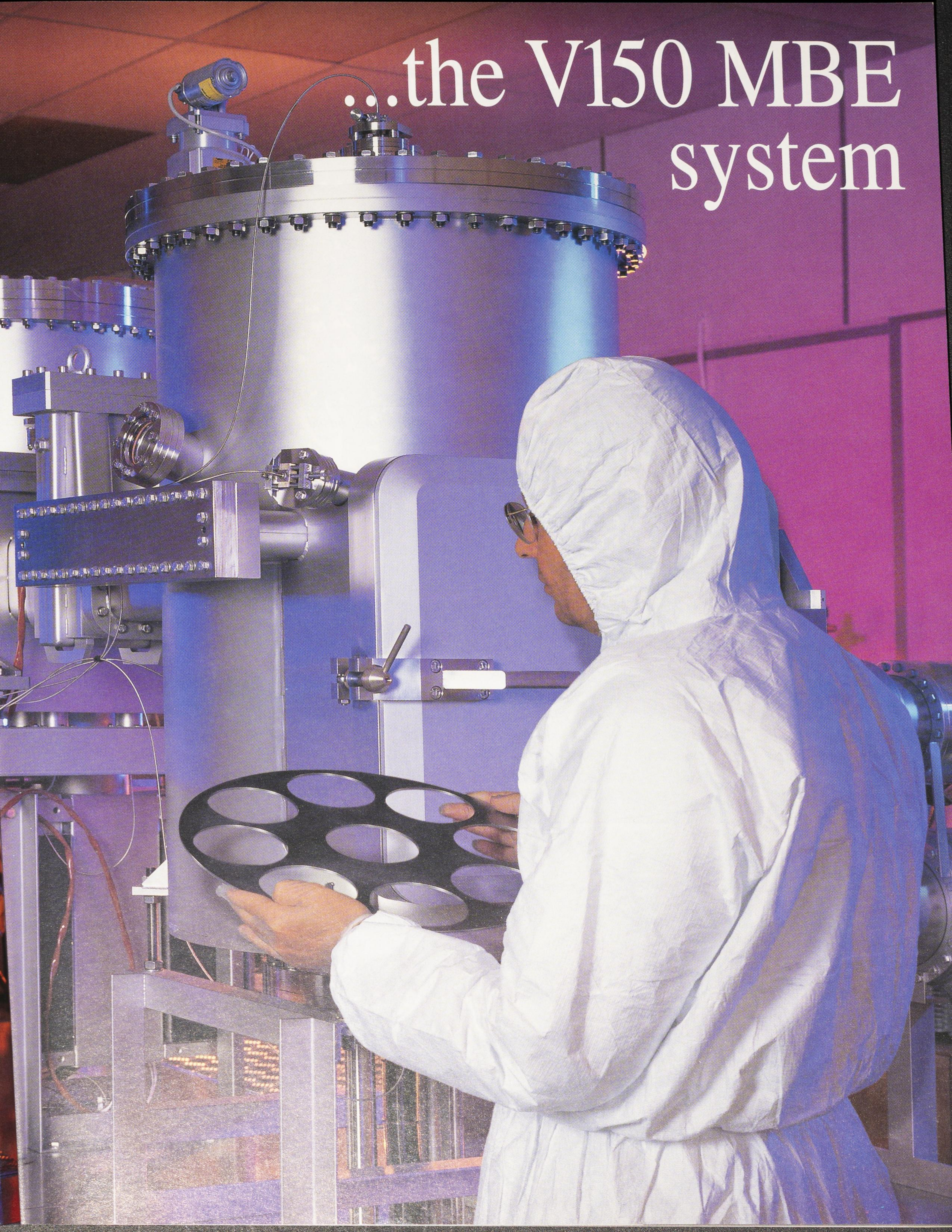
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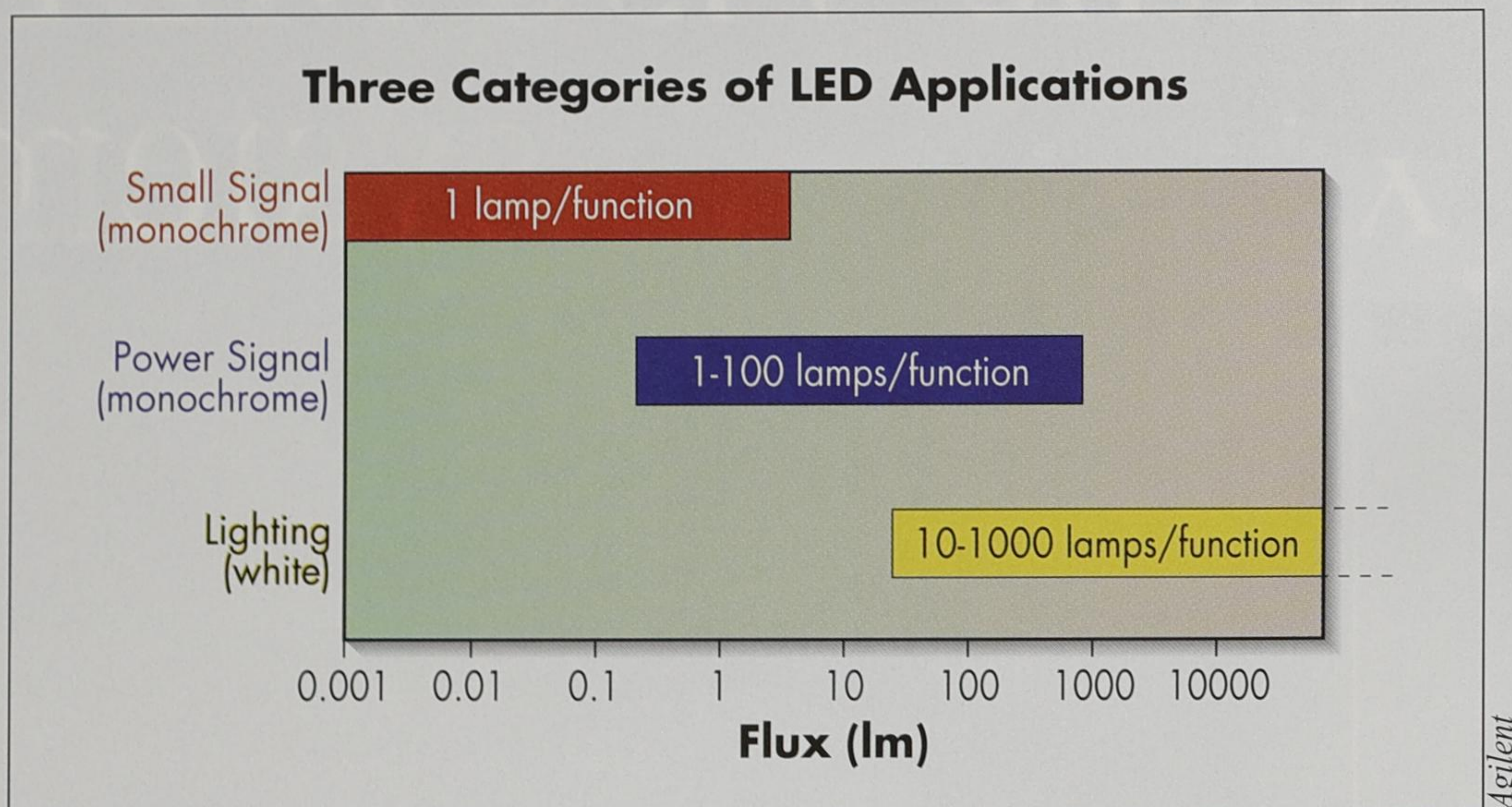


Figure 3. A classification scheme for the major categories of LED applications, based on the required output (in lumens) and the number of die required.

“white light LEDs”, but ultimately the goal is the same: to replace light bulb and fluorescent tubes with fixtures that use LEDs.

The global lighting market is current valued at \$12 billion. That includes incandescent, florescent and halogen technologies. It is impossible to estimate, at this point, what the ultimate share for solid-state technologies might be. The technology is just too immature.

Solid-state lighting is a completely new category of application for LEDs, as shown in Figure 3. As classified by a Roland Haitz, speaking on behalf of a study group from Agilent and Sandia National Lab, the traditional uses for LEDs as indicator lights in appliances, etc. are considered to be “small signal applications”. Most of the current uses for high brightness LEDs, such as the automotive applications discussed above, fall into the “power category”. To make this new “lighting” category a reality, significant improvements in white LED efficiencies will be needed.

Different targets were discussed at the conference, but the general consensus is that the industry needs to attain at least the 150 lm/W level. The presentations by Haitz, Craford and by Steve Denbaars of

Nitres made it clear that there is still a great deal of work to be done before these goals can be attained.

The Agilent/Sandia group has proposed 200 lm/W, which is approximately 20x better than the currently available technology. There is already a national program underway in Japan to improve white light efficiencies, and it was pro-

It will be necessary for the industry to achieve significant improvements in the efficiencies of all colors of LEDs in order to take advantage of the enormous opportunities presented by the general illumination market. If 50% efficient red, green and blue LEDs were available in production quantities, then it would be possible to reach the target of a 200 lm/w white light LED.

posed that the United States should do the same. (For more on this, see page 34).

The most familiar sort of white light LED today - the blue LED coated with a phosphor² - will likely not be the most common white light LED in the future. This is an inherently inefficient device, as a large percentage of the photons emitted by the LED are lost in the color conversion process. Color mixing will likely be used instead for general illumination markets. Color conversion LEDs will still have applications where a point source with a very simple fixture is required. A good example of such a use is the dome light in a car.

Color mixing can be done in a num-

ber of ways. Elsewhere in this issue we describe how one company is doing it using amber and blue LEDs (see page 43). A “true” white, more pleasing to the eye, can be achieved using three colors: red, green and blue. This method is, of course, the heart and soul of the large video screen application, but it can also be done on a compact scale. Still better color rendering, for more specialized applications, can be achieved by adding a yellow LED.

It will be necessary for the industry to achieve significant improvements in the efficiencies of all colors of LEDs - blue, green, yellow and red - in order to take advantage of the enormous opportunities presented by the general illumination market. The 100 lm/W red LED from Agilent mentioned earlier exhibited 50% quantum efficiency. Craford and others proposed that it would be a suitable goal to try to achieve this same performance in other colors as well. If 50% efficient red, green and blue LEDs were available in production quantities, then it would be possible to reach the target of a 200 lm/W white light LED. The consensus among the speakers who addressed this topic was that we are probably at least 5 years away from this goal.

Conclusion

The Strategies in Light Conference created the definite impression that the LED industry, already tremendously interesting, is going to be

even more exciting in the years to come. In the conclusion of his talk, Nobert Hiller observed that LEDs deserve to be considered as the lighting technology of the 21st century, the worthy successor to candles and incandescent bulbs. It seems to be a very apt description.

Next year's Strategies in Light Conference will be held Feb 8 -9, 2001. For more information, contact Strategies Unlimited at Tel: +1 650 941-3438; Fax: +1 650 941-5120; or Email info@strategies-u.com

² See page 21 for an alternative method of making a color conversion white LED.

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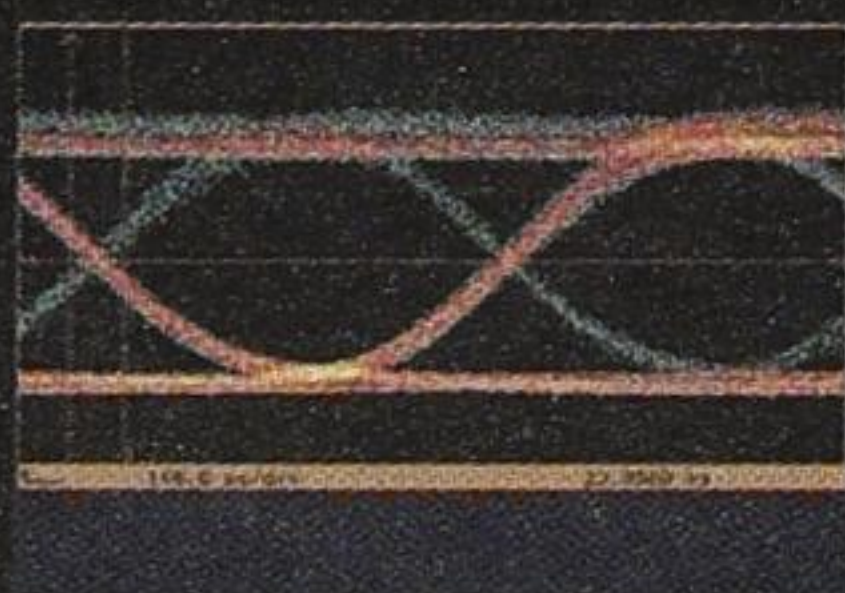
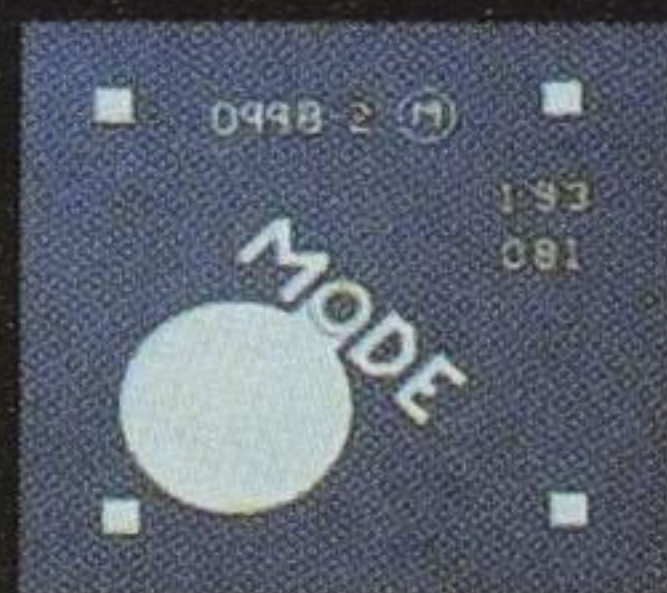


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Toyoda Gosei Spotlights New High Brightness LEDs

Toyoda Gosei continues to improve the performance of its high brightness blue and green LED devices, making them suitable for a wide range of applications.

RICHARD DIXON

Toyota is one of the world's leading car manufacturers. One of its business units, Toyoda Gosei, supplies rubber and plastic parts for its automobiles. Yet despite the fact that less than 5% of Toyoda Gosei's business is in optoelectronics, the company is also one of the world's largest suppliers of high brightness blue and green LEDs. Toyoda Gosei has also recently previewed new higher brightness versions of its blue and green LED devices.

Historical Perspective

Established in 1949 as the Nagoya Rubber Company, Toyoda Gosei changed its name to the present one in 1973. Currently it employs more than 6,000

"By the end of the year we hope to have reached a capacity of 50 million LEDs per month"

people and had a sales turnover of 199,300 million Yen (\$1.8 billion) in 1998.

The company's optoelectronics products division shares a 39,600 m² (~ 350,000 sq. ft.) facility with the functional parts, air bags and weather strips businesses at Nakashima in Japan. This division houses its LED production and also R&D, which includes GaN-based blue lasers (see below).

Toyoda Gosei's move into optoelectronics came relatively recently in its history. The company began shipping blue LEDs based on a *p-n* double heterostructure in 1995. Blue and green LEDs that employed a MQW structure were introduced two years later.

The company mainly produces chips, but also epiwafers and has Agilent Technologies as one of its customers.

Toyoda Gosei outsources LED packaging and has agreements with several companies in Japan, including Matsushita, one of its major customers, and Sanken.

It is also widely known in the optoelectronics industry that for the past three years, the company has been involved in

patent infringement disputes with Nichia [see CS 5(4) p. 6] concerning the development of *p-n* junction GaN devices. According to Ryo Onishi, general manager of the company's Optoelectronics sales division, Toyoda Gosei currently does not believe this to be a major problem.

Indeed, since the company entered the LED business it has continued to increase its presence, and is now rated as one of the top three producers of blue and green LEDs, behind Nichia and Cree [see CS 5(5), p. 15]. According to Onishi, Toyoda Gosei aims to increase production capacity to around 35 million LEDs per month by this spring. "By the end of the year," he says, "we will be adding even more capacity, when we hope to have reached a capacity of 50 million LEDs per month."

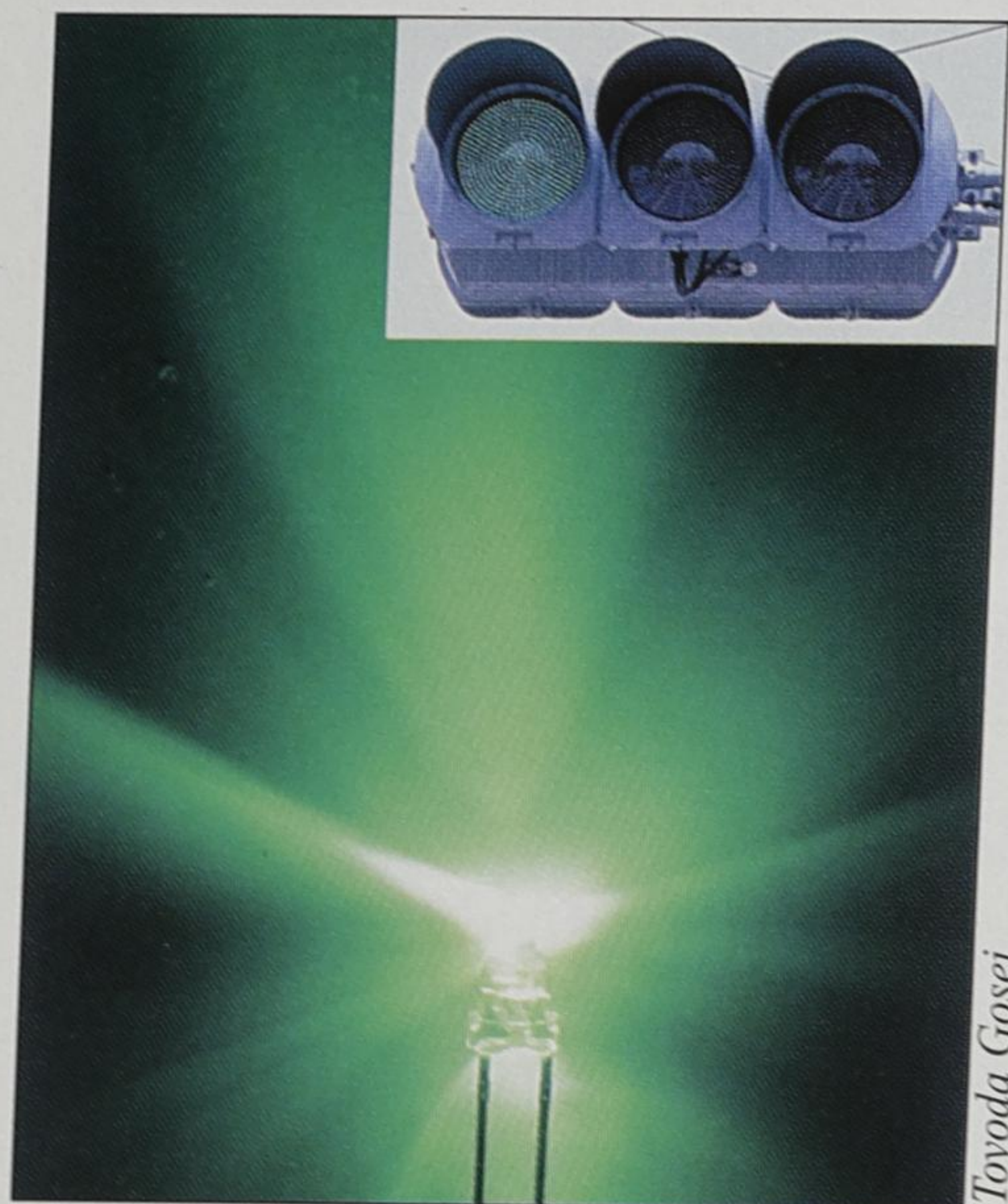


Figure 1. Toyoda Gosei's new high-brightness blue and green LEDs feature an inverted flip-chip design. This reduces total internal reflections and allows more light (up to 14 cd for the green device) to escape through the transparent sapphire substrate, making the LEDs very suitable for applications such as traffic lights.



Figure 2. Full-color LED video sign advertising one of Toyota's car showrooms in Tokyo.

Which is a lot of LEDs. Interestingly, Onishi says Toyota Gosei is actively seeking new applications for these light sources.

Displays and Signage

Traffic lights and full color displays are listed among the main applications for the company's LEDs. 1998 saw Toyota Gosei debut a 4 x 4 inch (96 x 96 mm) full color display unit. These panels were less than 1 inch (22.7 mm) thick and weighed just 5.6 oz (160 g), achieved by mounting the LEDs directly to the display's substrate.

For the high intensity displays, Toyota Gosei uses its 'Hi-series' LED lamps, which consist of sapphire substrate-based blue (470 nm) and green (525 nm) InGaN LEDs. These are available in round or oval type lamps or in chip form, with typical outputs of up to 2.5 and 5 cd, respectively, depending on the exact package configuration. Toyota Gosei buys red LEDs to complete the red-green-blue (RGB) 'pixels' used in its displays. These can be supplied as 4 mm, round-type 'pixel' LED lamps or as a '3-in-1' chip type device.

The company has also recently reported new high brightness InGaN LEDs that use flip-chip technology to optimize the available light output. These blue and green devices are now much brighter, offering wide viewing angles (up to 120°), and high resistance to electrostatic damage (ESD).

Certain cell phones contain several red, green and blue LEDs that can be programmed to provide a range of backlighting colors.

Toyoda Gosei's Masayoshi Koike chose this January's Photonics West meeting in San Jose (CA) to describe these new devices, which feature a double-layer MQW active region and flip chip arrangement that leaves the transparent sapphire as the front emitting face. This configuration leads to less scattering from the electrode materials used for the contacts. External efficiencies are now as high as 20% for the blue device and 17% for the green chip, says Koike. The new 464 nm blue (FWHM = 27 nm) devices offer a very usable 6 cd (at $I_f = 20\text{mA}$). The 515 nm version is a bluish-green LED with a 32 nm FWHM that is capable of an impressive 14 cd of luminous intensity (Figure 1). These LEDs will be used in future displays products and other applications, says Onishi.

Another popular use of the company's LEDs are as backlights for small displays used in cell phones. This represents a potential high-volume application for LEDs, says Onishi, particularly as the number of cell phones is increasing dramatically.

Onishi says that a cell phone typically uses 3 to 4 red, green and blue LEDs that can be programmed to change the color mix and provide a range of backlighting colors. The color is selected using a switch on the phone. This feature has proved very popular in Japan, he says, and is used in cell phones made by many of the big phone manufacturers, such as Panasonic, NEC, Mitsubishi, Sony and others.

Automotive Applications

Toyoda Gosei is also well set up to provide LEDs to automotive manufacturers, including Toyota (whose showrooms also

benefit from Toyoda Gosei's full-color displays - see Figure 2).

Automotive uses include high center mounted stop lights, and also interior lighting and variable dashboard illumination (see Figure 3). Dashboard moodlighting allows a range of back-lighting based on the preference of the driver. Another variation is the use of illuminated instrument indicators, which are available in red, green or blue on a traditional black background.

The company also incorporates what it describes as 'side-step' lighting on some of Toyota's cars. This combines both function and style - LEDs are placed in a line along the bottom of the door frame to replace the usual safety reflectors.

Laser Research

Toyoda Gosei's optoelectronics business unit also undertakes research into semiconductor lasers. The company has developed prototype devices, and is currently working on the reliability of InGaN-based blue lasers, the results of which were also outlined by Masayoshi Koike at Photonics West.

Koike described room temperature data from CW-operated separate confinement heterostructure (SCH) GaN/InGaN MQW lasers operating at 410 nm. These diodes have been improved by introducing GaN/InGaN optical guiding layers to replace the conventional GaN optical guiding layer, he says. AlGaIn is used for the cladding layers. In addition, an InGaIn/GaN double guide layer is incorporated in combination with mirror facet coatings. Koike reports that threshold current densities have been reduced to around 2.4 kA/cm² for room temperature CW operation.

Device lifetime still remains one of the major obstacles to commercialization. Koike revealed that constant current operation above threshold (60 mA) and with a power of 1 mW led to an increase in the operating current in around 20 hours.

The company is not the only one chasing Nichia's blue laser diode lead. But given its demonstrable commitment to research into InGaIn-based devices, Toyoda Gosei is well placed to maintain its position among the big optoelectronic players in the future.



Figure 3. Dashboard panel featuring user-selectable color backlighting, which is also being employed for small cell phone displays.

Another Semiconductor Revolution: This Time It's Lighting!*

ROLAND HAITZ and FRED KISH,
Agilent Technologies, Palo Alto, CA

JEFF TSAO and JEFF NELSON,
Sandia National Laboratories, Albuquerque, NM

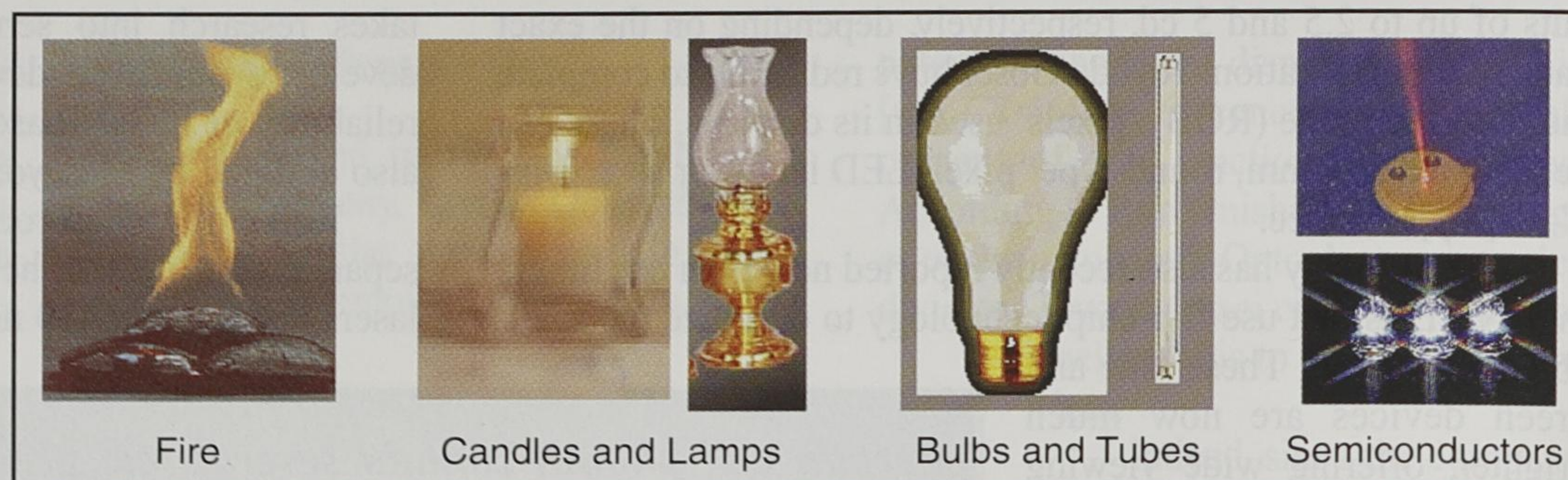
Energy is the lifeblood of our economy, and a critical building block for global peace and security. Its generation incurs huge economic and environmental costs (i.e., smog and particulate emissions, acid rain, global warming, waste disposal). And, the economic costs will only increase as concern heightens over how to reduce the environmental costs. As a consequence, there is great benefit to enhancing the efficiency with which energy is used—virtually all major energy consumers from transportation to heating to electrical equipment are constantly being examined for energy saving opportunities.

It is the purpose of this white paper to call attention to this new lighting technology and to the potential impact of a concerted national effort to advance it further.

Among the most widespread, important, and growing uses of energy is electricity used for lighting. In the U.S., about 20% of all electricity, and about 7.2% of all energy, is consumed by lighting. Worldwide, the percentages are similar. As a consequence, improvements in lighting efficiency would have major consequences on U.S. and worldwide energy consumption.

Until recently, significant improvements would have been considered impossible. As illustrated in Figure 1, none of the conventional “tube” technologies—incandescent, halogen, and fluorescent—has improved significantly during the last 30 years. Recently, however, semiconductor light-emitting diode (LED) technology has emerged. Red LEDs are now efficient and bright enough to be able to replace incandescent and halogen lamps in traditional monochrome lighting applications such as traffic lights and automotive tail-lights. And, recent developments in green and blue LEDs are enabling the first applications in white lighting.

It is the purpose of this white paper to call attention to this new lighting technology and to the potential impact of a concerted national effort to advance it further. Such an effort



would target the technology we believe has the highest potential to be the lighting source for the new millennium, and the highest potential, in our assessment, of reaching the lighting holy grail of an efficiency of 200 lm/W (lumens/Watt).

Semiconductor Lighting

The use of semiconductors to produce light is not particularly new. The first LED was demonstrated as far back as 1962 by General Electric, and the first LED products were introduced in 1968 by Monsanto (indicator lamps) and Hewlett-Packard (LED

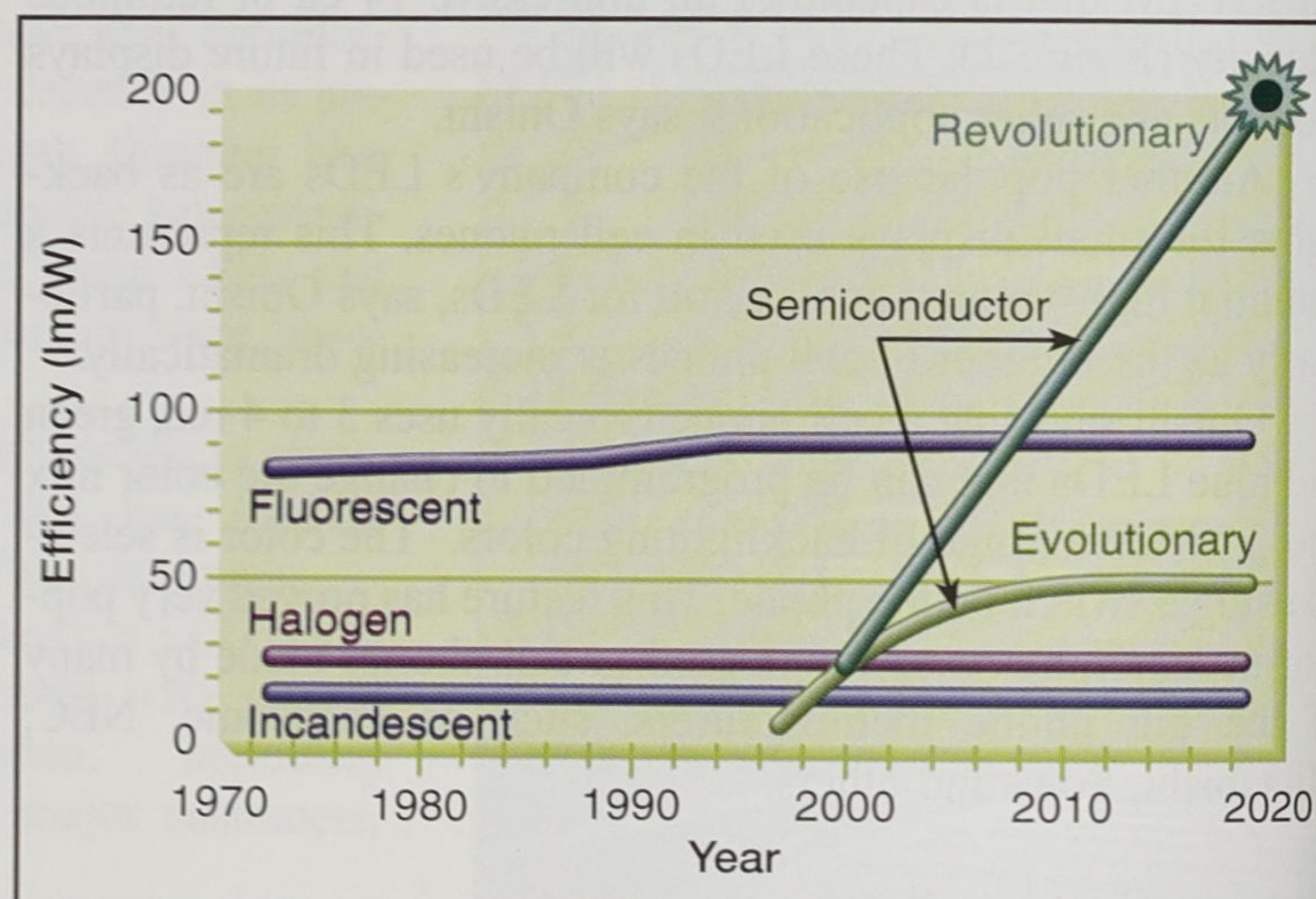


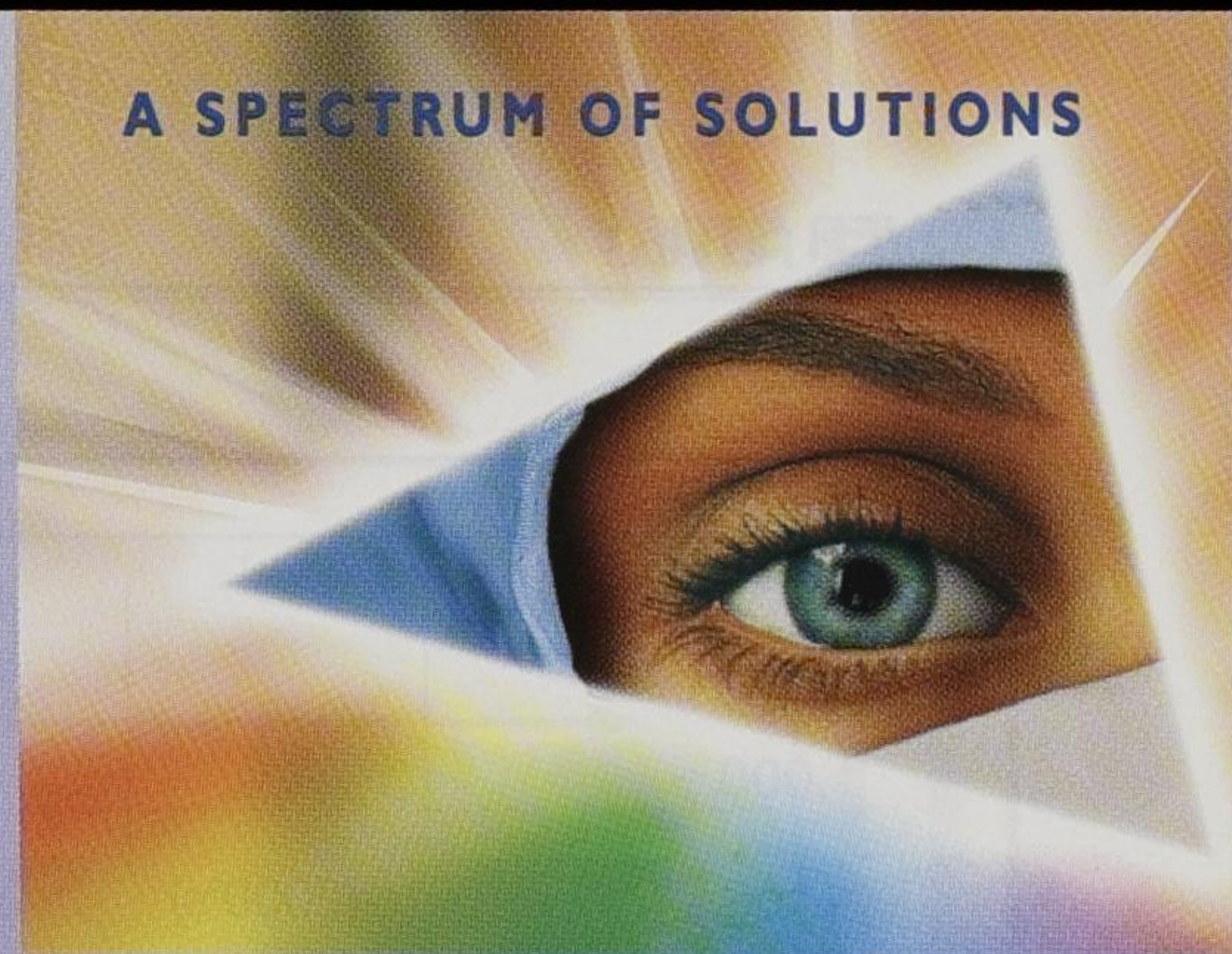
Figure 1. History and projection of efficiencies (in lm/W) of conventional “tube” (incandescent, halogen and fluorescent) and semiconductor (LED) white lighting technologies.

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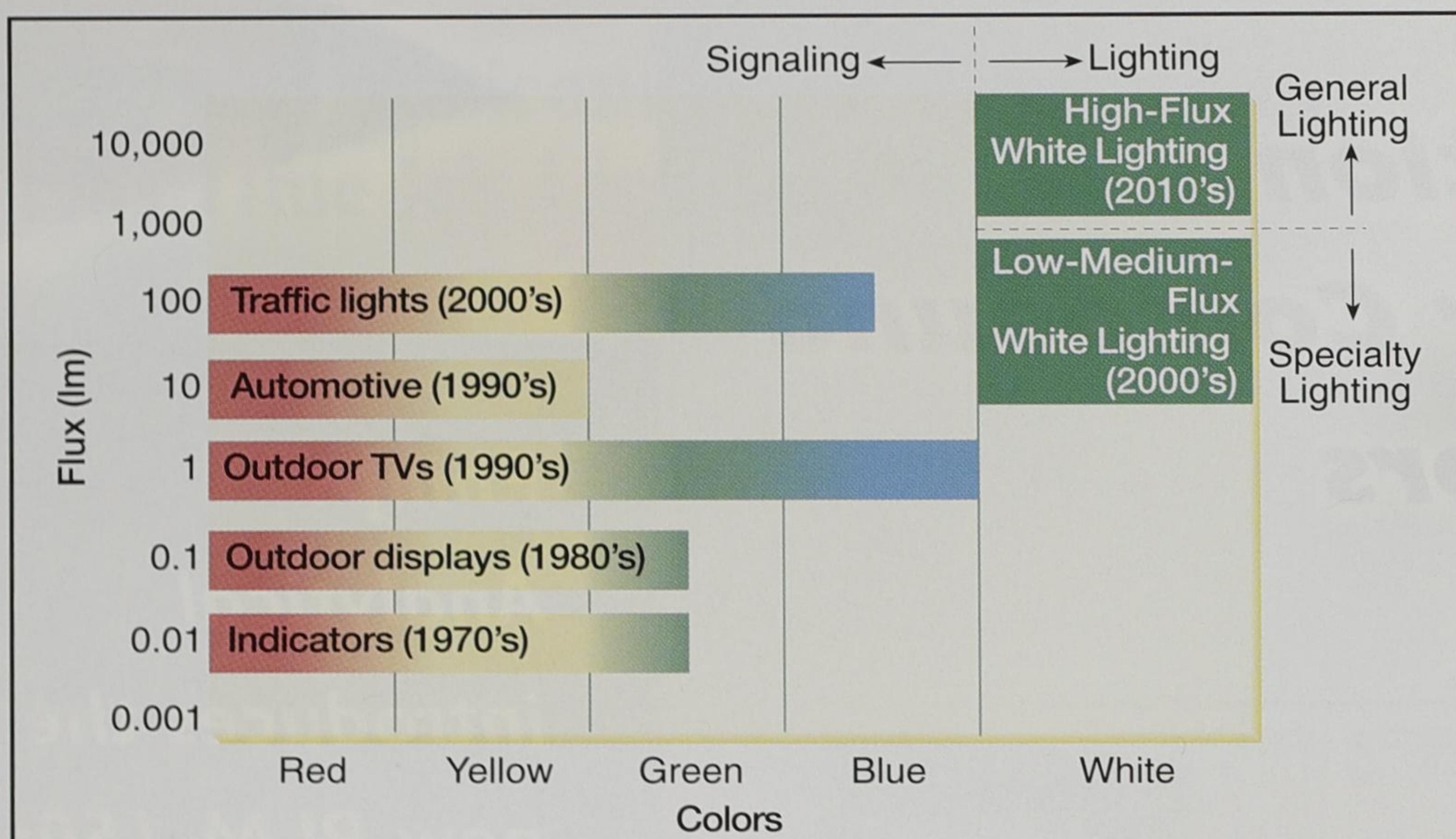


Figure 2. The stepping stones in output flux and color for semiconductor lighting applications from low-flux indicator lamps (lower left) to medium-flux power-signaling lamps and specialty white lighting (middle), to high-flux general lighting (upper right).

displays that replaced Nixie tubes). However, throughout the 1970's and 1980's, their output flux and electrical-to-optical conversion efficiencies were low, and their uses were limited to small-signal (10–100 milli-lumens) applications such as indicator-lamps and displays in the red to yellow-green part of the spectrum.

During the last decade, however, the technology of LEDs has improved remarkably in two ways: (1) higher

We do not believe that 50 lm/W represents the ultimate limit of the semiconductor lighting technology.

output flux and conversion efficiency and (2) coverage of the entire color spectrum including green and blue. Today, monochrome LED efficiencies substantially exceed the efficiencies of filtered incandescent lamps, and white light LED efficiencies are slightly better than the efficiencies of unfiltered white incandescent lamps. These improvements have opened up new applications in power signaling and specialty white lighting, which in turn will drive continued evolutionary improvements in LED technology. Our best projections are that white LED efficiencies will increase from 20 lm/W today to 30 lm/W in 2002, 40 lm/W in 2005, and 50 lm/W in 2010.

Indeed, with these projected evolutionary improvements, we also anticipate some penetration of general lighting (see Figure 2). The main impediment is the substantially higher cost of LEDs compared with conventional lamps, a cost differential that must be recovered within a “reasonable” time through energy savings. For that part of the general lighting market served by

incandescent lamps, we expect the cross-over point to be the year 2002, when the cost of the LED lamp can be recovered within 3–6 years through lower operating cost. From then on, LED-based lamps will gradually replace incandescent lamps. Assuming, conservatively, a 25–30% replacement of incandescent and halogen lamps by the year 2025, we estimate the global energy savings to be 400 TWh/yr, corresponding to a cost savings of about \$40 B/yr, and a decrease in required generating capacity of nearly 50 GW.

But, at an efficiency of 50 lm/W a white LED lamp converts only 12% of its input energy into light. *We do not believe*

that this level represents the ultimate limit of the semiconductor lighting technology. And we have good reasons to be hopeful. In 1997 Sandia National Laboratories demonstrated an energy conversion efficiency of over 50% for a novel device, a so-called vertical cavity surface emitting laser (VCSEL). This demonstration was done at a wavelength range in the infrared where it is fairly easy to design and build VCSELs: 850–980 nm. Another important milestone was a 1999 experiment by Agilent Technologies demonstrating a 45% conversion efficiency with a specially shaped red LED.

What keeps us from replicating these VCSEL and/or LED results in the rest of the visible spectrum between red and blue? Not the laws of physics, but the not so precisely definable law of “Conservation of Trouble.” So far, no one has succeeded in making a VCSEL at a wavelength shorter than red. And we need arrays of several hundred VCSELs in small chips that for cost reasons, should not exceed 1 mm². The shaped LED chips are a similar headache. They do not scale to larger chip size without giving up most of the efficiency we gained by chip shaping. And last, but not least, we have a color gap in the 530–590 nm range (see Figure 3). For an experienced III-V technologist, this set of circumstances looks like a “Mission Impossible.”

Why then do we propose a project of such extraordinarily high risk? One reason is our boundless optimism that is fueled by the steady and, at some times, surprising progress of semiconductor technology generally and LED/VCSEL technology in particular. The other reason is the pot of gold at the end of the rainbow. If the LED/VCSEL technology succeeds in building 200 lm/W lamps, then we can attack even fluorescent lamps, revolutionize the lighting industry, reduce the consumer's electricity bill and, at the same time, make a significant dent in the steadily increasing global consumption of electricity. No other major electricity application (motors, heating, refrigeration) represents such a large energy savings potential. And no other energy savings potential presents such an attractive return to investment ratio. To be specific, if the

LED/VCSEL breakthrough attempt is successful, we should be able to achieve a 50% market penetration (measured in fraction of light flux generated by LED/VCSEL technology) by 2025. Globally, this penetration should translate into electricity savings of 1000 TWh/yr, cost savings of \$100 B/yr, power generation capacity reductions of 120 GW, and carbon emission reductions of approximately 350 Mtons/yr (assuming that all the savings come from coal-fired plants).

The Breakthrough Attempt

In the previous section, we briefly touched on the degree of difficulty to achieve a breakthrough from the evolutionary LED projection of 50 lm/W to the revolutionary LED/VCSEL goal of 200 lm/W. To the authors of this paper, who have a combined III-V experience of 60 years, this task looks formidable. At one time, we compared it to the Manhattan Project. From this comparison arose the concept of a national program on semiconductor lighting research with the goal of attempting a performance breakthrough to the 200 lm/W level. But, this performance alone is not sufficient to revolutionize the lighting industry. In addition, we have to bring the lamp cost close to a level such that we have a "reasonable payback time" even when replacing the most efficient fluorescent lamps. And, finally, we have to meet a level of "lighting quality" that the user expects. This latter issue is not well defined at this time, because we don't know yet what lighting quality problems we will encounter.

It is because of this large risk, coupled to the enormous potential benefit, that we propose a concerted, coordinated national effort, and a major government investment: We recommend \$500 million over a ten year period.

Moreover, the U.S. also benefits as a nation in one additional indirect but important way. The compound semiconductors on which this new lighting technology would be based are the foundation for the next-generation high-performance optoelectronic and microelectronic components critical to national security. In terms of sheer volume, general lighting will be the "killer app" for compound semiconductors, and will drive the development of its tool and process infrastructure. The nation that is at the forefront of this killer app will be in the best position ultimately to exploit its spin-off applications for national security.

We propose a concerted coordinated national effort and a major government investment—we recommend \$500 million over a ten year period.

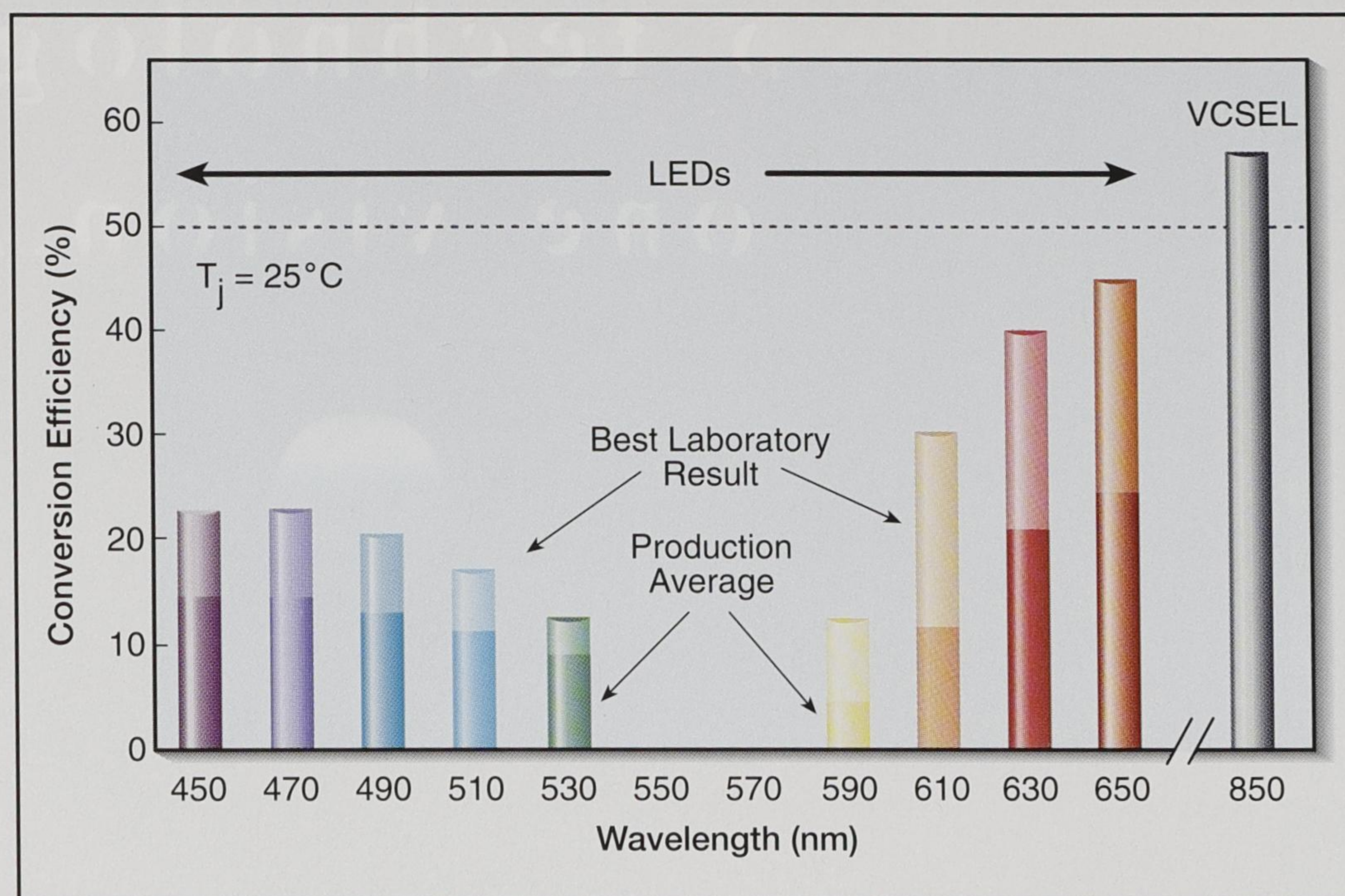


Figure 3. Best laboratory results and production averages for LED electrical-to-optical power conversion efficiencies. The two grand challenges are (1) to close the wavelength gap in the green/yellow, and (2) to raise the efficiencies at all wavelengths to 50%.

And, finally, vision is arguably our most basic sensory input. The quality of our living experience depends critically on the quality of the lighting that enables us to see. This new light source promises to change completely the quality of our lighting experience. LEDs and their semiconductor variants have the potential to be programmable in intensity and color, so that virtually any desired flux and color may be produced, at any time and at any place. And their compactness and cool operation have the potential to revolutionize the way in which lighting sources are integrated into our living environment.

We believe a major government R&D investment in semiconductor lighting, large in absolute terms but modest in relation to its energy impact, can trigger a paradigm shift benefiting every consumer in the country and, through its environmental impact, every human being on earth!

** A long version of this paper was first presented publicly at the 1999 Optoelectronics Industry Development Association (OIDA) forum in Washington DC on October 6, 1999, and is available by request from bjkazmi@sandia.gov.*

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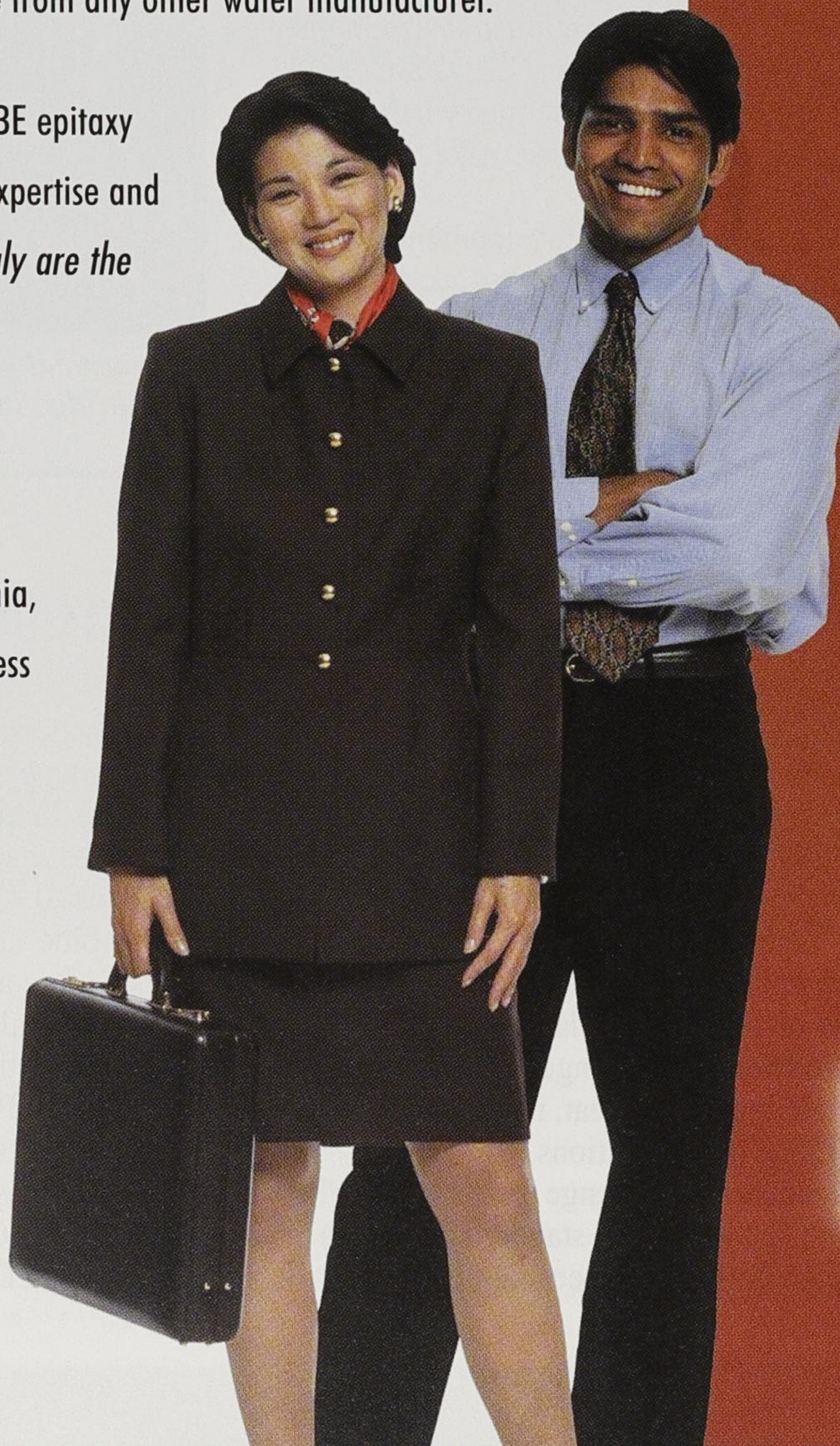
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Engineering with High Brightness LEDs

With advantageous properties such as high brightness and reliability, low power consumption and long lifetime, LEDs are ideal for a large number of applications including illumination, displays and signage. Here, we profile three companies - LEDtronics, Gentex and SACO SmartVision – that are applying their advanced design and engineering expertise to get the best from the humble LED.

RICHARD DIXON

High brightness LEDs are now found in a range of applications including traffic lights and signage, automobiles and large-area outdoor displays [see CS 6(1) p. 70]. A number of niche applications have also emerged for colored and white LEDs, including rear bicycle lights, white LED flash lamps, and architectural lighting (see front cover of this issue and figure opposite).

LEDs offer a number of advantages compared to existing light sources. These include increased lifetimes (up to 5-10x those of incandescent sources), reduced power consumption and size, higher brightness and better spectral purity. In addition, LEDs are “cold” light sources, allowing direct illumination in situations where excessive heat would be detrimental or would otherwise make the changing of fixtures difficult.

While there is now intense interest in the development of higher brightness LEDs for a range of new applications, each of these applications brings its own specific set of engineering considerations. Here, we look at how three companies are embracing LED technology and are incorporating these devices into their products.



140 vertical strips of white LEDs illuminate this 70-meter-long bridge in Duisburg, Germany.

LEDtronics Supplies LED Products for All Occasions

LEDtronics Inc., an LED lamp packaging company based in Torrance, CA supplies a wide range of innovative products based on colored and white LEDs. The company specializes in direct incandescent replacement LED lamps, with products including LED beacons, miniature lamps, flashlights and lighting products for safety equipment. LEDs have numerous advantageous features for such applications - they are lightweight, robust and make efficient use of power. LED lamps use 80% to 90% less power, and last ten to twenty times longer, than standard incandescent lamps and generate little or no heat, making them an ideal light source for a wide range of applications.

Among LEDtronics' products are a range of “specialty” lights with standard fixtures, including a standard (Edison) screw-type fixture called the DecorLED™ [see Figure 1]. This

features a wide viewing angle of 270°, and is designed for theme parks, and stage and architectural lighting. A 30° version is also available for outdoor temperature signs, scoreboards, billboards and animated displays. Using a 120 V supply, these LED lamps consume just 0.7 W and provide luminous intensities as high as 24 cd for blue and green, and 12 cd for white. Moreover, the products feature a rugged, UV-protective polycarbonate bulb that is shatterproof, all-weather and low maintenance. “You can kick this bulb across the room, screw it in and it will still light,” says Pervaiz Lodhie, President of LEDtronics.

Larger arrays of LEDs can be employed as safety beacons, says the company. The BeaconLED™ [see Figure 2] contains anywhere from 16 to 96 individual LEDs, the latter employing tiers of white LEDs arranged radially. These lights also have stan-



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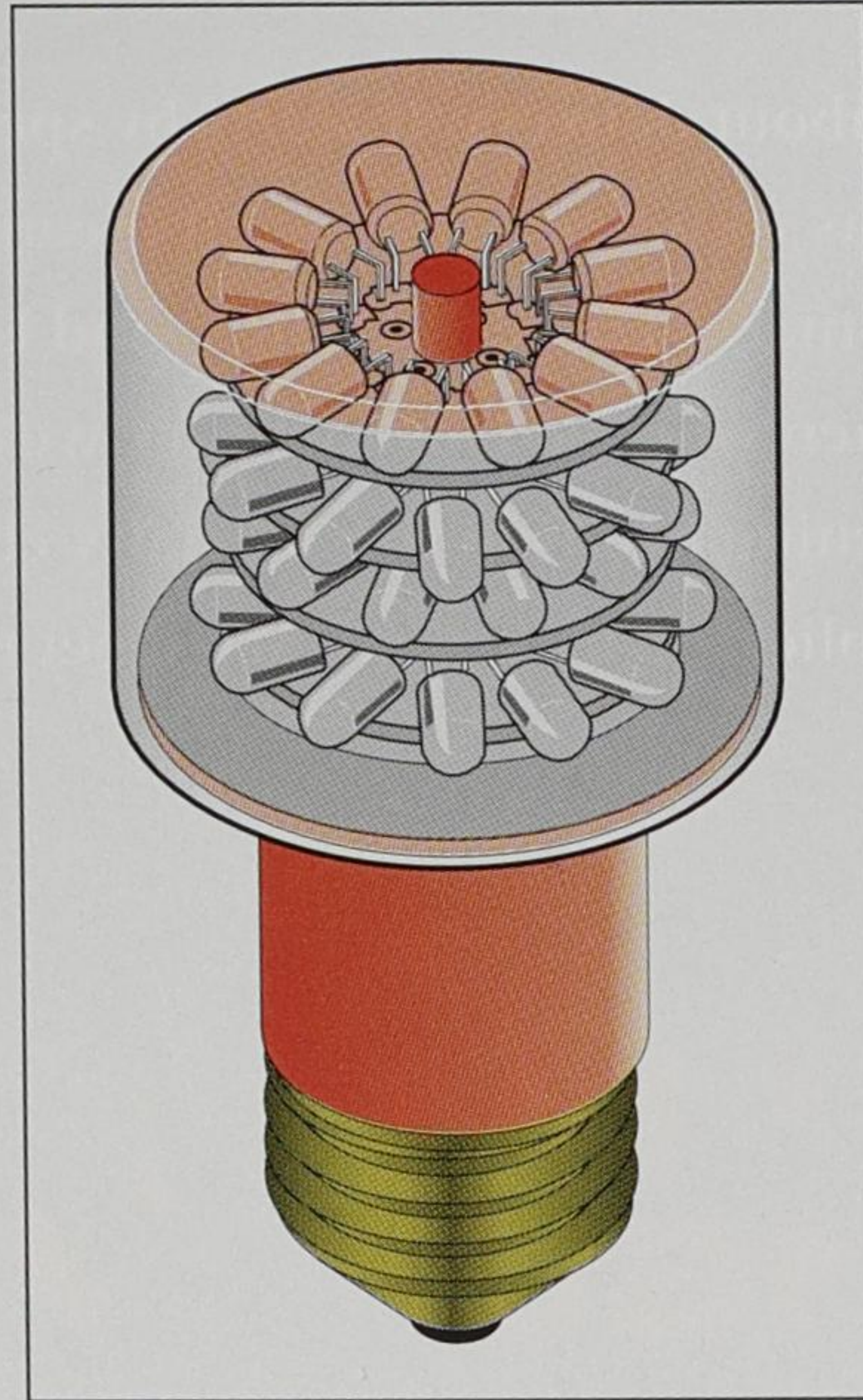
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LEDtronics

Figure 1. The DecorLED™ contains a cluster of 18 LEDs encapsulated in a polycarbonate bulb with a wide viewing angle of 270°. The lifetime exceeds 100,000 hours and the product is extremely resistant to shock, vibration and temperature extremes.



LEDtronics

Figure 2. The BeaconLED™ contains between 16 to 96 individual LEDs arranged in tiers in a radial fashion, and has a standard Edison screw-type base.

standard Edison screw-type bases and are aimed at heavy industrial applications such as machine tool marker lights, and as beacons for bridges, tall structures and other architectural applications. For remote locations or where power sources are not readily available, the SolarLED™ cluster LED lamp is designed to operate from a solar-powered photovoltaic source, and draws much less energy than equivalent incandescent bulbs.

As shown in Figure 3, clusters of three or six LEDs have been incorporated into flashlights FlashLED® and task lamps with a range of colors. Another application for red LEDs is in flashing safety vests [Figure 4]. These provide the wearer with high visibility in dangerous work environments such as highway construction, accident and emergency situations or traffic management.

Choosing the Right White LED

A large number of LEDtronics' products utilize white LEDs. Marketing manager Jordon Papanier says that the introduction of these devices has significantly increased the interest in LED lighting. However, he adds that these lighting devices have also raised an equal number of questions concerning both their capability and how they can be used. "Previously, the absence of white emitters limited the integration of LEDs into a wide range of applications," says Papanier. "Now, however, the misconception exists that InGaN-based white LEDs can illuminate a lens of any color, thereby simplifying lighting requirements."

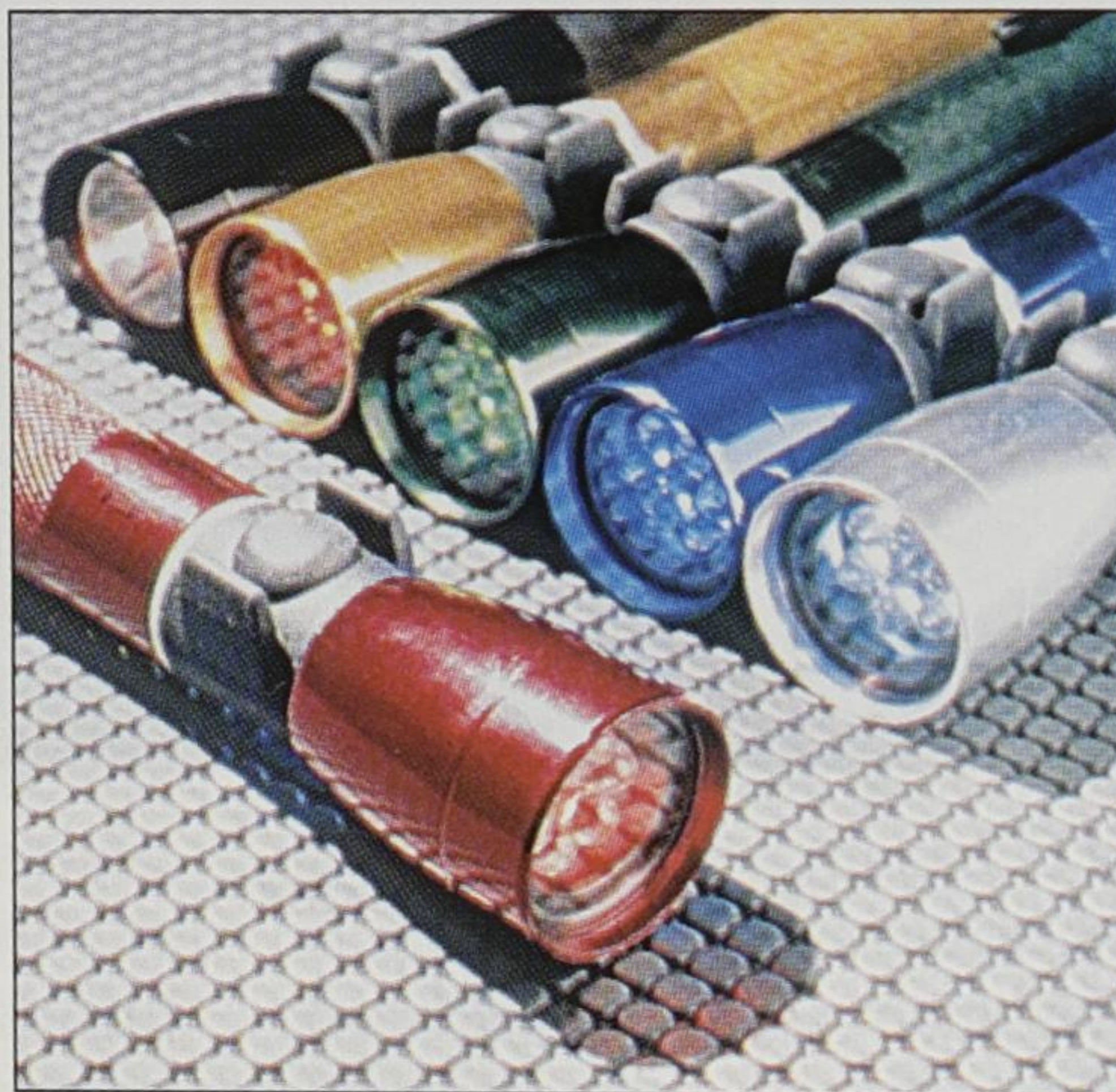
Papanier explains that white LEDs can only be used behind clear or milky white lenses. "Place a white

LED behind a red lens and the light produced is a pink color, a yellow lens turns a lemon-lime, a green lens shifts to aqua and an orange lens becomes yellow. To maintain accurate and brilliant colors, it is important to match the LED color with the lens color," he says.

LEDtronics employs white LEDs that use a single InGaN-based blue-emitting chip to irradiate a phosphor such as yttrium aluminum garnet (YAG). The short wavelength emission from the InGaN chip (around 400 nm) excites the phosphor, which re-emits the energy over a broad spectral range. The combined emission of the InGaN LED and the phosphor results in white light. There are other ways of making white, including the combination of red, green and blue LEDs in a single discrete package or in a cluster LED lamp. Binary complementary addition of blue and yellow light to produce white, an approach adopted by Gentex (see below), is also possible.

According to Papanier, the chosen approach depends on the application. "The technique of mixing red, blue and green (RGB) LED chips is used in signage because RGB LEDs can be combined to create 256 colors, making it a cost effective and efficient solution," he says. "If a lighting application requires a rainbow of colors from a single-point light source, then the RGB LED is the answer."

The desired appearance of the white light has also to be taken into account. A fluorescent light source has a relatively low color temperature and gives off a "cool" white (i.e. white with more blue content), while an incandescent source gives off a "warm" color with more yellow content. The brightness and color purity of InGaN-based white LEDs depends on the amount of phosphor coating – less phosphor results in cool white light, more phosphor results in a warm light. If less phosphor is used, conversion efficiencies are higher; cool white is thus the brightest and warm white the dimmest. For applications requiring cool white light, InGaN-based technology results in superior reliability and color integrity, says Papanier. "InGaN:phosphor LEDs



LEDtronics

Figure 3. These flashlights FlashLED® contain clusters of either three or six LEDs, and are available in a range of colors.



Figure 4. LEDtronics supplies solid-state illuminators that can be incorporated into safety wear, taking advantage of the LED's small size, high brightness, robust packaging and low power consumption.

would be used in elevator panel lights, for example, because illumination of only one color is needed," he says.

To get the best use of LEDs, the operating temperature must also be taken into consideration. LEDs are current-driven and the ambient temperature directly rises affects the operating current (usually specified as 20 mA). "In order to maintain the projected

longevity (usually 100,000 hours), the LED and its components should be redesigned to operate within the specified temperature range (usually -45°C to 35°C)," says Papanier. "A 30°C rise in the operating temperature to 55°C , for example, means that the LED's operating current should be lowered by 10 mA to maintain its 100,000 hour lifetime."

Gentex's Binary Complementary White LEDs

Gentex Corporation, a company based in Zeeland, Michigan that is best known for its self-dimming rearview mirrors for automobiles, is pioneering an alternative approach to generating white light from LEDs. This patented system, known as the binary complementary white LED system, synthesizes white light by adding and mixing the output of blue-green InGaN LEDs and amber AlInGaP LEDs. Gentex released its first binary complementary white LED products – map reading lamps incorporated into rearview mirrors – two years ago. Production of the LED map lamp has gradually increased, and the company estimates that it will produce 300,000 modular map lamps based upon binary complementary white LED technology this year. Current customers for these LED illuminators include GM, Ford and Daimler Chrysler.

"The white-light LED technology Gentex introduced as map lamps in its mirrors on the Oldsmobile Intrigue GLS initially represented a value-added feature," says Executive VP Kenneth La Grand. "But the total cost of ownership is significantly lower for consumers because LEDs do not burn out in the same way as incandescent lamps and should outlast the vehicle in which they are installed." As La Grand points out, LEDs are inherently compact, generate little heat and do not burn out. This eliminates the need to design for replacement, and allows designers to use low-cost, low-temperature plastic materials for system optics and packaging near the LED lamps. These are ideal characteristics for the confines of electrochromic rearview mirrors or other applications where space is limited, and where heat and reliability considerations are significant.

How It Works – The Binary Complementary White LED

The present binary complementary white LED map light system uses 4 amber AlInGaP LEDs, 2 blue-green InGaN LEDs and a lens to project an additive color mixture that the eye perceives as white. According to John Roberts, Gentex Senior Research Scientist, this combination produces illumination having approximately a 4:1 amber/blue-green flux ratio, an ideal proportion for the synthesis of white light [see Figure 5].

The lens array used in Gentex's LED map lamp helps align the LEDs, collimate and uniformly mix LED output and steer the resulting white-light beam toward a target surface to be illuminated [see Figure 6].

The AlInGaP Advantage

A significant advantage of the binary complementary white LED system, compared to white InGaN:phosphor LEDs, is that 80% of the luminous flux needed to produce white light comes from the AlInGaP LEDs. "White LED illuminators based on binary complementary technology derive their power-to-light conversion efficacy, cost structure and other key properties primarily from AlInGaP materials," explains Roberts.

AlInGaP LED devices are the most cost effective LEDs currently in production, producing light at a cost of \$0.05-\$0.10 per lumen in various package configurations, compared to a cost of \$0.90 per lumen or more for InGaN:phosphor white devices. AlInGaP also outperforms existing solid-state and non-solid-

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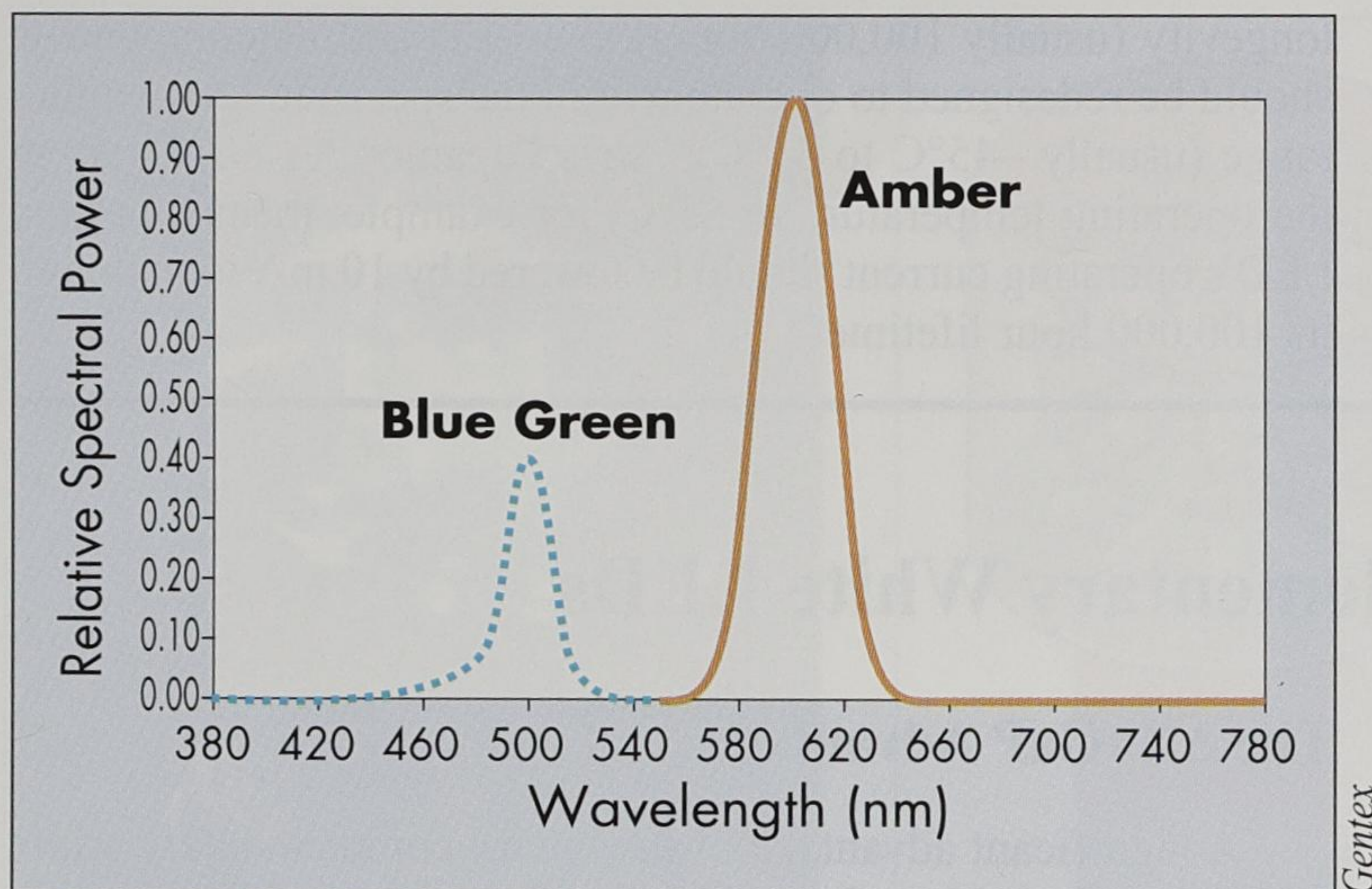


Figure 5. Relative spectral power for blue-green and amber LED illuminators. In the Gentex synthetic white LED package, twice as many amber LEDs are used as blue-green emitters to achieve a 4:1 amber/blue-green flux ratio.

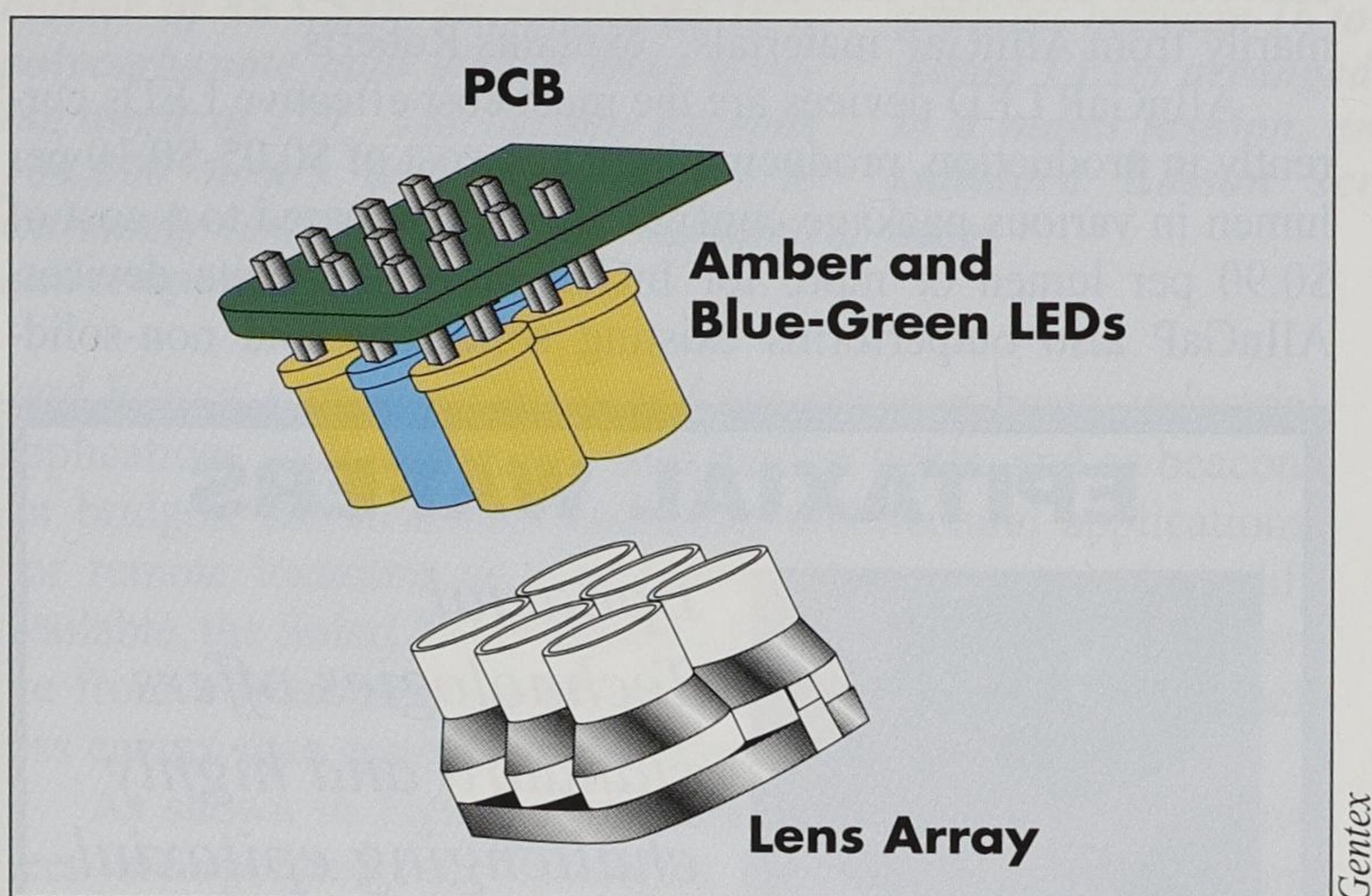


Figure 6. Gentex's lens array is responsible for the additive mixing of amber and blue-green LED components, and is used to align the LED components, collimate their output, and steer the resulting beam.

state light sources in the area of efficacy. "Recently, amber AlInGaP chips with 100 lm/W in luminous efficacy been demonstrated [by Agilent]," says Roberts. "This is superior to any other LED material and also superior to incandescent, fluorescent and most high-intensity discharge light sources. In contrast, the best available InGaN:phosphor LED devices produce white light at a maximum of 20 lm/W luminous efficacy."

Another commercial advantage of the binary complementary white LED system, says Roberts, is that AlInGaP is also the most widely available high brightness LED chip material. "Numerous AlInGaP epi growers and wafer fabs represent unsaturated capacity competing for a worldwide customer base," he says. "InGaN epi and wafer fabs, on the other hand, are more scarce, capacity-constrained and oversold. This results in availability problems, strategic weakness and upward cost pressure for InGaN:phosphor LED devices."

AlInGaP LEDs also offer superior durability (sufficient to

dominate today's demanding automotive exterior LED signal lamp market), while InGaN:phosphor LEDs exhibit a decay-life of substantially less than half that of AlInGaP devices.

Binary complementary white LED systems also deliver adjustable color temperature (a measure of how "warm" or "cold" the color is). Variances can be controlled during production and the desired color temperature can easily be set according to customer preferences at the latest stage of the value-added chain. "The color temperature of single-chip InGaN:phosphor LED devices, on the other hand, is difficult to control in manufacture, and is frozen early in the value-added chain," says Roberts.

Future Application of Binary Complementary White LEDs

So could these binary complementary white LED systems be scaled up for general illumination? Gentex says it is implementing binary complementary white sources in the low to medium flux range (i.e. up to 200 lumens) for a variety of automotive and non-automotive lighting applications, especially spot/flood lights and panel backlighting. "We see no fundamental technological roadblocks that will prevent broad adoption," says Roberts. But Roberts is also quick to point out that success with a high-performance LED system requires the fusion of many technical disciplines - optics, illumination, color science, human factors, electronic engineering and manufacturing, mechanical and thermal design and industrial design. Some applications are more direct, he says, requiring less engineering and development, and these are the company's most immediate targets.

The long-term future may be brighter still. "With chip and package advancements expected over the next few years, we foresee high-flux general illumination applications of the binary complementary LED system," says Roberts. Gentex recently announced a "second generation" of high brightness LEDs offering "as much as 10x the output of conventional devices", according to a company press release. The company has been reluctant to release many details, pending validation tests. However, it seems clear that Gentex has incorporated a number of improvements into its new package design, perhaps in combination with higher performance amber AlInGaP and blue-green InGaN devices. On this subject, Roberts confines his comments thus: "There are many ways to obtain more light from LEDs without compromising reliability," he says, "if all constituents of the component and system are optimized for that purpose."

General Evolution of Semiconductor Illumination Markets

Roberts believes that InGaN:phosphor white LEDs will play an important role in the future of the LED market, but suggests that this role may be limited somewhat by cost and performance issues. "We question the consensus assumption that InGaN:phosphor is the heir apparent to the future lighting market," says Roberts. "Today's diverse lighting industry clearly shows that different sources find their own niches based on needs and cost differentiation, and that these niches tend to be very large. Established examples of these technology-specific niches, h

says, are: 1) incandescent lamps for vehicle and home lighting, 2) fluorescent lamps for office and store lighting, and 3) high intensity discharge lamps for illumination of high-ceiling factories, streets and parking lots.

"Similarly, we expect semiconductor illumination applications to be dominated by three or four different technologies," he continues. "These technologies are likely to include binary com-

plementary white LED systems, InGaN LED systems employing either a fluorescent phosphor or dye, RGB LED combinations, and possibly organic LEDs or electroluminescent polymer materials." This being said, Roberts adds "We have seen no other approach to white semiconductor illumination that can even come close at this point to the low cost-to-flux ratio of the binary-complementary white LED technology."

SACO's Record-breaking LED Display Screen

At the end of last year, the Nasdaq Stock Exchange unveiled an eight-story video screen in New York's Times Square, comprising almost 19 million LEDs. The screen, the largest in the world, is 90 feet wide and 120 feet tall and displays high-resolution, full-motion video in real time, with special effects and animated high-intensity graphics. The manufacturer, SACO SMARTVISION Inc. of Montreal, Canada, was even able to design the display to be curved, wrapping it around the corner of Broadway and 43rd Street [see Figure 7].

In the 1980s, SACO's first LED components were designed for use in power plants, subways, railroad applications and industrial manufacturing, all of which have a zero tolerance for failure. Although individual LEDs do fail, fixtures generally contain many LED sources and can continue to operate if one device breaks.

Gary Nalven, president of SACO SMARTVISION Corp. in White Plains, NY, explains that LED displays have all but replaced cathode-ray tube (CRT) technology in the giant display screen industry because they're more efficient, brighter, and can be built into larger forms. "LEDs are more manufacturable and lighter," he says, "and have a wider range of pitches. They also offer an outstanding useful life, higher contrast ratios at wider viewing angles, and energy savings." Perhaps less obvious, he says, is that the quality of LED displays has also raised the bar of viewer expectations.

SACO built its first full-color LED screen for a tour by the rock band U2. At 150 feet wide by 50 feet high, the huge display was foldable and was transported around the world, seeing use at over 100

shows. In principle, says Nalven, there is no limit on size. "The physical dimensions of a video display were once determined by electrical components and physics," he says. "Now, such displays are now simply tiled together using modules that are typically one square foot in size. Our LED screens can be built to accommodate any size and shape, and we've built screens as wide as 150 feet and as high as 120 feet."

Engineering Considerations

"There are many engineering aspects that require precision to properly build a large format video display," says Nalven. "Among these are the use of LEDs with consistent brightness and color ranges, the accurate production of modules and metal systems that are huge but built to tight tolerances, and electronics that process the image data correctly."

To deal with the LED consistency problem, SACO says it obtains its high brightness blue and green LEDs (rated at 7 and 25 lm/W, respectively) from a single supplier, Nichia. These devices, together with red LEDs from another supplier, are packaged by Nichia to form RGB pixels. Nalven says these are not the cheapest devices, but lead to better consistency and lifetime, and pay dividends in reliability terms.

The Nasdaq Marketside Tower screen has also been designed with maintenance in mind. Nalven explains that the screen is set about 5 feet away from the building's façade in order to allow access from behind. Each LED module contains 16 x 16 RGB pixels, and measures around one square foot in size depending on the pixel pitch. The rear of

the modules can be accessed through a series of catwalks. Usually, LED displays do not require cooling, but Nalven says SACO has chosen to cool the Nasdaq screen to ensure longer lifetimes for the LED panels, which should last over 10 years.

The quality of video images and variations in color and brightness are easily detected by the viewer, says Nalven. "It's SACO's job to get the most out of the LEDs, which is why high quality manufacturing and processing are so important," he says.

Gary Nalven also expects a proliferation of LED displays in future. "LEDs inspire architects, designers, and corporate executives to think beyond the traditional application of video," he says. "The concept of LEDs as architectural elements offers an opportunity to dynamically change the face of a building."



Figure 7. The Nasdaq Marketside Tower in New York's Times Square contains almost 19 million high brightness LEDs.

SACO SmartVision

Semiconductor Optical Amplifiers

JONG-RYEOL KIM, HO-IN KIM and JEONG-SEOK LEE
 Samsung Electronics Co.
 Suwon, Korea

Extending the transmission distance of optical signals in optical communication systems has been the subject of intense research and study in recent years. Dispersion and loss in optical fiber are the main causes that limit the transmission distance. To overcome these limitations, classical optical-electronic-optical (O/E/O) repeaters have been widely used. Such repeaters are very complicated and expensive because they convert the optical signal to an electric signal, then regenerate the optical signal.

Several types of optical amplifiers have been proposed as replacements for these complicated repeaters. Semiconductor optical amplifiers (SOAs) were studied as one of the most promising candidates. However, it is the erbium-doped fiber amplifier (EDFA) that is actually being used in most optical communication systems these days. Because of the superior signal-to-noise ratio (SNR), signal gain and output power of the EDFA, it is very unlikely that SOAs will replace EDFAs.

However, SOAs have found applications in optical switching and optical functional devices that are very important for future optical communication systems and networks. This is due to the small size of the SOA, its capability to be integrated with other optical devices, and its non-linear optical characteristics. A brief introduction and a review of some important issues relating to SOAs are presented in this article, together with an overview of applications.

General features of SOAs

Semiconductor optical amplifiers have the same basic structure as semiconductor lasers. The incident light is amplified

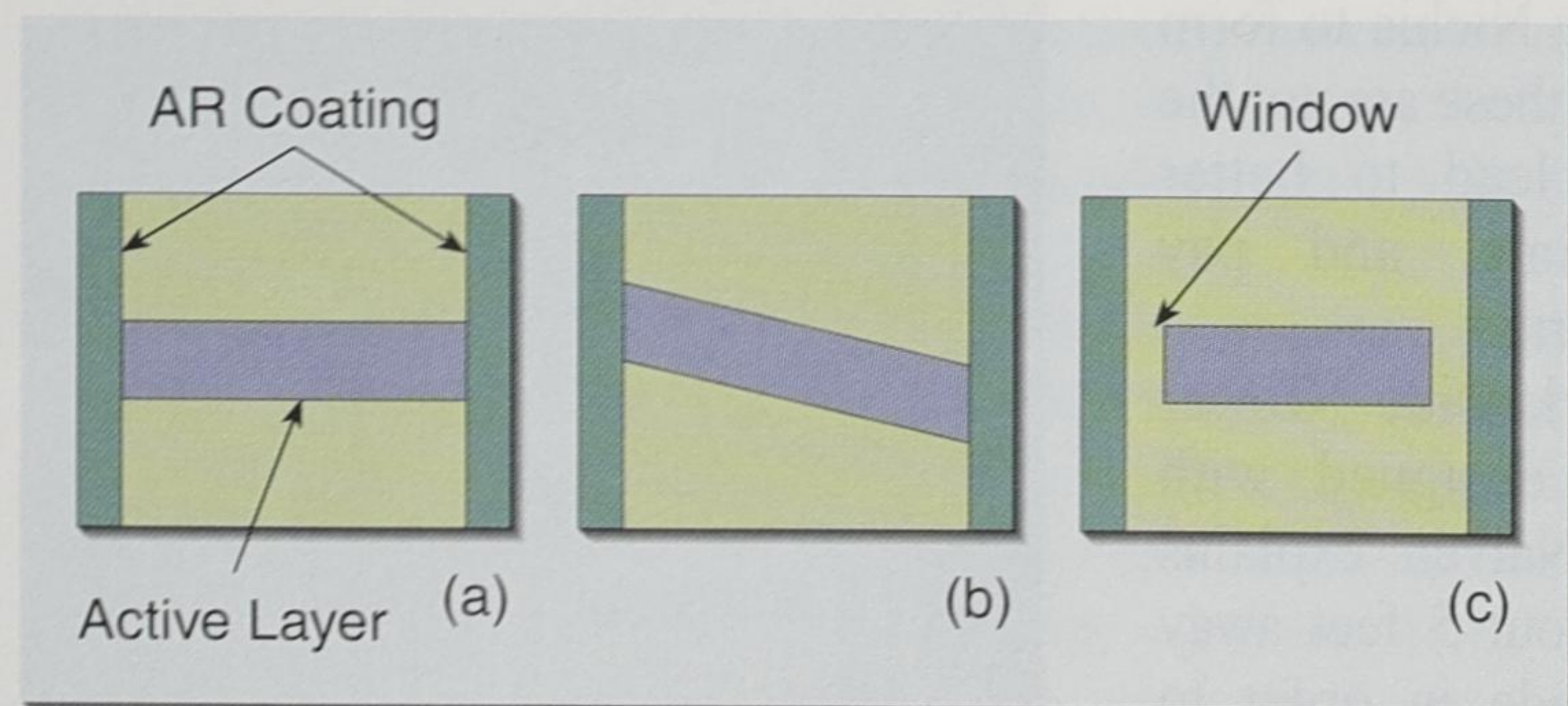


Figure 1. Schematic diagrams of different types of anti-reflection treatments used to reduce the gain ripple in SOAs: (a) Anti-reflection coatings, (b) Tilted stripe structure, and (c) Window facet structure.

by stimulated emission during its passage through the gain medium of the SOA. Conventional semiconductor lasers were first studied as SOAs by applying currents below the threshold condition. These SOAs are called Fabry-Perot amplifiers (FPAs)[1]. The signal gain of an FPA is attained at around the narrow resonance frequencies as in the semiconductor laser. Therefore it is necessary to adjust the input signal frequency very carefully. Also the saturation output power of FPA is low because of its low threshold current.

In order to overcome these problems of FPAs, the end facets of SOAs were anti-reflection treated to retain the resonance in the cavity. The anti-reflection treated SOA is called a travelling wave amplifier (TWA), and has a uniform signal gain over a broad wavelength range and a high saturation output power due to its high threshold current [2, 3]. By virtue of its superior characteristics, the TWA has replaced the FPA in both research and system applications.

The gain medium of the SOA can be prepared as either a bulk or a multiple quantum well (MQW) active layer. MQW-SOAs are more appropriate for applications requiring a high output saturation power and a wide gain spectrum [4-6]. However it is very difficult to make MQW-SOAs that are polarization insensitive, which can be a significant problem in many applications. Also, the gain of these devices is not high enough compared with that of bulk SOAs. Even though there may be other issues depending on the specific device applications, the most important issues of SOAs for device applications are the polarization insensitivity, anti-reflection treatment, and gain saturation. These issues are reviewed in more detail in the following sections.

a. Polarization Insensitivity

One of the most undesirable characteristics of SOAs is the sensitivity of their gain to the optical polarization. In conventional amplifiers, the gain for the transverse-electric (TE) and transverse-magnetic (TM) polarizations can be different by as much as 5~10 dB [7]. The optical confinement factor and the effective mode index are different for the TE and TM polarizations because of the different physical dimensions of width and thickness of the active layer. This feature makes the amplifier gain depend on the polarization state of the input beam, which in turn requires cumbersome adjustment in many system applications where the polarization state changes with propagation along the fiber. Several schemes have been devised to reduce the polarization sensitivity.

Clearly, an SOA will become nearly polarization-insensitive if the width of the active layer is made equal to its thickness [8, 9]. In order to maintain the single mode characteristics, however, the active layer thickness should be less than 0.5 μm . It is very hard to control the active layer width in such a small dimension.

Another possible solution is to use two SOAs [10]. These can be placed in series in such a way that the active layers of two SOAs are aligned so that their polarization directions are orthogonal to each other. The first SOA mainly amplifies the TE mode while the second amplifies the TM mode, in order to reduce the polarization sensitivity. Another way is to align two SOAs in parallel in the same scheme as the series configuration. However, these methods are hard to apply in practice because they require two SOAs of equal polarization characteristics together with very complicated alignment tools.

A preferable alternative is to apply a slight strain to the bulk active layer in order to increase the gain of the TM mode to compensate its low confinement factor [11, 12]. It is also possible to apply strain to the MQW layers, but this is much more difficult to control than in the bulk active layer case [13, 14].

b. Anti-Reflection Treatment

It is necessary to decrease the reflectivity of the end facets of SOAs in order to reduce the gain ripple that is found in an FPA. A reflectivity of 10^{-4} is needed to reduce the gain ripple down to as low as 1 dB. Several ways have been suggested to reduce the facet reflectivity.

The simplest method is to do the single layer anti-reflection (AR) coating on both facets. However the thickness margin is so narrow in the single layer AR coating that a multi-layer coating with wide thickness margin is preferred for the practical application (Figure 1a). Because the AR coating conditions are different in the TE and TM modes, it is very hard to meet the requirement of 10^{-4} reflectivity for both modes simultaneously using the AR coating alone [2, 3]. An additional method is to tilt the active region stripe

from the facet normal by 5–10 degrees (Figure 1b) [15, 16]. Such a structure is referred to as the tilted stripe structure. The reflected beam at the facet is physically separated from the forward beam because of the tilted facet. Some feedback can still occur but the combination of an anti-reflection coating with the tilted stripe can produce a reflectivity below 10^{-4} .

In an alternative scheme a transparent window region is inserted between the active layer end and the facet (Figure 1c) [8, 17]. The optical beam spreads out in the window region before arriving at the end facet. The reflected beam spreads even further and does not couple much into the thin active layer. Such a structure is called the window facet structure and has provided reflectivities below 10^{-4} when combined with an anti-reflection coating.

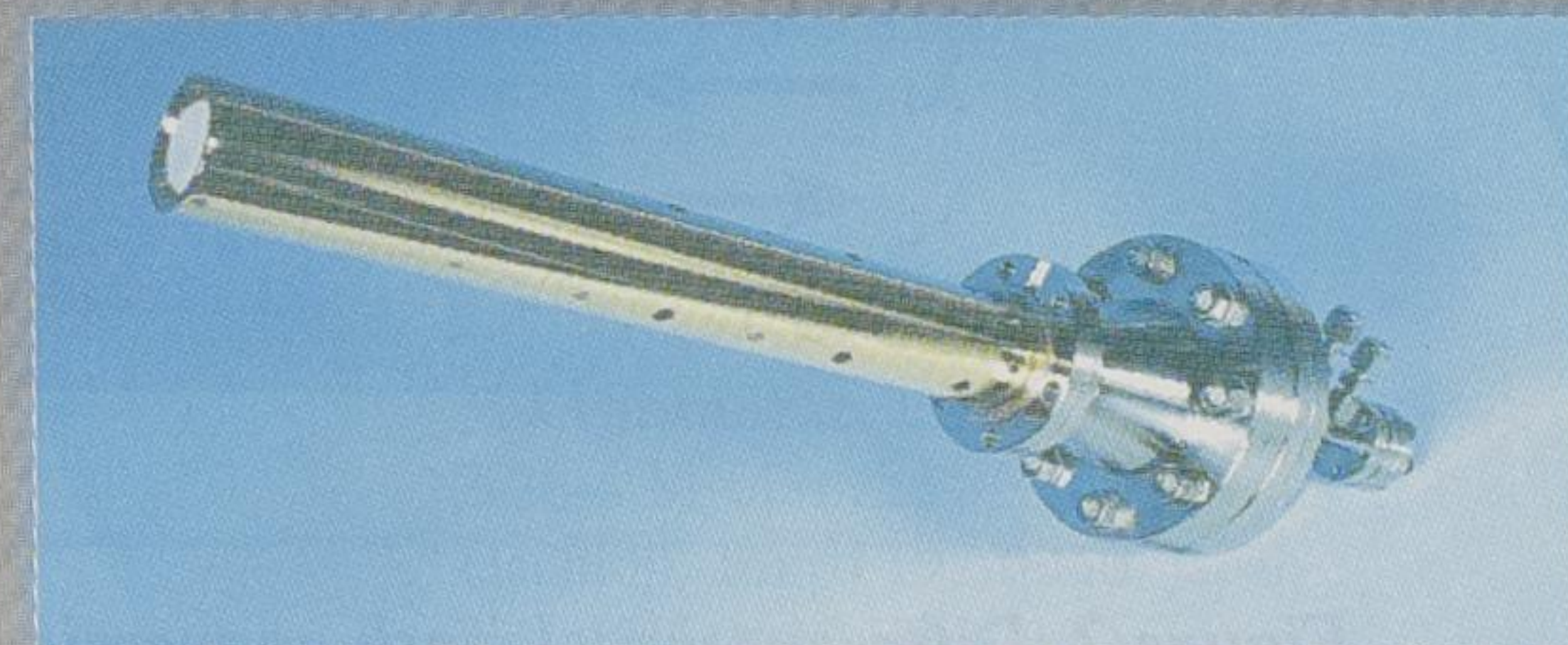
c. Gain Saturation

As the input optical power increases, the carrier consumption by stimulated emission increases rapidly and starts to surpass the carrier supply. Then the gain of the amplifier starts to saturate. This gain saturation limits the maximum output power of SOA. The saturation output intensity is inversely proportional to both the differential gain (A_g) and the carrier relaxation time (τ_s), and is determined mainly by these two factors [18, 19]. It is common to reduce the carrier relaxation time τ_s to increase the output saturation power. One effective way to reduce τ_s is to increase the carrier density by increasing the injection current. The residual reflectivities of the end facets may cause resonance as the injection current increases, and this limits the maximum injection current allowed. The carrier relaxation time can also be reduced by increasing the doping concentration in the active layer.

The maximum gain shifts to shorter wavelengths as the injection current increases. Then, the differential gain is large at the shorter wavelength and small at the longer wavelength. As a result, the gain saturation is rather slow at the longer wavelength.

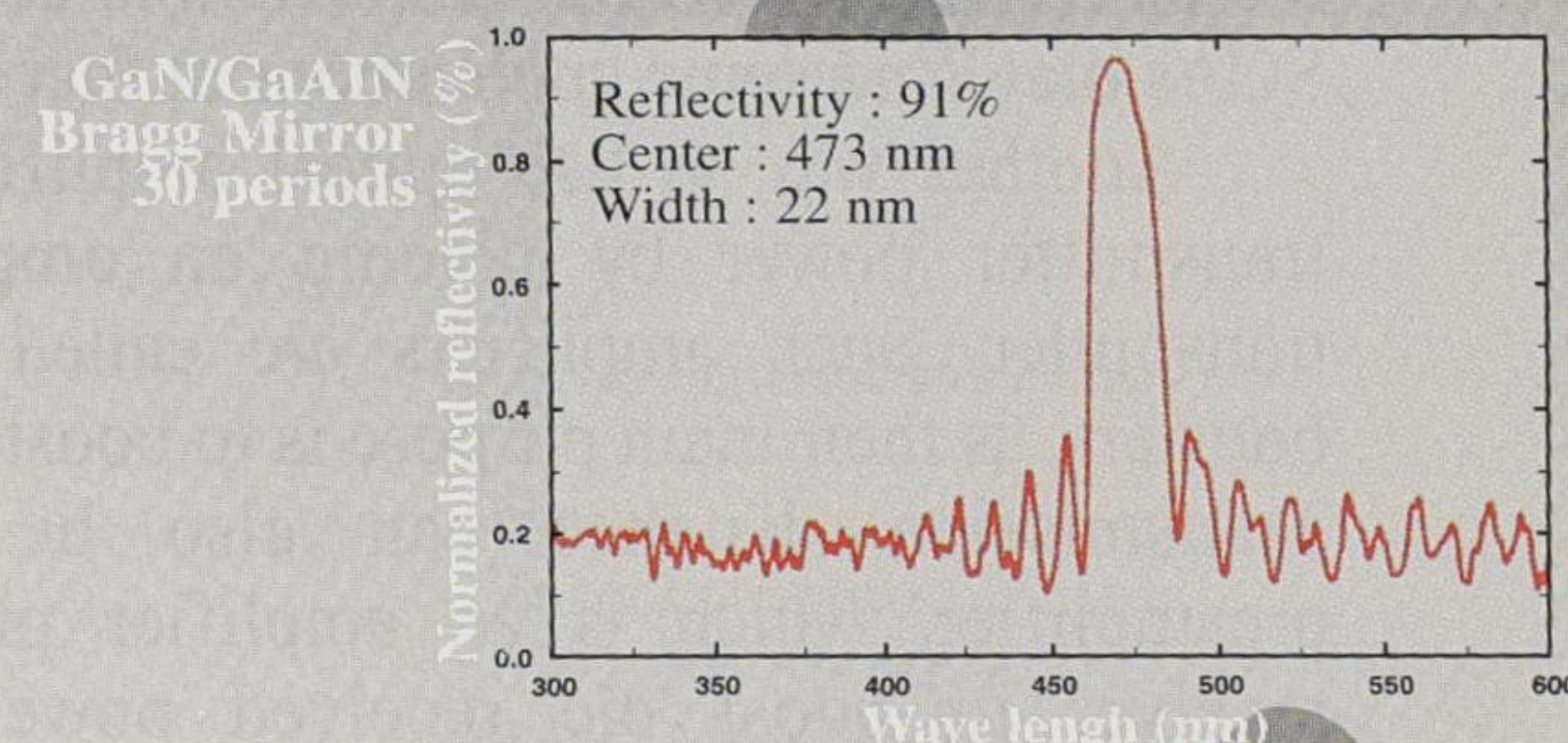
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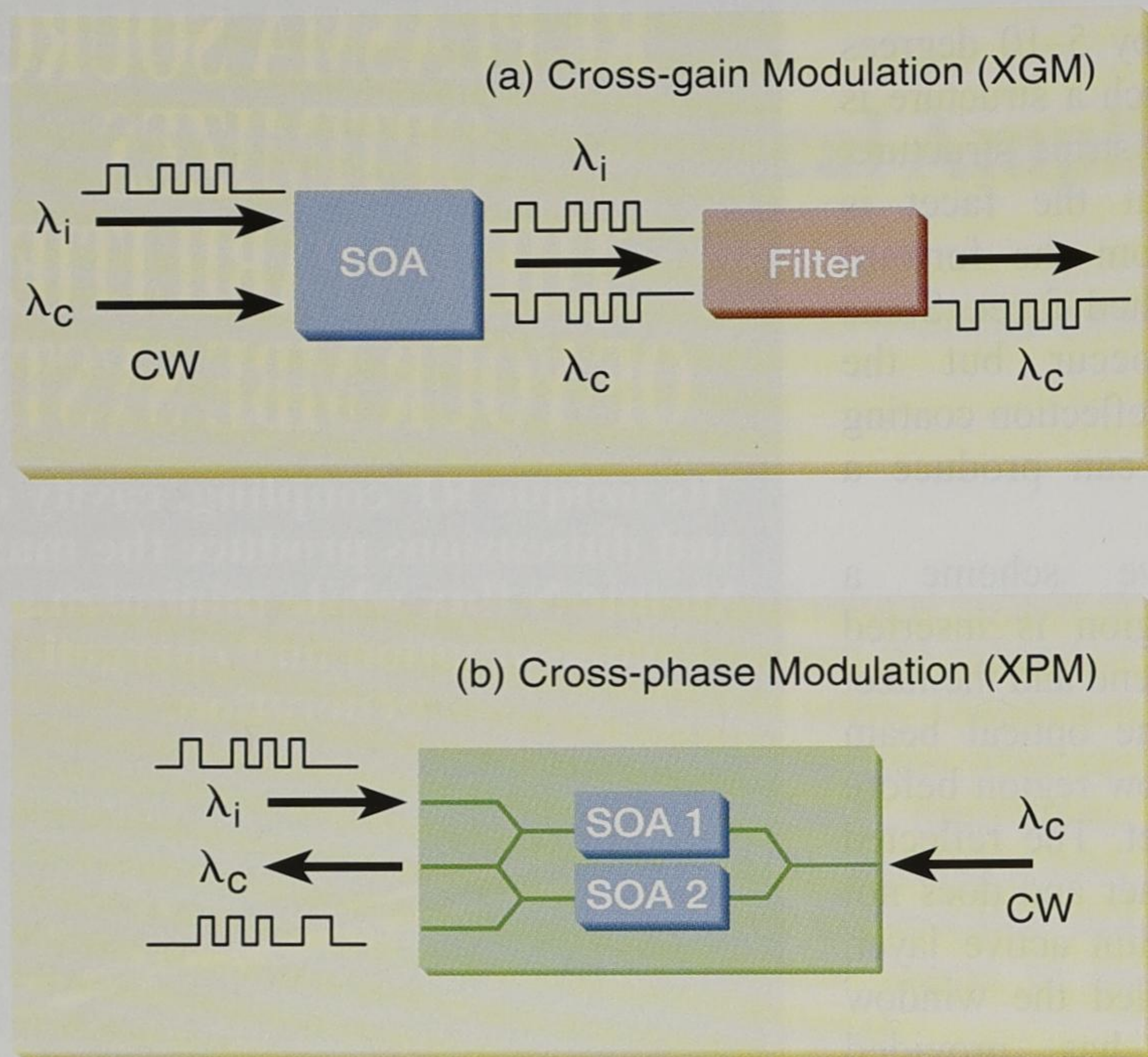


Figure 2. Different wavelength conversion schemes using SOAs: (a) Cross-gain modulation or XGM, and (b) Cross-phase modulation or XPM. In both cases the optical signal is transferred from an incoming wavelength λ_i to a second wavelength λ_c .

Applications of SOAs

a. Optical Communication Systems

Due to the current superiority of erbium-doped fiber amplifiers (EDFAs), it is unlikely that SOAs will be used as in-line amplifiers in 1550 nm optical communication systems. However, the performance of fiber amplifiers is deficient at 1310 nm, so SOAs may find some applications at that wavelength.

Another way to use optical amplifiers is to increase the transmitter power by placing an amplifier just after the transmitter. Such amplifiers are called power amplifiers or boosters, as their main purpose is to boost the transmitted power. Transmission distance can also be increased using a preamplifier, which is an amplifier placed just before the receiver to boost the received power [20, 21]. Another application of optical amplifiers is to use them for compensating distribution losses in local area networks [22].

b. Wavelength Converters

Wavelength conversion is one of the most interesting functions that can be achieved with SOAs. This is particularly important considering the fast progress in wavelength division multiplexing (WDM) networks. WDM technology uses multiple wavelengths to transmit independent data on each wavelength channel. Wavelength converters that transfer

signals from one carrier wavelength to another are necessary to avoid wavelength contention in WDM systems.

The simplest conversion scheme relies on the cross-gain modulation (XGM), as shown in Figure 2a [23]. Gain saturation of a single SOA can be used to convert the signal from one wavelength to another. The modulated input signal (λ_i) and the other signal of constant power (λ_c) enter a single SOA simultaneously. The gain is modulated by the input signal (λ_i) and this modulation is imposed on the target wavelength signal (λ_c). XGM converters are however known to give a chirped output signal and to reduce the extinction ratio for conversion from shorter to longer wavelengths [24].

More advanced converters with better performance are obtained by integration of two SOAs into a Mach-Zehnder interferometer (MZI) or Michelson interferometer (MI) [25, 26]. The conversion principle is shown in Figure 2b. The light to be switched (λ_c) is split into two paths that each contain an SOA. The optical switching signal (λ_i) enters one of the SOAs, inducing a relative phase shift and saturating the gain. When the light is recombined, constructive or destructive interference will occur depending on the phase difference between the two paths. This cross-phase modulation (XPM) in the SOAs is power efficient and essentially wavelength independent. Additionally, it has been shown that this type of wavelength converter has more improved regenerative features such as the large extinction ratio, reduced chirp, and suppressed amplified spontaneous emission and crosstalk.

Wavelength converters can be applied to other functional devices, such as optical demultiplexers, regenerators and so on. Because of these wide applications, wavelength converters are expected to be the most prominent application of SOAs.

c. Optical Switching

Another important application of SOAs is in high-speed optical matrix switches that use SOAs as gate elements (Figure 3) [27, 28]. LiNbO₃ is widely used as an optical switch for its low loss and high coupling efficiency characteristics. However, LiNbO₃-based devices are so large that it is hard to achieve large-scale integration where many optical switches are necessary. The switching speed of these devices is also rather slow and high operating powers are required.

Optical switches with an SOA gate array are expected to overcome some of the problems of LiNbO₃ switches. It is

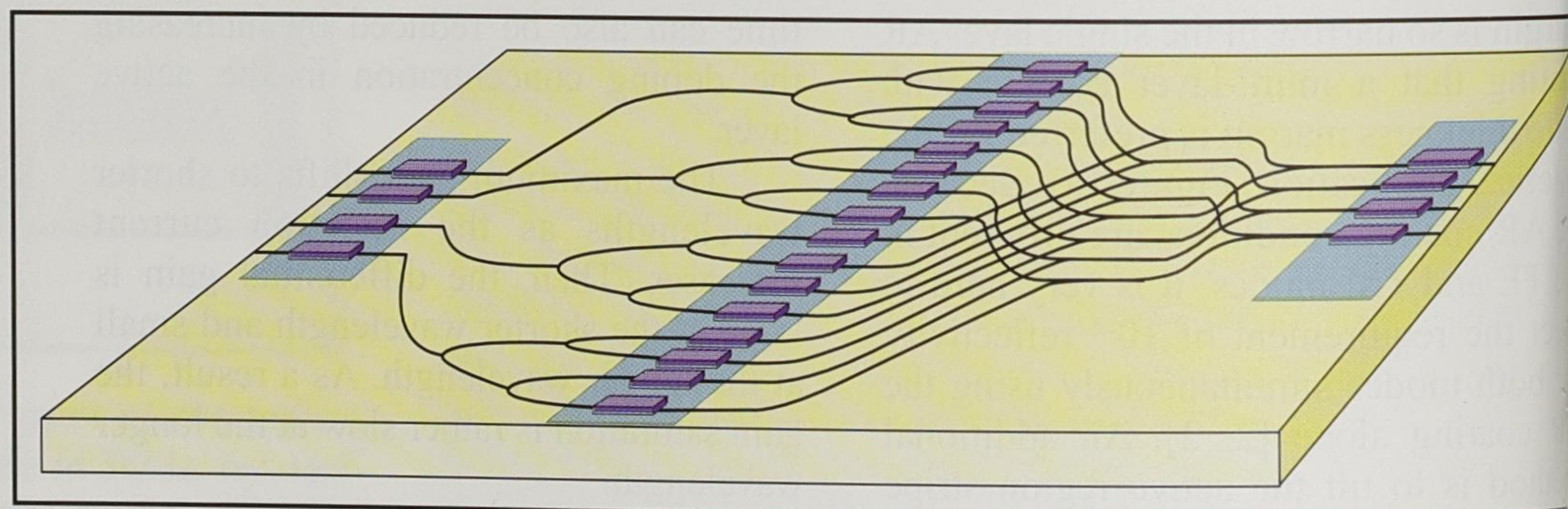


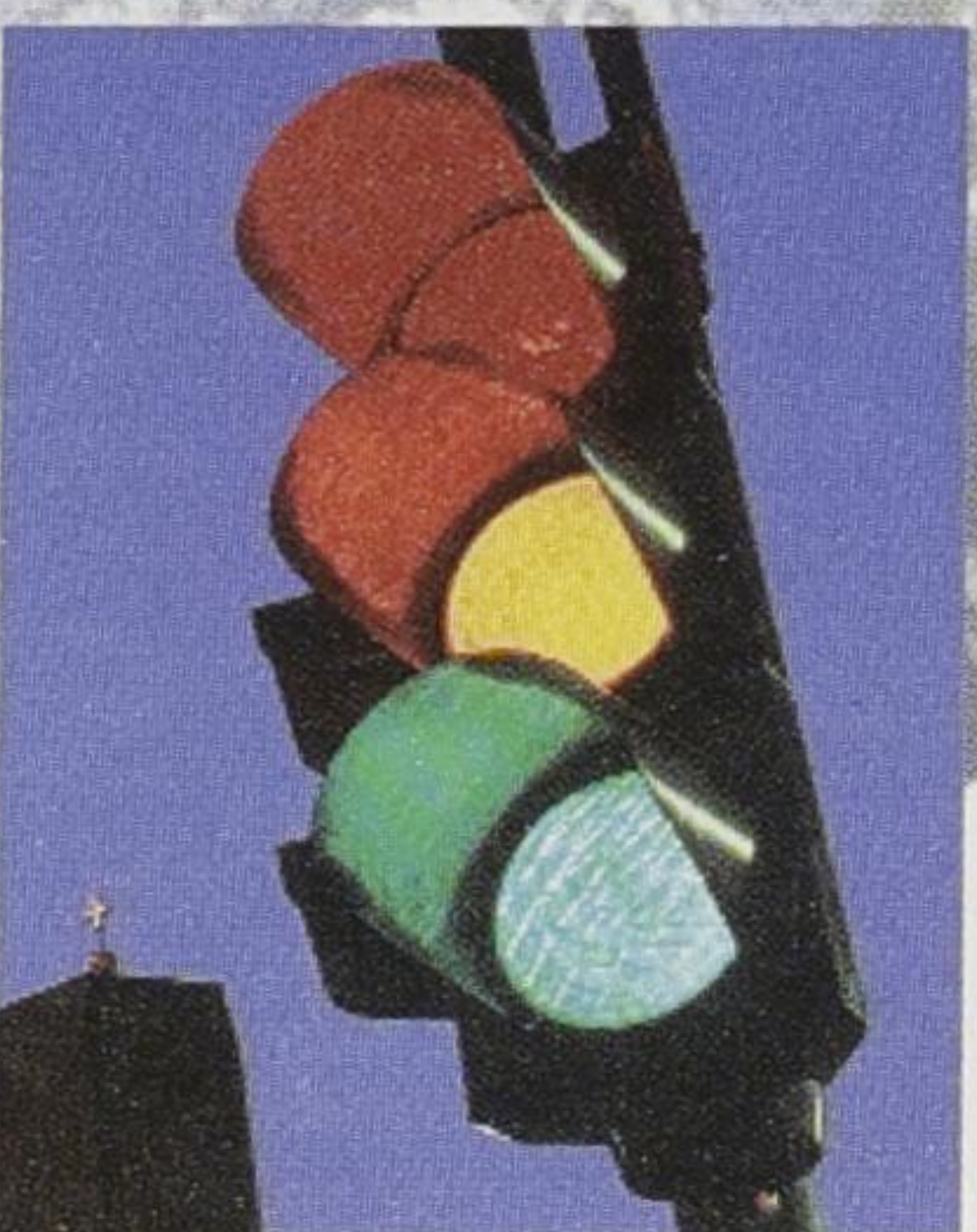
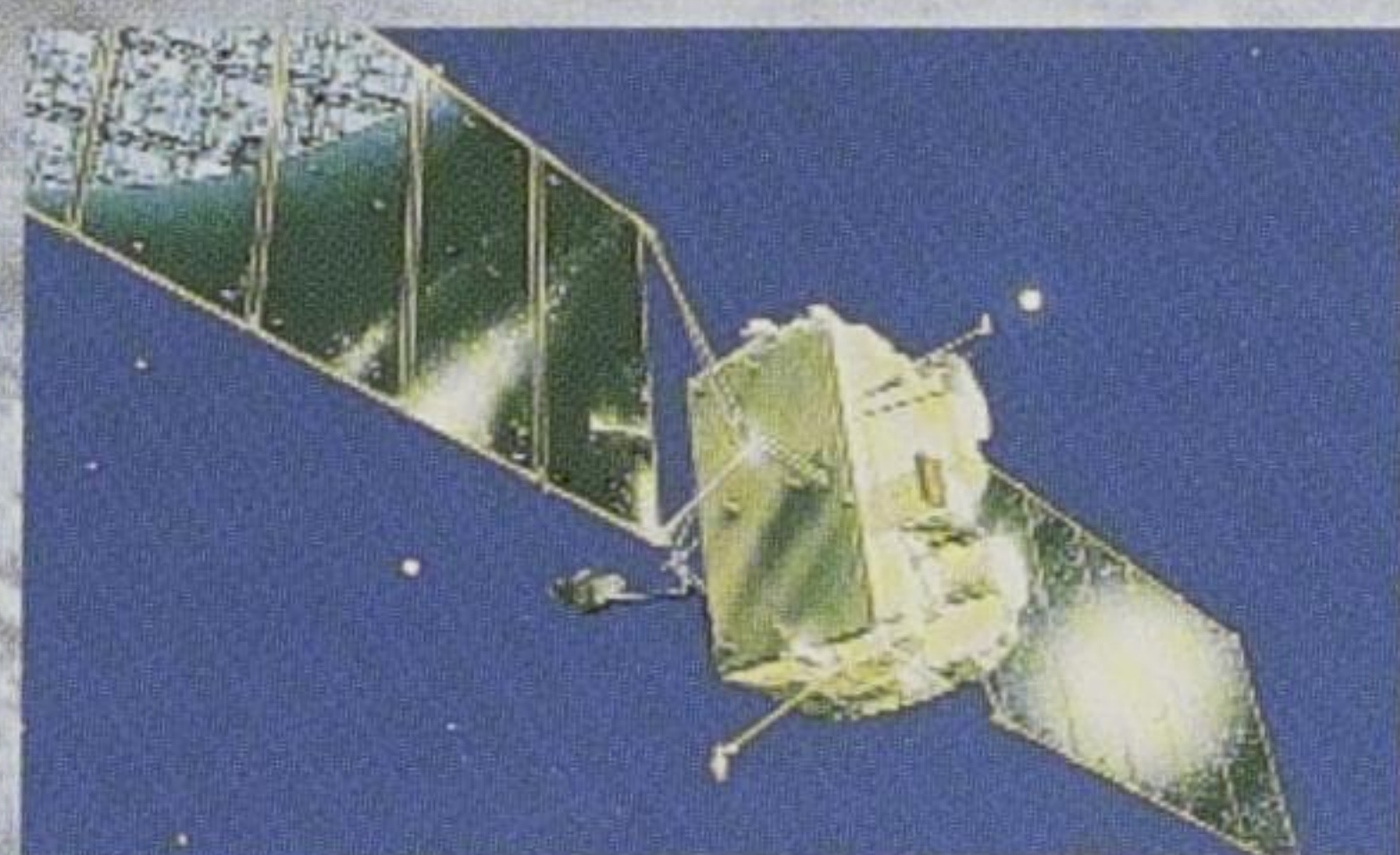
Figure 3. Schematic diagram showing an all-optical 4×4 SOA gate switch array.

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possible to monolithically integrate many switches with other devices, and it is also possible to compensate optical losses with this switch.

Summary

We have reviewed the fundamental principles, key features and applications of SOAs. Many research groups are working on SOAs to improve the crucial drawbacks for practical use. As mentioned in this article, SOAs have a number of merits, including compact size and the possibility of integration with other devices. Even the non-linear optical characteristics, which can be a major drawback for in-line amplifiers, are positively utilized in functional applications. With these unique characteristics, SOAs have found themselves as indispensable devices for future optical communication systems. We expect that SOAs will play a great role in the near future as the demand of high-speed optical communication increases rapidly.

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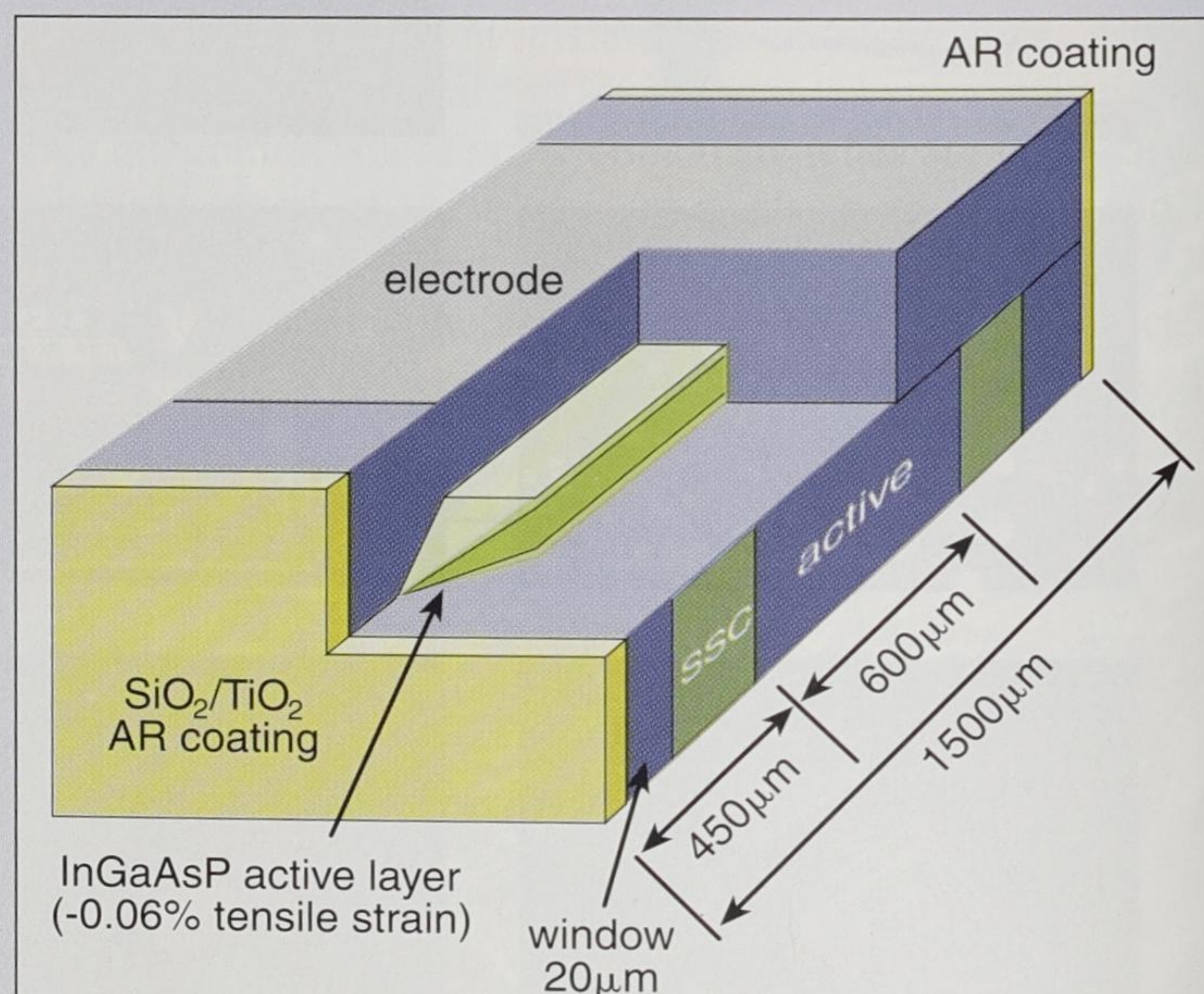
Spot-Size Converter Integrated Polarization-Insensitive SOA

The use of a spot-size converter (SSC) in SOAs improves the coupling efficiency into optical fiber. The figure below is a schematic diagram of an SOA with a spot-size converter at each facet to expand the mode size. The SSC, located at each end of the gain region, consists of a laterally tapered passive region followed by a window region. The passive and active regions are 450 μm and 600 μm in length, respectively, giving a total device length of 1.5 mm. The active stripe of the device is tilted by 7° from the crystal axis to reduce the reflectivity of the end facets.

The device consists of a 0.2- μm -thick, slightly tensile-strained bulk InGaAsP ($\lambda = 1.55 \mu\text{m}$) active layer and 0.1 mm InGaAsP ($\lambda = 1.3 \mu\text{m}$) waveguides. The structure was grown by MOVPE, using selective-area growth (SAG) to implement the SSC sections simultaneously with the active section. SAG provided the vertical taper, while the lateral taper was introduced by wet chemical etching. Polarization insensitivity was attained by controlling the strain in the active layer.

After formation of the tapered stripe, an InP current blocking layer was selectively regrown, followed by a 5- μm -thick InP cladding layer and a p+-InGaAs cap across the whole structure. Both facets were antireflection-coated using a single TiO_2 - SiO_2 pair.

The far-field pattern of the device showed FWHM values of 8° horizontal and 15° vertical. The SOA chip gain was 29.7 dB at a drive current of 200 mA, and the polarization sensitivity was less than 0.8 dB. The amplitude of the gain ripple was less than 0.2 dB even at 200 mA, corresponding to a reflectivity of less than 10^{-5} on both facets.



Schematic of a polarization-insensitive spot-size converter SOA with an angled window structure. From ref [12].

DC to 65 GHz Wide Bandwidth InGaAs Photodiodes and Photoreceivers

Discovery Semiconductors manufactures wide bandwidth InGaAs photodiodes and photoreceivers for optical communications applications and is currently developing fully integrated opto-electronic ICs that combine a photodetector and an amplifier on the same chip.

ABHAY M. JOSHI*

Discovery Semiconductors, Inc.
Princeton Junction, NJ

As the demand for bandwidth in optical systems continues to increase, photodiodes and photoreceivers with an operating frequency range up to and beyond 50 GHz are required. Commercial optical communications applications include high-speed SONET/SDH fiber-optic networks operating at 10 Gb/s and 40 Gb/s, as well as digital cable TV and fiber-based local area networks (LANs). Important military applications include optically fed phased array systems and optically controlled microwave networks for airborne and spaceborne applications.

These applications require wide bandwidth components that can be manufactured reproducibly at low cost. While the maturity of MMIC technology makes it feasible to combine amplifiers with optical components such as photodetectors to make front-end receivers [1-3], demonstrations of hybrid integrated optical receivers to date have mainly been at frequencies lower than 10 GHz [4-6]. Although high speed p-i-n photodetectors and narrow band MMIC amplifiers with a frequency response in excess of 20 GHz are commercially

available, wide band amplifiers with frequency and gain performance necessary for photoreceivers above 2.5 Gb/s are currently difficult and expensive to manufacture. Integrated photoreceivers operating in the 40 Gb/s range have only recently been demonstrated.

An ultimate goal is to fabricate truly monolithic photoreceivers combining optical, microwave and digital functions on the same chip. Opto-electronic integrated circuits (OEICs) of this nature are not yet commercially available at any frequency.

Discovery Semiconductors, a small company of 15 employees based in Princeton, NJ, manufactures a range of InGaAs photodiodes and photoreceivers for fiber-optic applications with bandwidths up to 65 GHz. The photodiodes have a minimum responsivity of 0.5 A/W at both 1300 nm and 1550 nm, and demonstrate a ripple factor of less than ± 1 dB from DC to 50 GHz. The salient feature of the p-i-n photodiode is an on-chip co-planar waveguide (CPW) output for proper impedance matching.

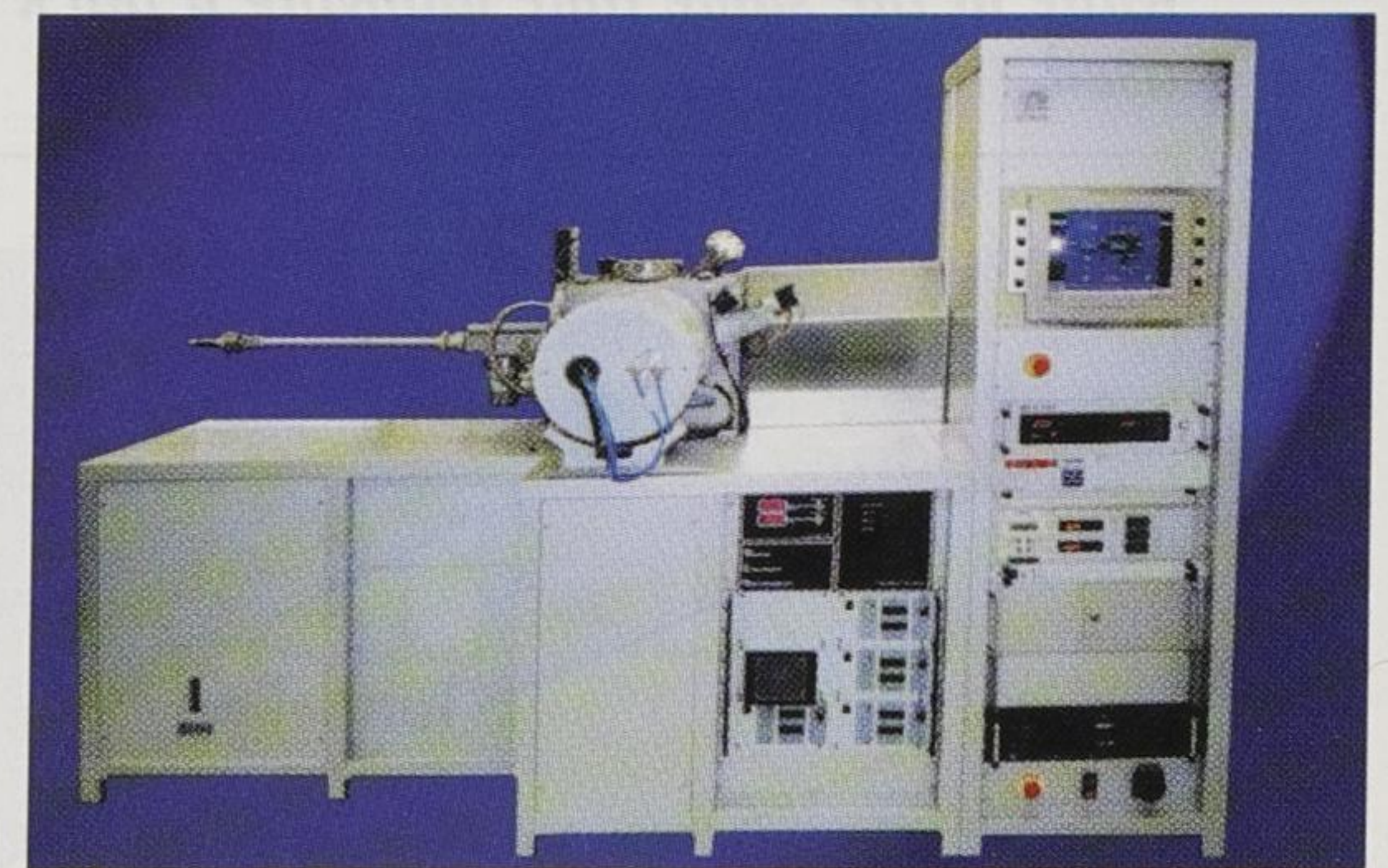
Discovery's current commercially available photoreceivers combine InGaAs photodiodes with ultra wide bandwidth MMIC amplifiers fabricated in GaAs PHEMT technology. The company has also developed fully monolithic

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photoreceiver OEICs that combine InGaAs photodiodes with InGaAs/InP PHEMTs.

Discovery has expertise in the design of detectors, amplifiers and OEICs, as well as extensive modeling capabilities. The company has capability for high volume manufacturing of detectors and photoreceivers. Other capabilities include coupling of very small diameter detectors to single-mode fiber, microwave hybridization and packaging, and ceramic stripline design and manufacturing.

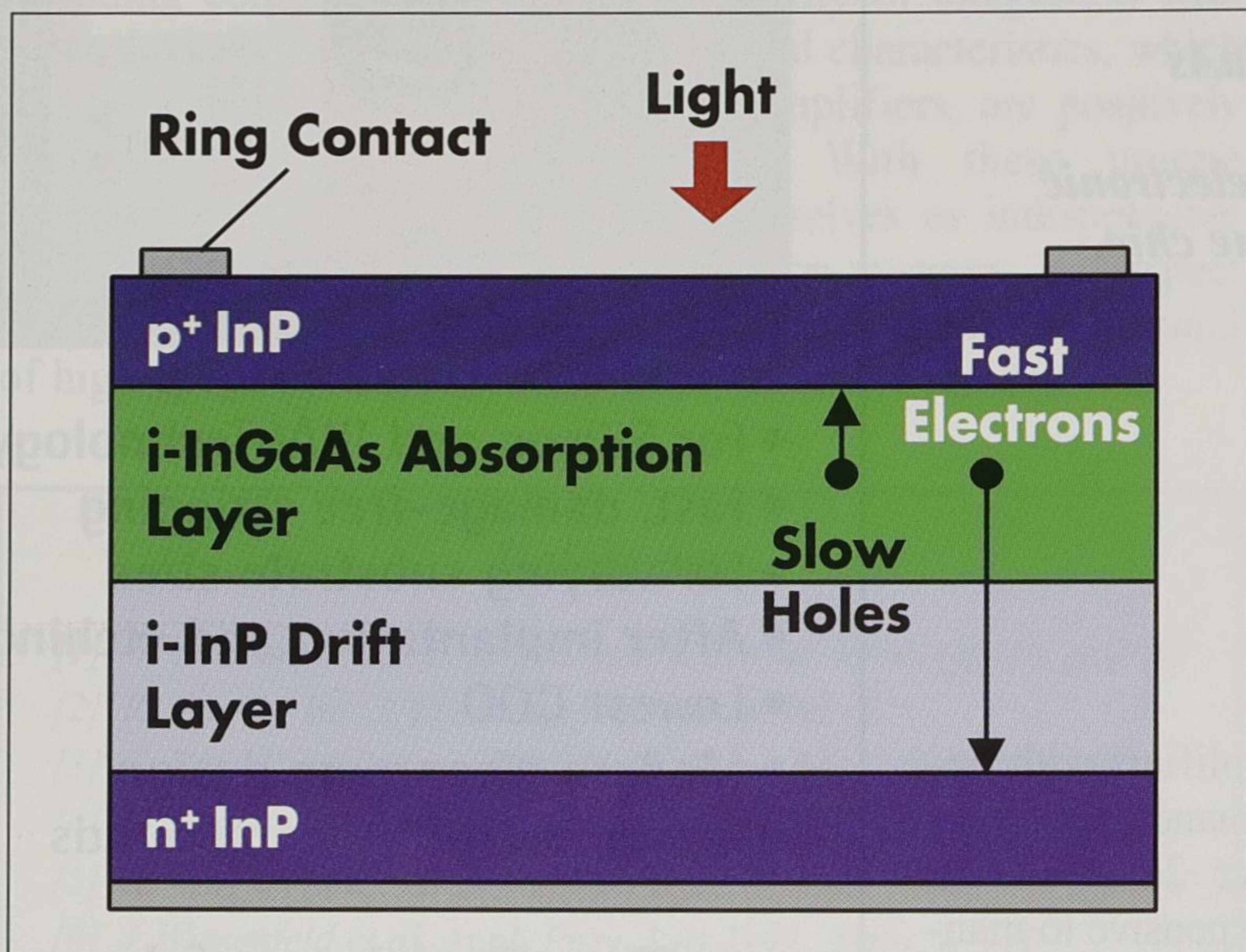


Figure 1. Schematic of Discovery Semiconductors' high speed, dual depletion layer InGaAs/InP p-i-n detector. Absorption and carrier generation occurs in the InGaAs layer close to the p-contact. Because electrons travel much faster than holes in InGaAs and InP, this design leads to a reduced transit time while at the same time allowing a thick absorption layer to be used.

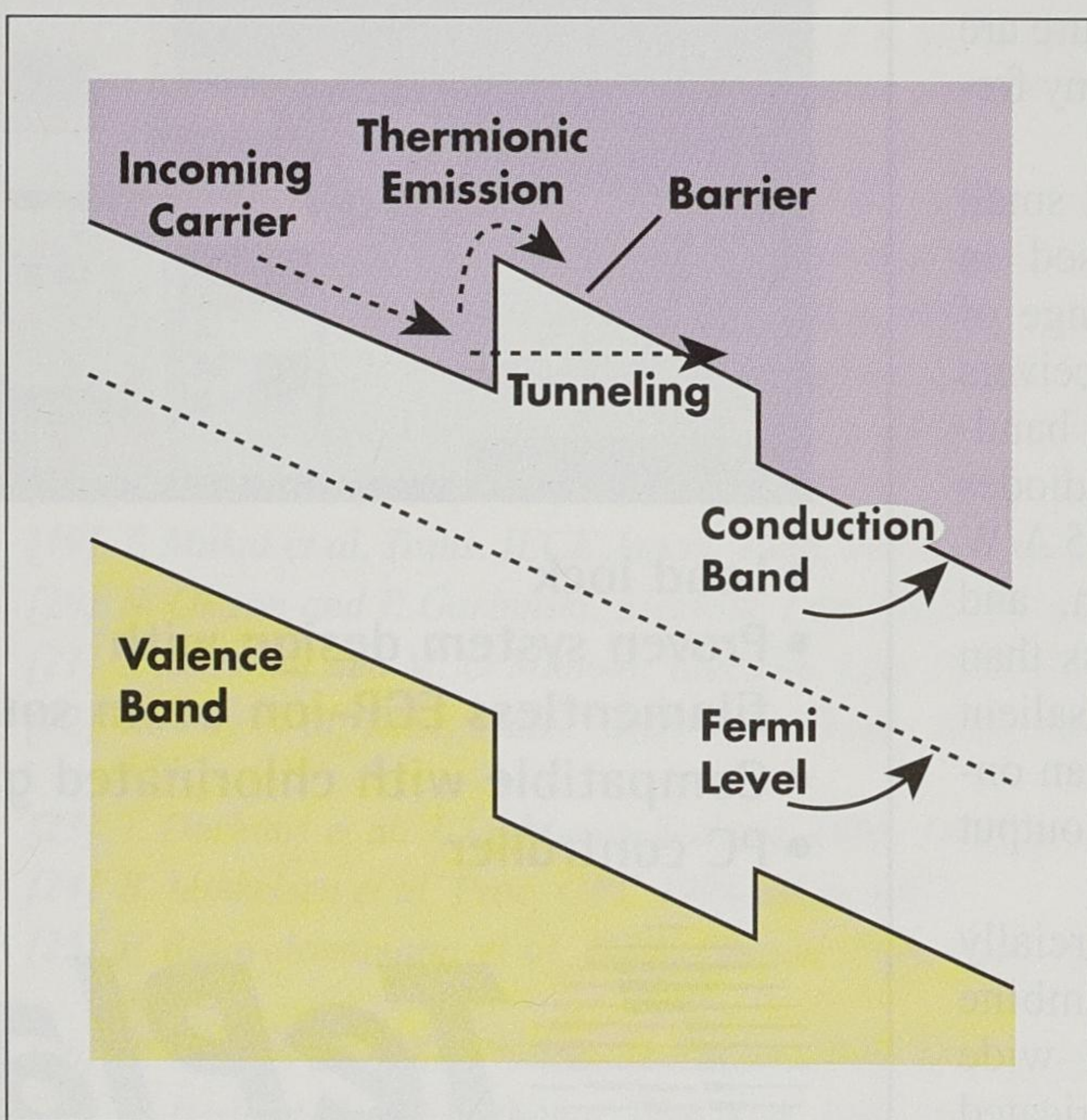


Figure 2. A diagram of an energy barrier found in heterojunction semiconductor diodes.

Design of Ultrafast, High Power InGaAs Photodiodes

Since 1995, Discovery Semiconductors has pioneered a high-speed detector technology known as the dual-depletion p-i-n detector [7]. This design allows good responsivity, high speed, and high saturation currents from a front-illuminated diode that is relatively easy to manufacture and integrate. The basic issues for high bandwidth detectors are the electrical capacitance of the detector and the transit time for carriers in the detector. For high optical input power, the non-linear effects of space-charge effects, barrier trapping, and saturation must also be considered. In the design process, one must balance all of these factors to achieve the optimum detector performance.

When the device is operating in the linear regime, the two major limits on device speed are the capacitive time-constant and the carrier transit-time. The two major capacitances in optical detectors are the intrinsic capacitance of the diode itself, and the parasitic capacitance of the preamplifier circuitry [7]. The intrinsic capacitance is given by the simple parallel plate capacitance of the p-i-n structure, and its value determines the electrical time constant of detection (in association with the load resistance of the amplifier). Hence, the intrinsic capacitance should be minimized, which requires a thick depletion region.

The transit time is the time required for photogenerated carriers in the intrinsic region of the detector to move to the electrode surfaces. Given that the carriers are moving at their saturation velocities, the transit time is proportional to the intrinsic region thickness. A thick detector will have a long transit time, and thus a slow response.

Fortunately, the properties of InGaAs and InP are such that electrons can travel up to ten times faster than holes at certain fields [7]. If the detector is designed so that the carriers are generated only near the p-contact, the slower holes travel a shorter distance than the faster electrons. This allows a thicker intrinsic region (and hence a lower intrinsic capacitance) without the transit time penalty.

Discovery Semiconductors has fabricated detectors with a diameter of 10 μm and a thickness of 1 mm, with response speeds up to 50 GHz [7]. Selective carrier generation was accomplished by fabricating an InGaAs/InP dual-depletion detector as shown in Figure 1. This works by using two different layers in the depletion region: an InGaAs layer, which is absorbing, and a transparent InP layer. Because carriers are generated only in the absorbing material, the transit time is reduced by placing this layer adjacent to the p-contact.

Model Development

Using carrier drift models developed in-house, the dual depletion photodiode design was re-optimized to achieve a 60 GHz response. Physical effects such as parasitic inductance of the wire-bonds and potential barriers at the contacts were added to the existing model. Also, the model was migrated to a user friendly "visual basic" software platform, and a theoretical basis was developed for extending the model further to include space charge and bandgap barrier effects.



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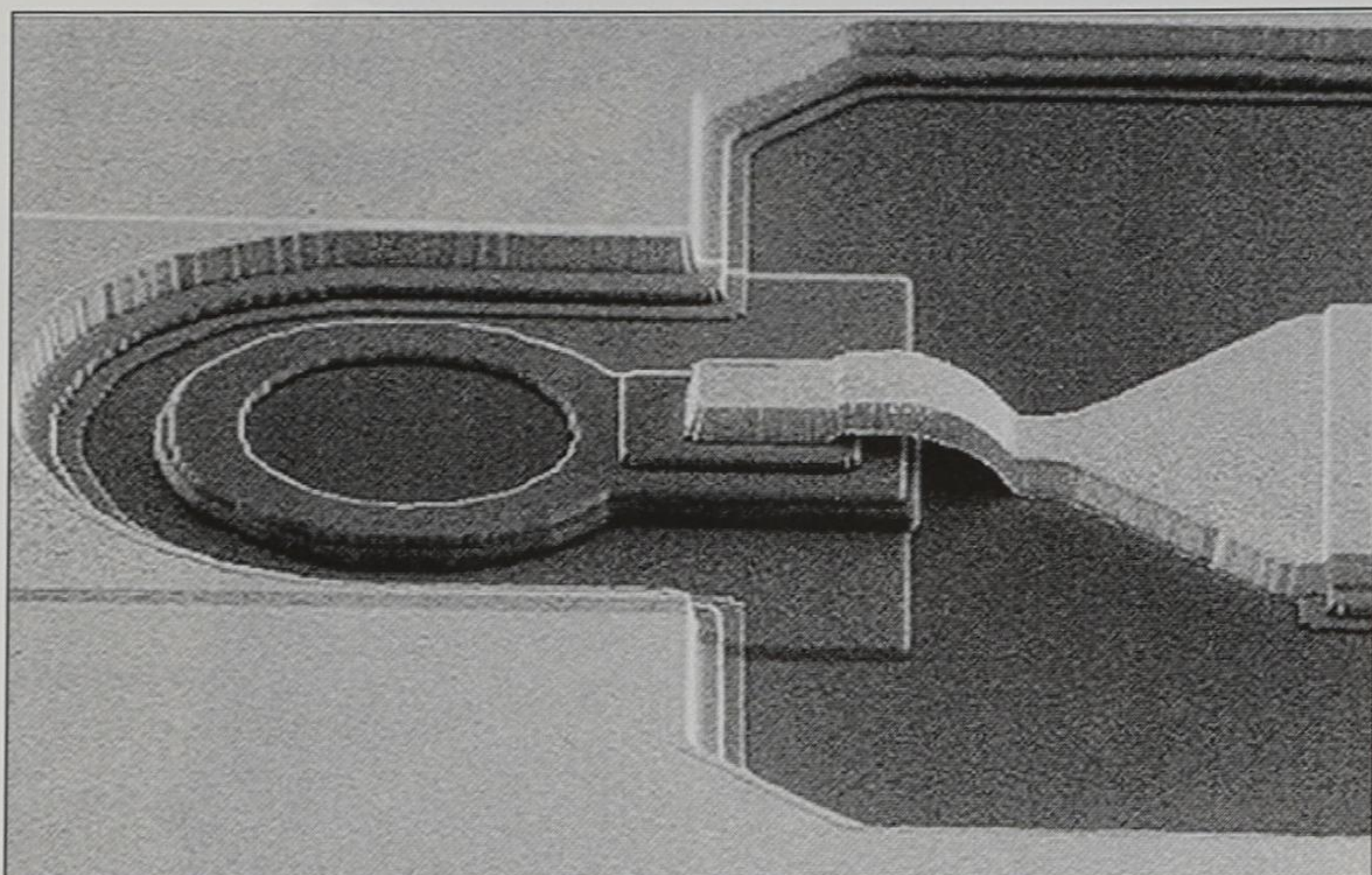


Figure 3. A scanning electron microscope (SEM) photograph of the front-illuminated InGaAs p-i-n detector with a co-planar waveguide (CPW) output.

One important aspect missing from the model is the effect of potential barriers at heterojunctions [see Figure 2]. The factors at play at these junctions are the energy discontinuity (the height of the barrier), the width of the barrier (dependent on the electric field and/or the structure parameters), and the energy of the carriers. These parameters determine the probabilities of thermionic emission over the barrier and quantum tunneling through the barrier. In turn, these probabilities determine the carrier current through the barrier for a given concentration of carriers on the low side.

These barriers can be incorporated into the finite difference model by partitioning the device into segments. The model creates a picture of the dynamics of carrier motion, calculating the current and carrier densities for every segment junction. At the "special" heterojunctions – those with energy barriers – the current density predicted by the drift conduction equation is compared with that predicted by the barrier emission and tunneling equations. If the barrier current is less than the drift current, carrier pile-up occurs on the low energy side of the barrier. Eventually, the carrier concentration increases to the point where the barrier current is large enough to support the drift current, and the barrier will reach a steady state. This chain of events will produce distortions in the signal, and limit the response speed of the devices; these are the important device characteristics that need to be studied and controlled.

The numerical "core" of this model is now being coded and tested and will then be incorporated into a graphical user interface. The eventual product will allow the designer to create arbitrary structures of varying semiconductor composition and doping, and then model the impulse response of the resulting diode. This will be a significantly higher level of flexibility than any other model of its kind.

InGaAs Photodiode Fabrication And Characterization

Discovery Semiconductors' InGaAs p-i-n detectors incorporate a number of advantageous features for DC to 65 GHz wide bandwidth applications. For example, the use of a semi-insulating InP substrate reduces parasitic effects. The devices have a co-planar waveguide (CPW) output with 50 Ω output impedance matching on the chip. The CPW comprises of a microwave footprint with signal-ground-signal configuration (100 μm spacing) for easy on-wafer RF testing using standard microwave probes. Also, the detector is a front-illuminated mesa diode that eliminates any "tail effects" as seen with planar diode technology. Finally, the use of "air bridge" technology allows the InGaAs p-i-n detectors to be front-illuminated for maximum coupling efficiency and photoresponsivity without increasing the parasitics (see Figure 3). The eye diagram of a DC to 50 GHz wide bandwidth photodiode is shown in Figure 4.

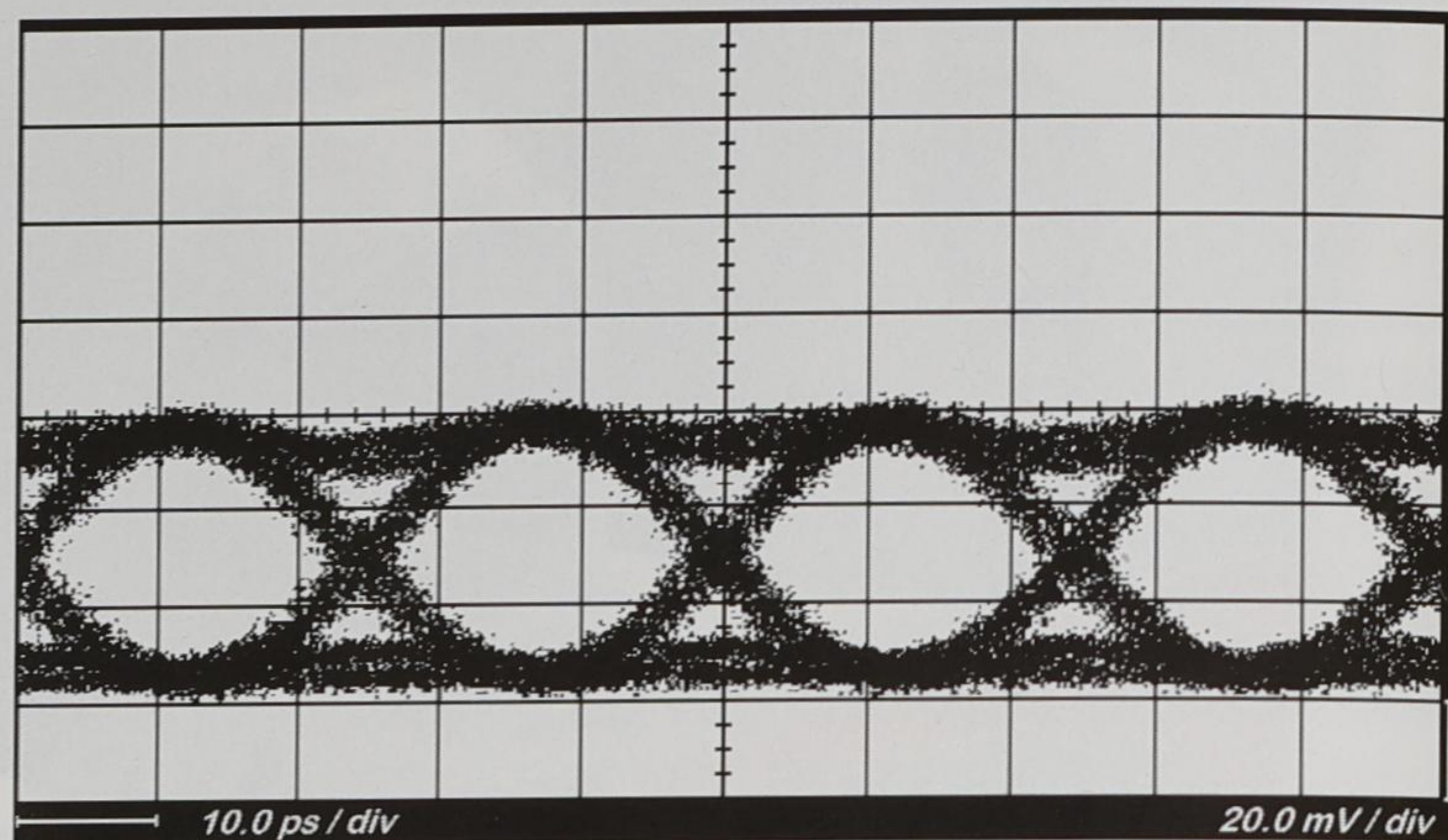


Figure 4. 40 Gb/s NRZ eye diagram of Discovery Semiconductors' 50 GHz InGaAs photodiode. The clear eye diagram illustrates the technical advancement and maturity of these devices.

The desired AC characteristics of a 40 Gb/s photodiode are wide bandwidth with a very low ripple factor and excellent phase stability across the entire pass band. This requires skillful microwave packaging of the photodiodes and photoreceivers. Figure 5 shows the fiber pigtailed microwave package with a RF connector. A packaged 65 GHz photodiode demonstrated a flat frequency response with less than ± 1 dB variation plus a smooth roll-off – both these characteristics are necessary to produce the clear eye diagram shown in Figure 4.

The ripple factor of the photodiodes is less than ± 1 dB for a wide frequency range from DC to 50 GHz. The accurate high frequency InGaAs p-i-n computer model described in the previous section has vastly improved the performance to the best ripple factor of any commercially available microwave InGaAs p-i-n diodes. This results in typical group delays of less than ± 10 ps.

At 65 GHz bandwidth, the lack of good front-end amplifiers has created a need for high optical power photodiodes. These photodiodes are expected to handle large amounts of optical input power (10 dBm or higher) and generate enough photocurrent to directly drive into a 50 Ω load. These InGaAs p-i-n photodiodes can handle average photocurrents of 5 mA at a reverse bias of 6 V or more without exhibiting significant non-linearity. At lower duty cycles, the devices can handle even larger amounts of maximum optical input power without any degrada-



Figure 5. Fiber-pigtailed microwave package with a K or V RF connector for wide bandwidth photodiodes and photoreceivers.

tion of the impulse response. Furthermore, as these devices are front-illuminated, the space charge effects are far less severe than the back illuminated photodiodes and hence, they handle larger optical input power [8, 9].

MODEL	- 3 dB Bandwidth (GHz)		Typical Voltage Gain @ 1.55 μm (V/W)	Power Gain (dB)		Bias Voltage (V)
	Min	Typical		Min	Typical	
DSC R401	12	14	80	7	10	+5/-0.5
DSC R402	10	11	350	15	20	+8
DSC R403	9	10	1000	25	30	+8/-0.5
DSC R404	45	50	60	7	10	+5/-0.5

Table I: Discovery Semiconductors' wide bandwidth photoreceivers combining InGaAs photodiodes and GaAs PHEMT-based MMICs.

Wide Bandwidth Photoreceivers

Discovery has also designed and fabricated a number of wide bandwidth photoreceivers for OC-192 (10 Gb/s) and OC-768 (40 Gb/s) systems (see Table). These products, which were introduced to the commercial market in January 1999, combine InGaAs p-i-n photodiodes with GaAs PHEMT-based MMIC amplifiers.

In the 50 GHz photoreceiver, the InGaAs p-i-n photodetector is DC-coupled to the GaAs MMIC amplifier with a 50 Ω input and output impedance, and about 10 dB power gain. The voltage con-

version gain of the amplifier is about 60 V/W at 1550 nm. Thus, 10 dBm optical input power will result in a signal output of 600 mV sufficient to drive the subsequent decision circuits.

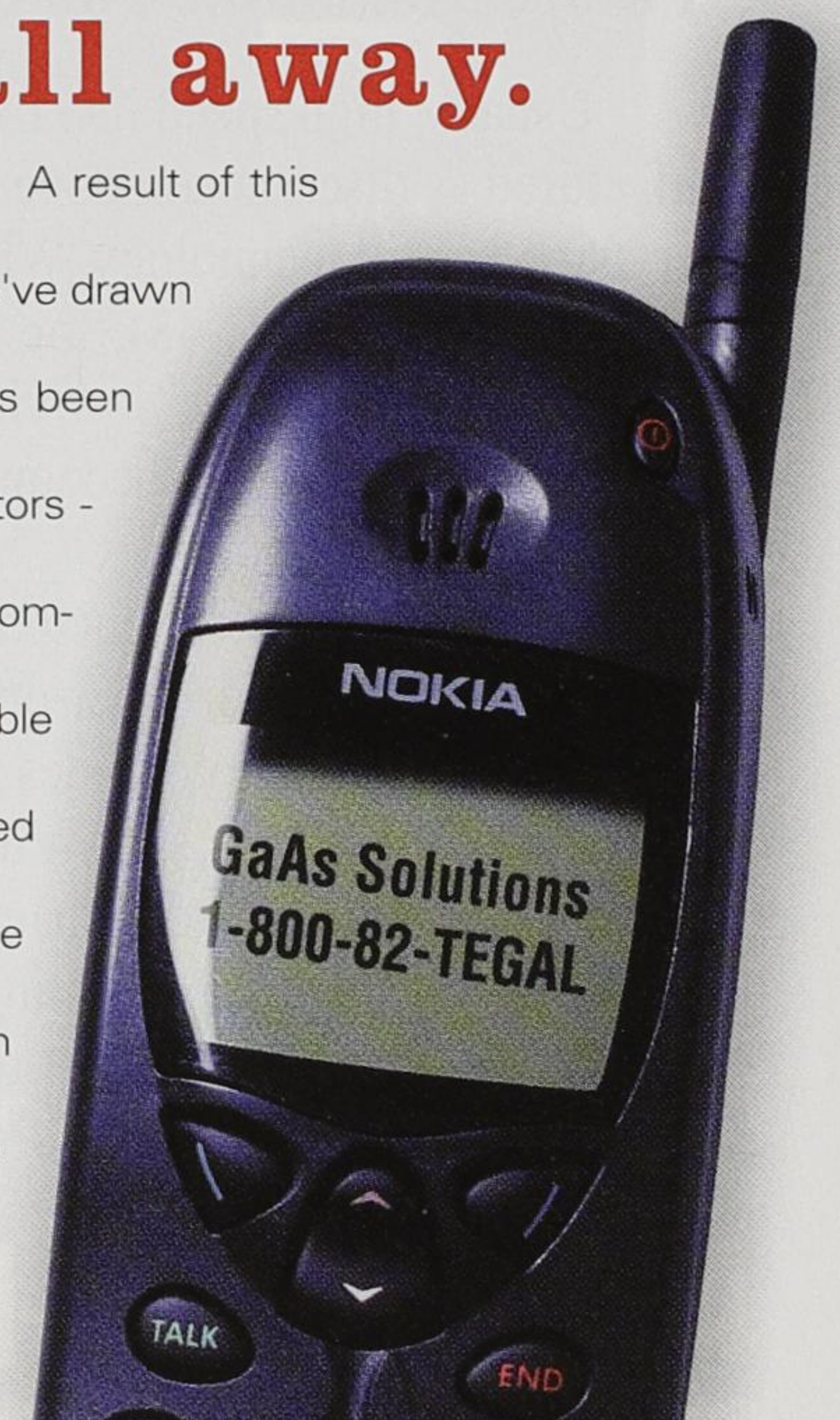
Although the 50 GHz InGaAs p-i-n diodes can handle large optical input power as described earlier, the development of the 50 GHz InGaAs photoreceiver (Model R404) is essential to prevent the problems of thermal runaway and to achieve better reliability [10]. The active diameter of the 50 GHz p-i-n diode is only 10 μm , and the device exhibits very high photocurrent and electric power den-

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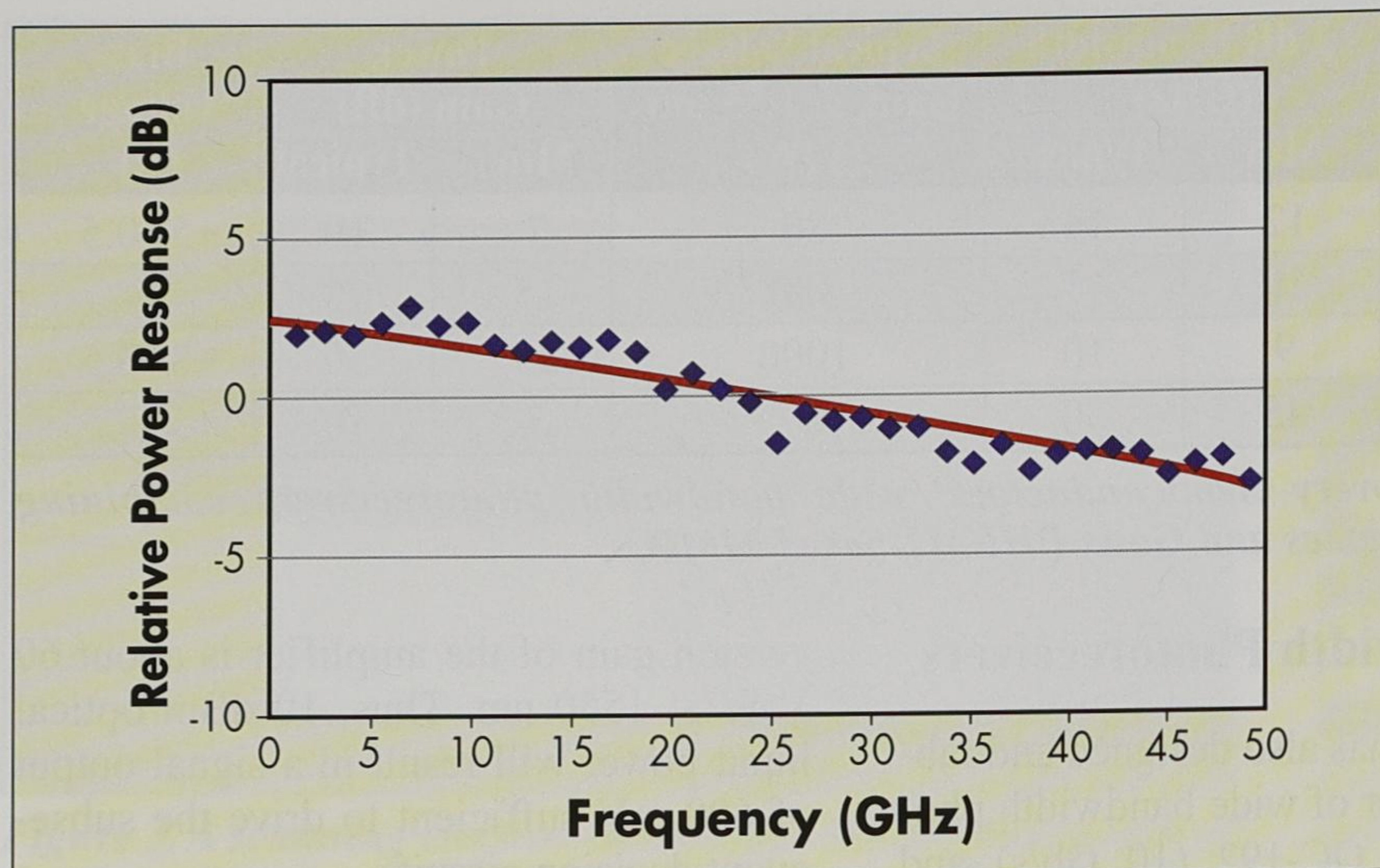


Figure 6. Response of the 50 GHz wideband photoreceiver as a function of frequency. The measurement was made at discrete frequency points as set by the optical heterodyne system. The response at the low frequency is limited by the input capacitor and at high frequency by the amplifier.

sity. This may lead to thermal runaway and cause catastrophic device failure.

The frequency response of the wideband photoreceiver from DC to 50 GHz is shown in Figure 6. The photoreceiver package was placed in a fixture so that the fiber could be aligned to the detector. Compared to a photodetector alone, the photoreceiver showed an approximate 10 dB increase in frequency response over the entire DC to 50 GHz bandwidth.

Future Monolithic Photoreceivers

Usually, high speed InGaAs detectors and GaAs amplifiers are manufactured as discrete components, and subsequently wire-bonded together using hybrid technology. While this is sufficient for most applications up to 2.5 Gb/s (OC-48), the hybrid approach has several drawbacks, namely increased labor, low yield, low reliability, and increased parasitic losses. These problems become increasingly severe at 10 Gb/s (OC-192) and 40 Gb/s (OC-768).

Discovery Semiconductors is actively developing totally integrated monolithic OEICs for fiber-optic applications. These InP-based OEICs combine InGaAs photodiodes and InGaAs/InP PHEMT amplifiers; one of these prototypes is shown in Figure 7. This monolithic approach will not only eliminate the drawbacks of the hybrid method, but will also take advantage of the high operating transistor speed ($f_T > 100$ GHz) of InP-based devices. Over the next few years, the company plans to manufacture these monolithic OEICs on a commercially basis for the 10 Gb/s (OC-192) and 40 Gb/s (OC-768) standards.

Conclusions

Wide bandwidth photodiodes and photoreceivers are key components of the emerging and future SONET/STM standards of OC-192 and OC-768. Their development requires the insertion of new technology for the fabrication of InGaAs p-i-n photodiodes, MMIC amplifiers and monolithic OEICs, as well as for microwave packaging. Through its innovative wide bandwidth products, Discovery Semiconductors is filling this gap very effectively.

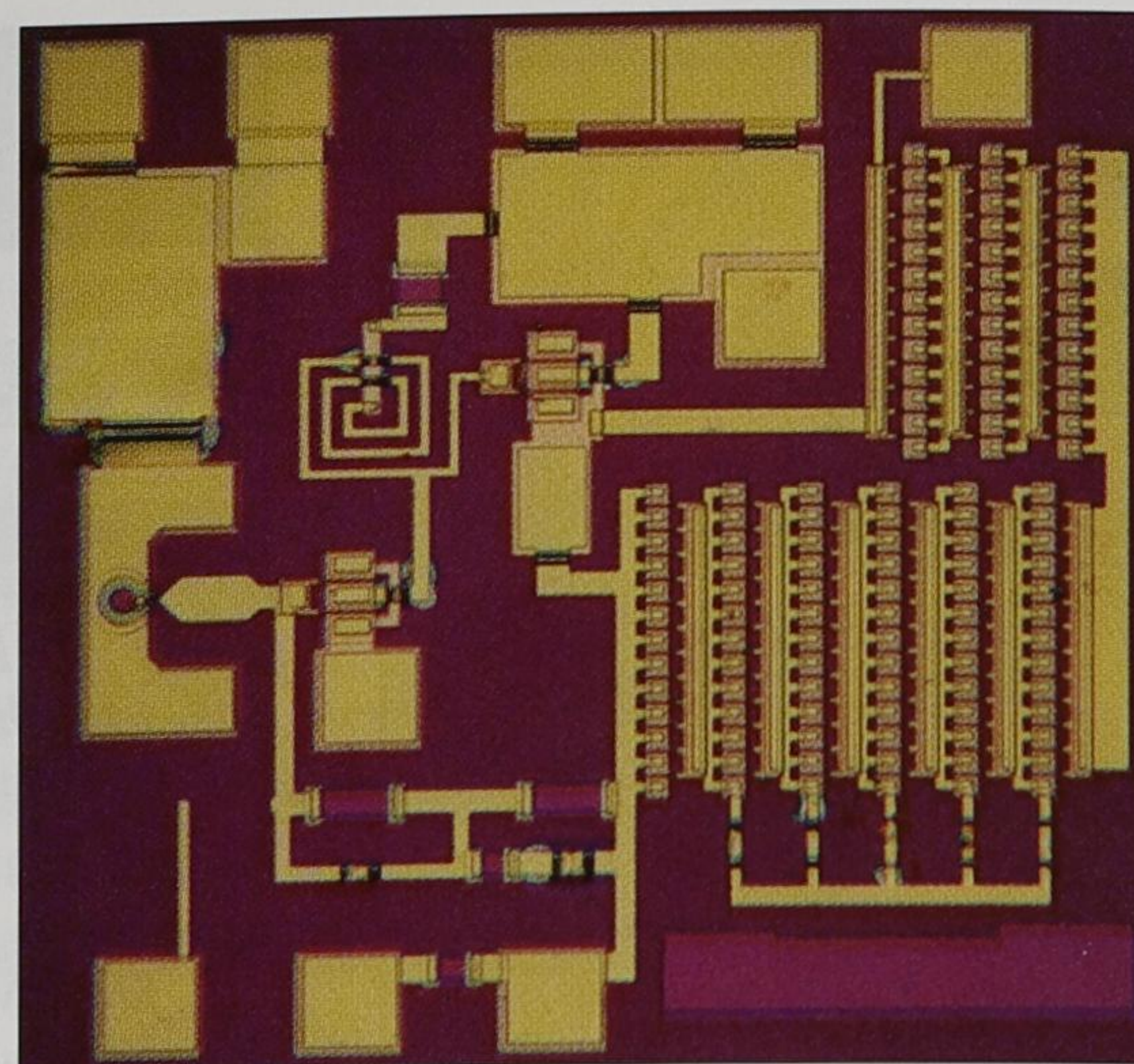


Figure 7. Discovery Semiconductors' next generation monolithically integrated InGaAs photodiode and amplifier OEIC for wideband telecommunications, RF photonics, and CATV applications.

Acknowledgment

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COMPANY PROFILE

SpectraSensors Commercializes NASA Technology

TIM WHITAKER

A California company is finding commercial applications for a technology originally developed to measure the atmospheric composition of Mars and Earth. SpectraSensors, Inc. manufactures gas sensor systems based on tunable diode lasers that have applications for oil and gas pipeline monitoring, environmental monitoring, atmospheric science, industrial process control and aircraft safety. The company was founded in a technology incubator, ViaSpace Technologies, which was established to commercialize space technologies developed at NASA's Jet Propulsion Laboratory (JPL). SpectraSensors obtained exclusive rights to JPL's tunable diode laser technology from the California Institute of Technology (Caltech), which manages JPL under a contract with NASA. Caltech is an equity stakeholder in SpectraSensors.

The venture represents ViaSpace's second operating subsidiary and has been under way since September 1998. Another ViaSpace company, QWIP Technologies, manufactures focal plane arrays using quantum well infrared pho-

todetectors (QWIPs) – another technology developed at JPL [see CS 4(4), p. 24]. SpectraSensors was incorporated in June 1999 and is now a separate entity from ViaSpace, although the companies operate in the same facility in Altadena, CA. The company operates low unit production facilities for the assembly, test and calibration of gas sensors systems. At present, the laser diodes at the heart of the sensor systems are fabricated by JPL. SpectraSensors is currently investigating foundries for its long-term diode laser production needs.

Since 1985, over \$16 million has been invested in the development of tunable diode laser technology at JPL, with most of the funding supplied by NASA and the Ballistic Missile Defense Organization (BMDO). BMDO required the lasers for high-speed optical communications while NASA was primarily interested in gas sensing applications. NASA has used gas sensors on aircraft and balloons to study weather, climate, global warming and aircraft emissions (see Figure 1). Laser-based gas sensors from JPL were aboard the Mars Polar Lander spacecraft that was scheduled to land on Mars in December 1999 – unfortunately, contact was lost with the spacecraft after it reached Mars. The spectrometers were designed to measure water vapor and carbon dioxide in the Martian atmosphere and in gases evolved from heated soil samples to provide information on the geological history of Mars as well as to analyze the planet's potential to support life. These were the first space-qualified near-infrared diode laser sensors ever developed, and the technology they incorporated is now being made available by SpectraSensors for a wide range of commercial gas monitoring applications.

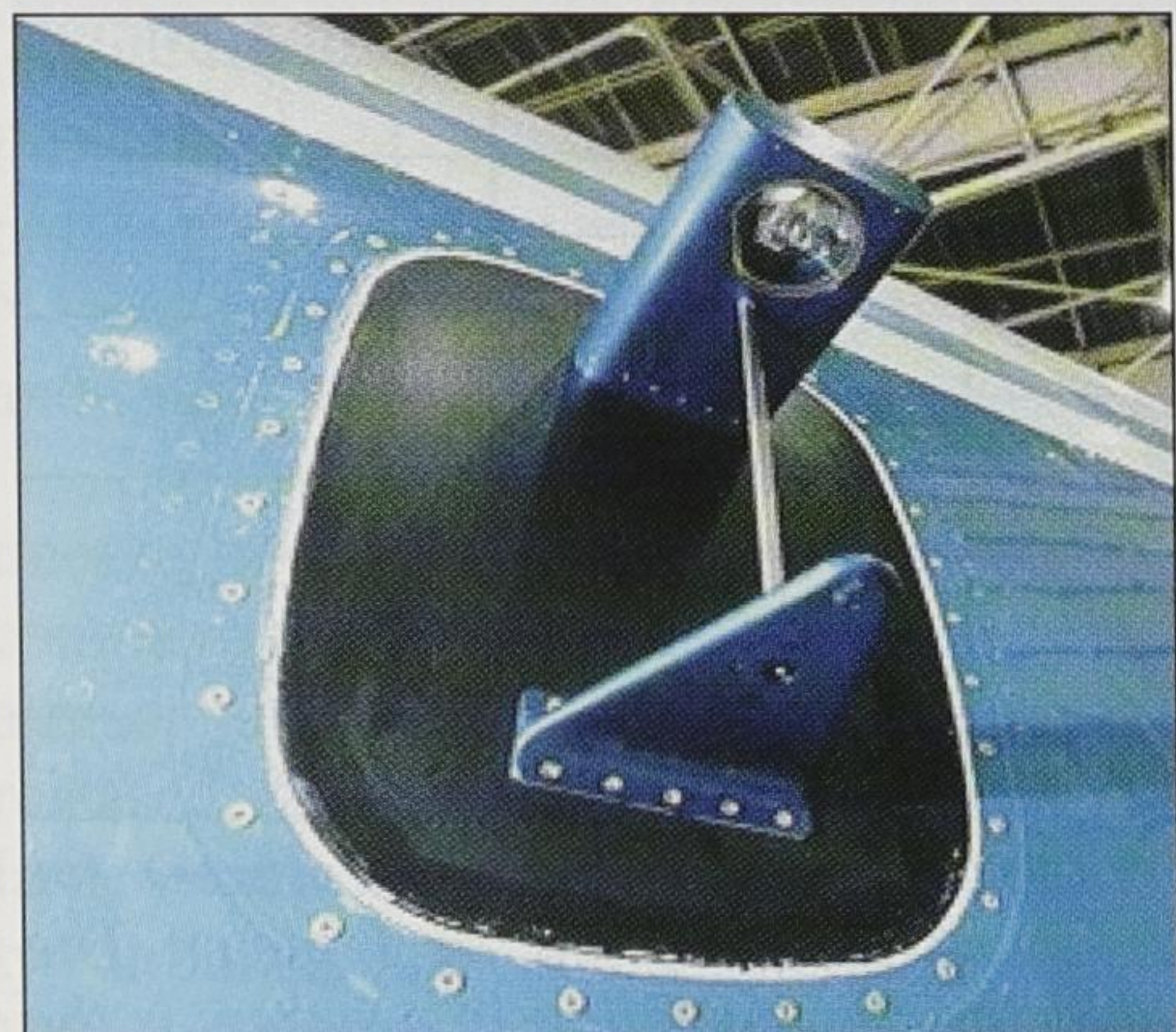


Figure 1. Laser hygrometer for water vapor measurement on board a NASA DC-8 research aircraft.

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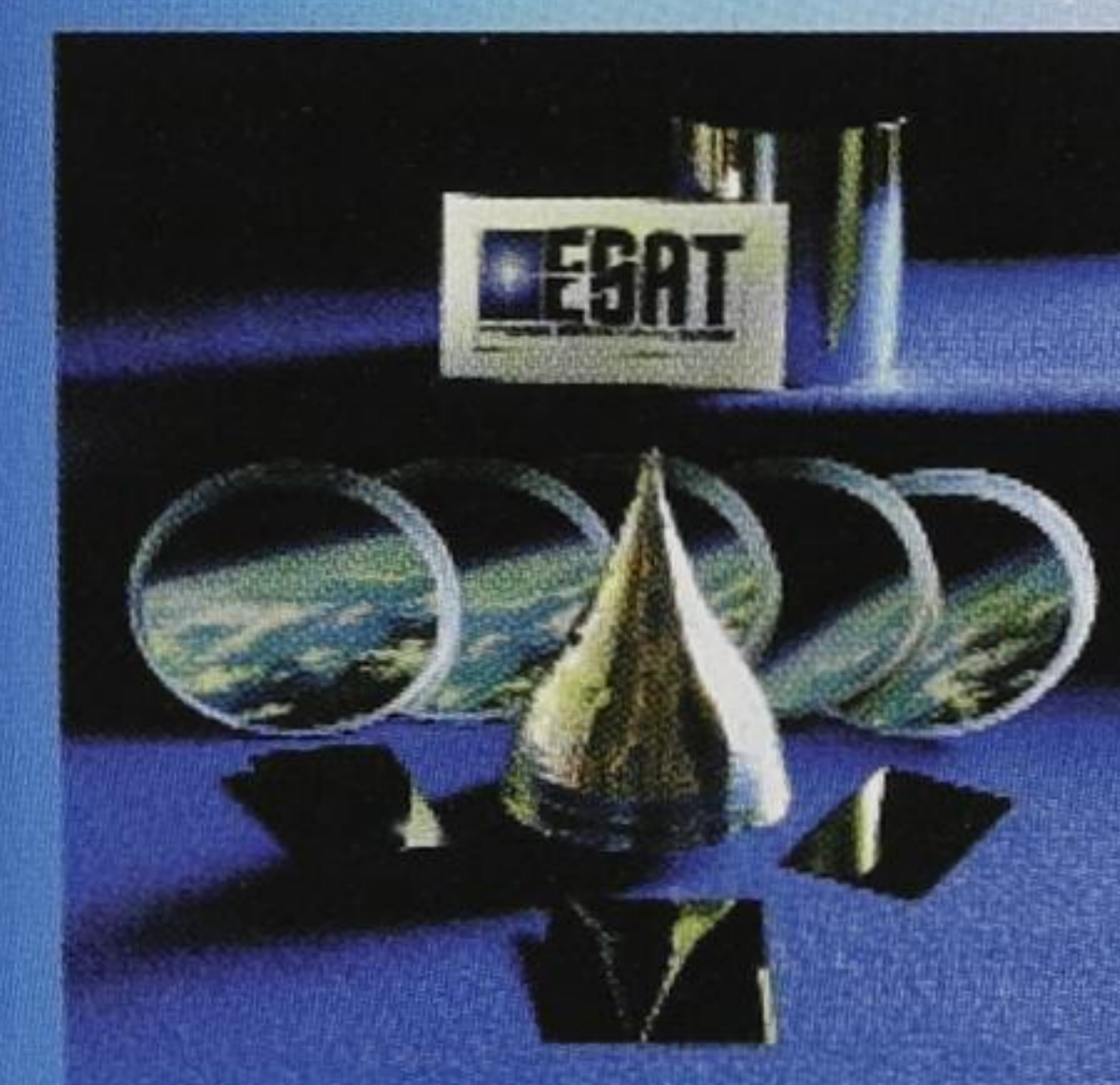


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Tunable Diode Lasers

SpectraSensors' gas sensor products are based around InGaAsP/InP laser diodes with strained multi-quantum well structures that operate in the 1.2-2.06 μm wavelength range (see Figure 2). The devices are single frequency distributed feedback (DFB) lasers with a side mode rejection of more than 30 dB, and offer a CW output of more than 5 mW. The company, in collaboration with JPL, is also developing GaSb-based lasers in the 2.1-2.6 μm range.

Any wavelength within the 1.2-2.06 μm range can be achieved with an accuracy of ± 5 Å. The output wavelength is initially determined by the composition of the active region. Fine-tuning is accomplished by adjustment of the device temperature – in a DFB laser, the temperature determines the refractive index of the grating region which in turn determines the precise wavelength at which feedback and stimulated emission occurs. Further fine-tuning can be obtained by adjustment of the laser operating current. In this way, the laser output can be precisely tuned to overlap an absorption line of the target gas molecule (see Figure 3).

Gas Sensor Systems

To fabricate a gas sensor system, the laser light is directed through the region where the measurement is to be made, and is focused onto a detector. These are InGaAs detectors obtained from a variety of commercial sources. If the gas sample contains molecules with absorption lines that match the laser energy, the laser light is absorbed. Measurements are made by comparing the detected signal when the laser wavelength is tuned to, and detuned from, the absorption peak.

A package of electronics controls the laser temperature and current, and processes the detector signal. Together with a software subsystem, this arrangement measures and quantifies the concentration of a target gas by monitoring the level of absorption of the laser beam at specific, predetermined wavelengths. The absorption wavelengths of selected gas molecules are shown in the table.

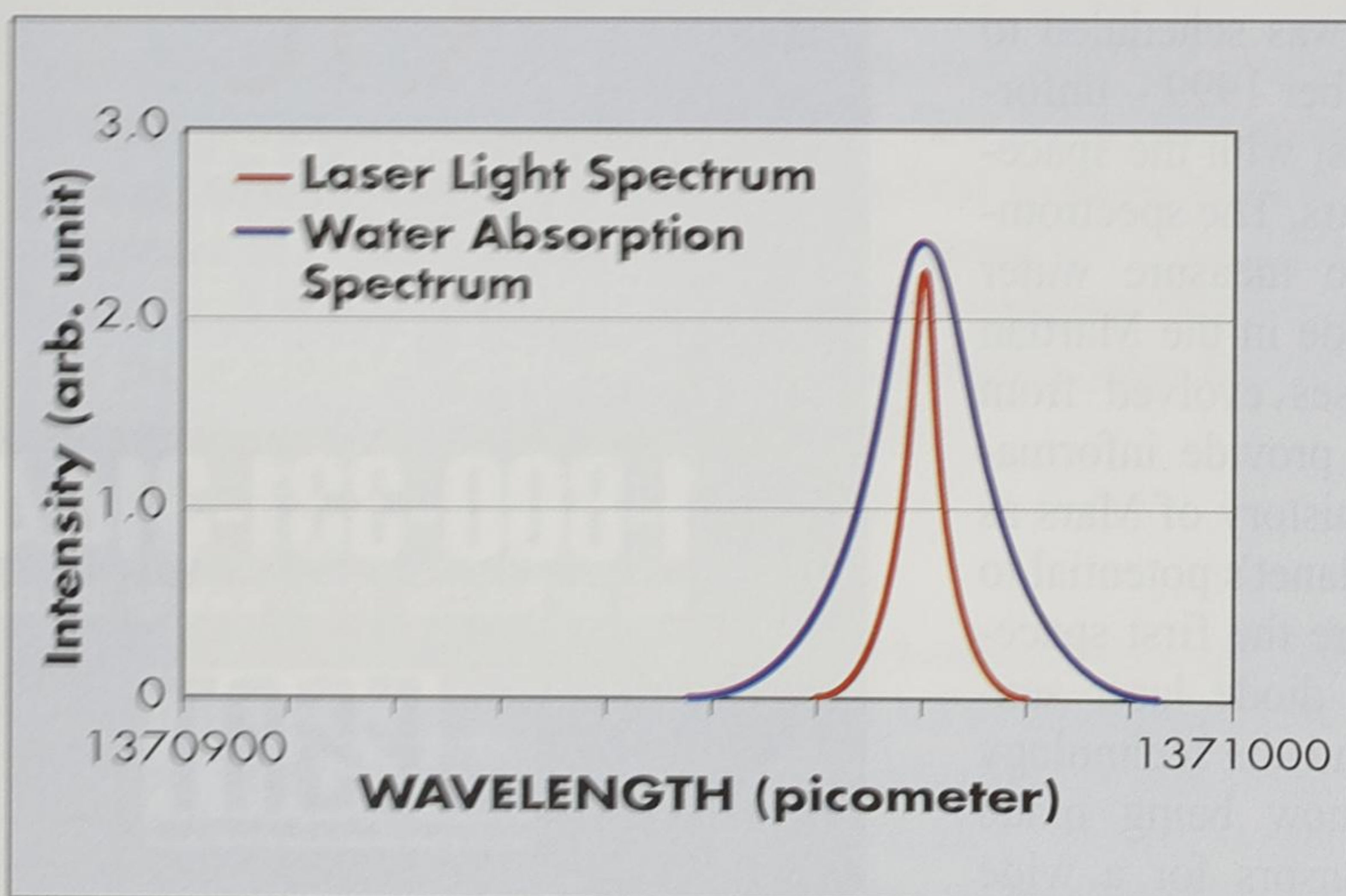


Figure 3. Graph of the output of a tunable laser diode overlapping an absorption line of water vapor.



Figure 2. A tunable diode laser in a TO can package next to a U.S. one cent coin.

Various optical configurations are incorporated into the systems depending on the required optical path length. A longer path length through the gas sample results in more absorption and therefore a higher sensitivity. Folded optical paths that use sets of customized mirrors allow this to be accomplished in a compact system, and several other configurations are also utilized. Path lengths can range from 1 mm to 1 km, using either open or closed single-or multi-pass cells. System prices depend strongly on configuration and quantity – pre-aligned analyzers that operate in benign environments are currently priced in the \$7-20 K range, while ruggedized analyzers designed to operate in harsh environments and/or over extreme ranges of temperature cost \$15-50 K. Currently, the laser diodes are the most expensive sub-component of the system, and the company is working on reducing these costs to provide more affordable gas sensing systems to its customers.

Gas sensors based on tunable diode technology are much more compact and efficient than conventional spectroscopy systems using gas or solid-state lasers. In most cases the lasers operate at room temperature, eliminating the need for bulky and

Molecule	Wavelength (μm)	Detection Limit (ppmv)
Oxygen (O_2)	0.76	0.04
Hydrogen fluoride (HF)	1.27	0.05
Water (H_2O)	1.37	0.30
Ammonia (NH_3)	1.50	4.00
Acetylene (C_2H_2)	1.52	0.40
Methane (CH_4)	1.65	3.00
Hydrogen chloride (HCl)	1.74	0.75
Carbon dioxide (CO_2)	2.00	5.00
Carbon monoxide (CO)	2.33	2.50

Detection limits in ppmv (parts per million by volume) for selected molecules with an absorption path of 1 meter. The actual minimum detectable gas concentration in a system is the detection limit shown above divided by the path length – a longer path length results in more absorption and higher sensitivity.

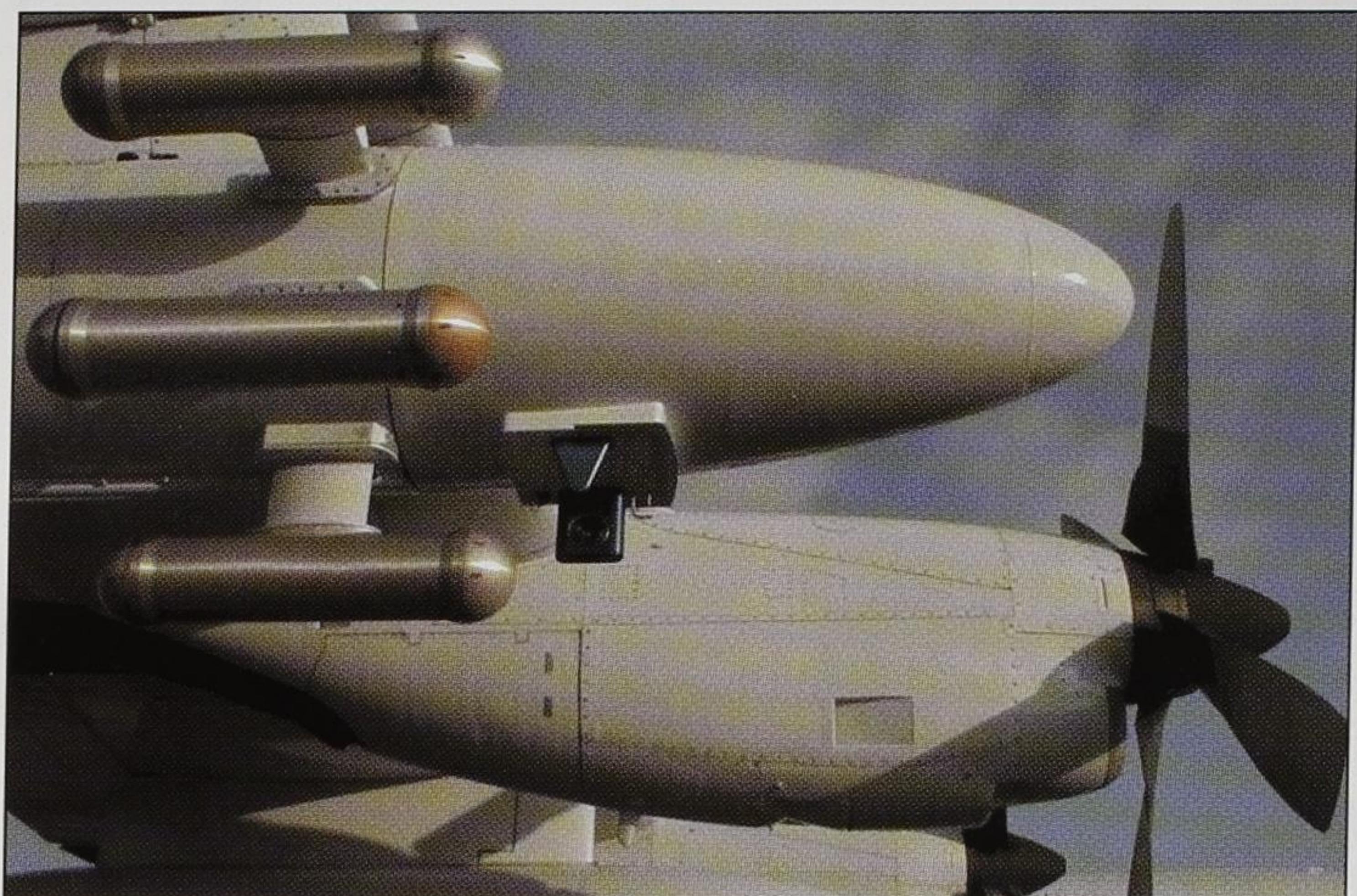


Figure 4. SpectraSensors' laser hygrometer shown mounted on NCAR's C-130 research aircraft.

expensive cooling systems. The lasers are also inherently robust, and are suited to operation in harsh environments. The ability to line the output wavelength to precisely match the absorption band of interest results in high sensitivity and selectivity. Also, the ability to modulate the laser current (and therefore the output wavelength) at high frequencies permits detection of very low gas concentrations with very short signal integration times.

Commercial Applications

A number of applications have been identified for SpectraSensors' gas sensing technology. The first is the use of hygrometers (water vapor sensors) on aircraft. The company has already supplied a hygrometer for use in a research aircraft (see Figure 4) operated by the National Center for Atmospheric Research (NCAR), to perform environmental monitoring tasks such as the study of cloud formation and dynamics. JPL recently ordered a hygrometer to be flown on a NASA research aircraft to study rocket and shuttle exhaust plumes.

SpectraSensors also received a contract to develop a water vapor sensor for commercial aircraft. Water vapor is a key atmospheric variable, and the energy released when water condenses has a large impact on aircraft ceilings, visibility, turbulence, thunderstorms and icing. Water vapor has a significant impact on air traffic safety and capacity, and water vapor measurements from fleets of com-

mercial aircraft would also provide important data for weather prediction, climate models and global warming. A third application is the use of water vapor and carbon dioxide sensors to analyze the composition of gas in natural gas pipelines. This is expected to lead to safer and more efficient distribution of the natural gas product. The company is presently developing a combined H_2O and CO_2 laser-based sensor. SpectraSensors has also identified several parties interested in the detection of both hydrogen fluoride (HF) and acetylene (C_2H_2). A major chemical company is seeking to monitor acetylene as a process gas, and the electric utility industry requires acetylene monitors for early detection of transformer failures. HF monitoring has applications in aluminum smelting and lithium battery manufacturing, and for safety monitoring in nuclear fuel enrichment processes.

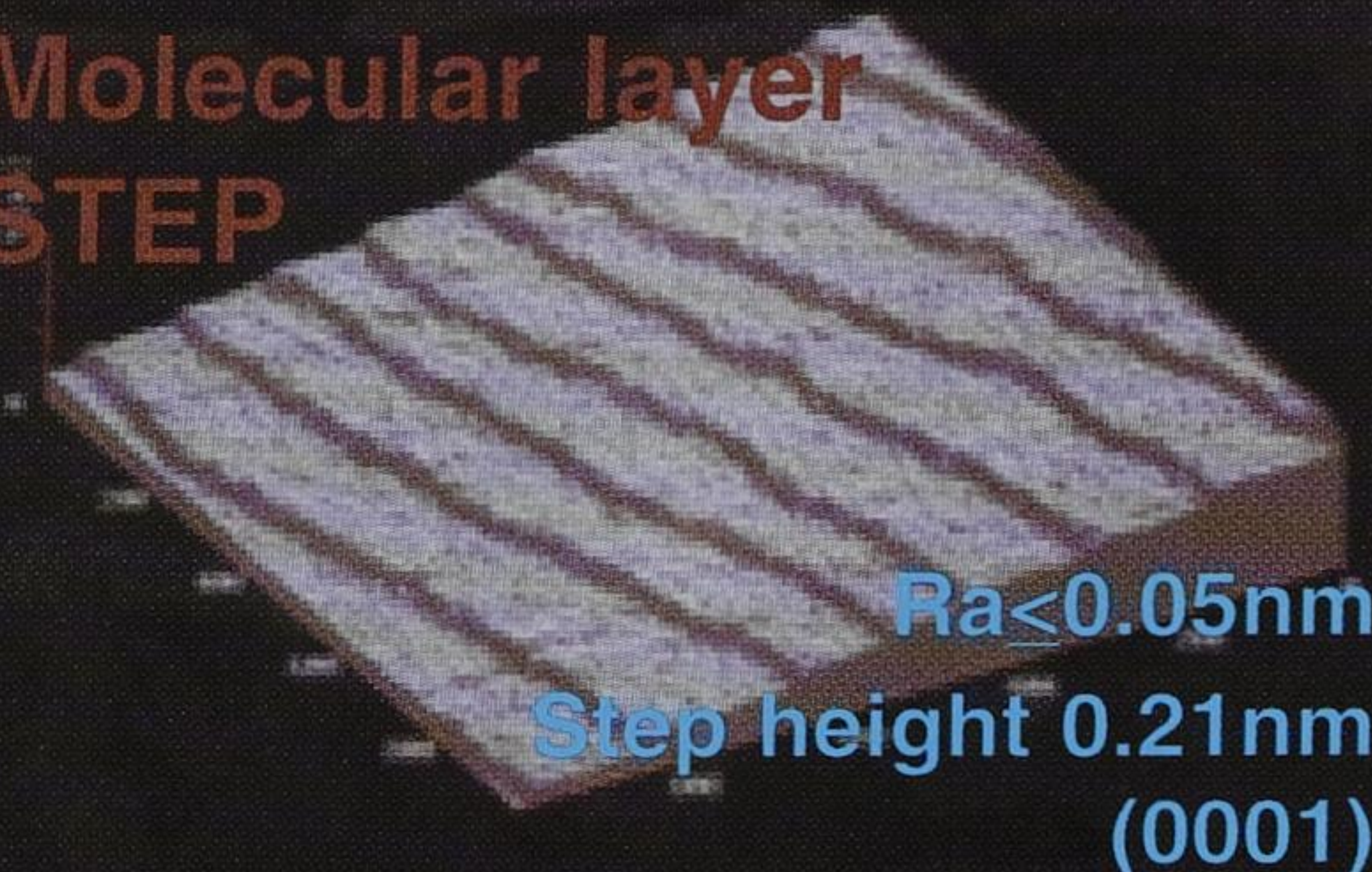
Many other applications have been suggested, ranging from the measurement of HF, HCl, NH_3 and CH_4 emissions from industrial smoke stacks, to the monitoring and analysis of humidity level and byproduct gases in the production of semiconductors, to the detection of toxic levels of farm animal waste gases.

The combined worldwide market for gas sensors is currently estimated at around \$1 billion, according to a Frost & Sullivan market research report. The strongest attributes of SpectraSensors' tunable diode laser gas sensors - high sensitivity, fast response time, durability in harsh environments and cost-effective manufacturability - should position the company well to address many of the potential application areas for this technology.

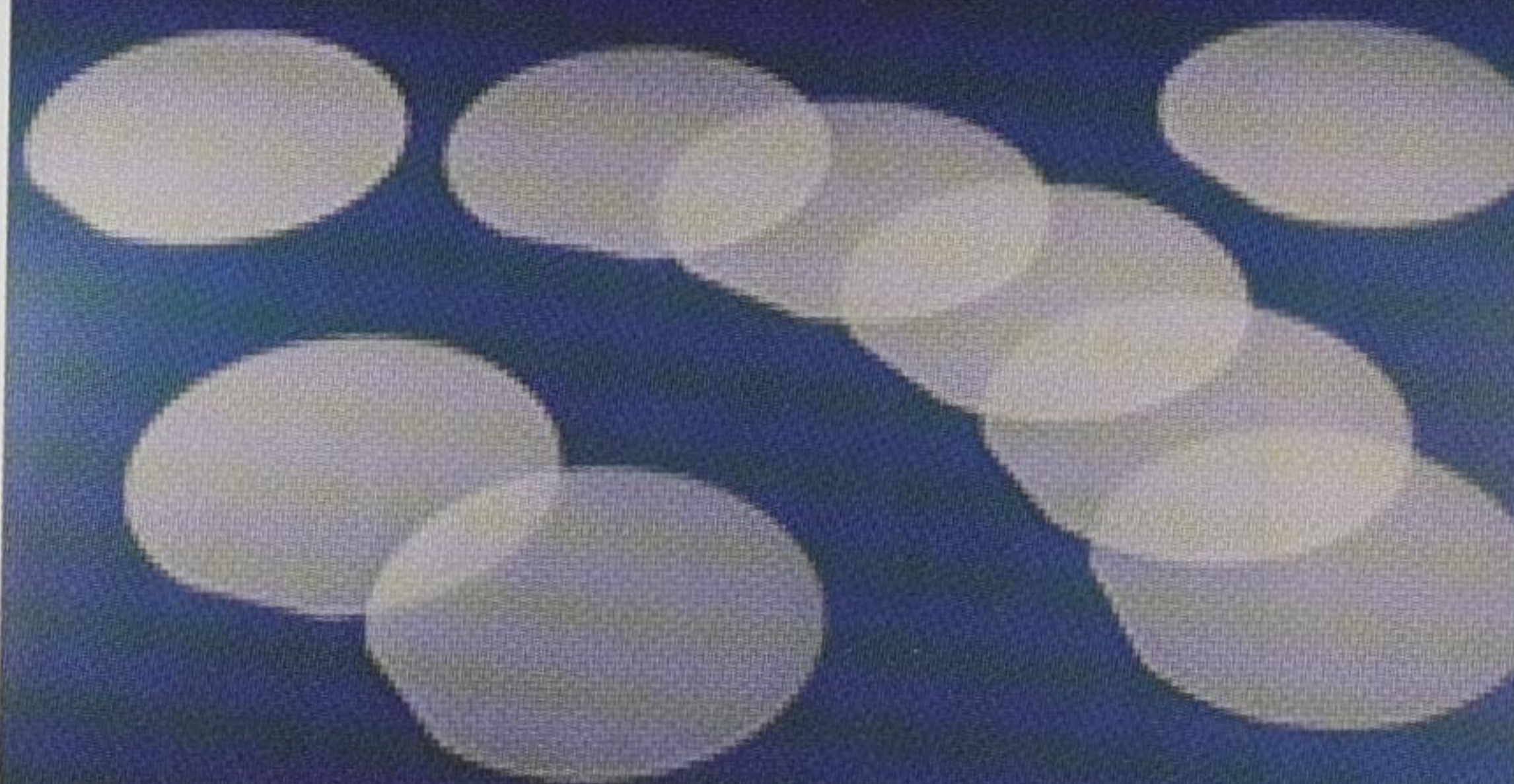
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VCSELs

652 nm VCSELs with 400 μ W Power

VCSELs emitting at 650 nm are important for low cost optical interconnects based on plastic optical fiber (POF). Devices were fabricated with five strained InGaP QWs in an AlGaInP separate confinement heterostructure, and $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ mirrors. The current aperture was defined by selective oxidation, resulting in devices providing 2 mW output power at 670 nm and nearly 0.5 mW at 652 nm for a $5 \times 5 \mu\text{m}^2$ aperture, and a record 400 μ W for a $2 \times 2 \mu\text{m}^2$ aperture.

[K. Choquette et al., **Sandia National Labs**, Proc. LEOS '99, p. 395]

Wafer Bonded GaAs-on-Si VCSELs

Wafer bonding of dissimilar materials at high temperature creates problems such as cracking during sample cooling. A new technique has been developed to bond GaAs-based VCSEL epiwafers with Si wafers at 80°C in high humidity for 18 hours. Before bonding, thin reactive layers were deposited on both surfaces. Following removal of the GaAs substrate, VCSELs were fabricated with a differential quantum efficiency of 53% and a CW output power of 7.1 mW.

[Y-H. Lo et al., **Cornell University and Sandia**, Proc. LEOS '99, p. 427]

VCSELs for 12.5 Gb/s Fiber Transmission

VCSELs are highly suitable transmitters for high speed optical interconnects. 12.5 Gb/s fiber transmission was demonstrated using selectively oxidized 850 nm VCSELs. The transmission distance over which the bit-error-rate exceeded 10^{-11} was 100 m in multi-mode fiber and 1 km in single-mode fiber.

[F. Mederer et al., **University of Ulm**, Proc. LEOS '99, p. 697]

1 W CW VCSEL Module

An array of 19 bottom emitting 980 nm VCSELs was soldered junction-side down on a diamond heat spreader and a micro-channel cooler to maintain a heat sink temperature of 18°C. The array had a threshold current of 286 mA and a maximum output power of 0.97 W at a drive current of 2.5 A. With a center-to-center spacing of 100 μm for the devices in the honeycomb-shaped array, the power density was 0.81 kW/cm². Under pulsed operation, a power density of 2.4 kW/cm² was achieved, suitable for materials processing applications.

[M. Grabherr et al., **University of Ulm**, Proc. LEOS '99, p. 265]

Fiber-Optic Transmission

L-Band WDM Transmission Records

The bandwidth of DWDM systems is being extended by utilizing the L-band transmission window in addition to the conventional C-band window.

- L-band transmission using eight 40 Gb/s channels over installed dispersion-shifted fiber (DSF) was demonstrated for the first time. The transmission distance was 176 km, and the 8 channels ranged in wavelength from 1578.7 to 1590.4 nm. InP HEMT-based ICs were used for the 40 Gb/s multiplexer in the transmitter and the dynamic flip-flop IC in the receiver. A uni-travelling-carrier photodiode provided a high receiver sensitivity of < -27 dBm.

[K. Yonenaga et al., **NTT**, Elec. Lett. 2000, 36(2), p. 153]

- Transmission of sixty-four 10 Gb/s channels over a distance of 10,127 km was demonstrated using L-band EDFAs. Signal wavelengths ranged from 1573.3 to 1599.5 nm with an ITU grid spacing of 50 GHz. A total of 12 EDFAs were used, each containing both 980 nm and 1480 nm pump lasers to achieve a low noise figure and a high output power.

[N. Shimojoh et al., **Fujitsu**, Elec. Lett. 2000, 36(2), p. 155]

10 Gb/s Optical Receiver Using APD and GaAs HBT ICs

An optical receiver with a sensitivity of -26.5 dBm has been developed. The receiver combines an avalanche photodiode (APD) with three GaAs HBT ICs: a preamplifier, a voltage-controlled-oscillator (VCO) and an equalizing amplifier, clock and data recovery circuit. The latter IC measured $4 \times 4 \text{ mm}^2$ and contained 1300 transistors and 1200 resistors. The HBTs had f_T and f_{max} values of 70 and 120 GHz, respectively.

[T. Yamamoto et al., **Fujitsu**, Elec. Lett. 2000, 36(2), p. 158]

Microelectronic Devices and Circuits

10.5 GHz SiGe Bipolar LNA

A monolithically integrated low noise amplifier fabricated in a 0.5 μm SiGe HBT technology demonstrated a noise figure of 2.0 dB with a gain of 26 dB at 10.5 GHz. This noise performance, a record for Si/SiGe LNAs, demonstrates the suitability of this technology for X-band receivers for use in applications such as satellite links.

[D. Zöschg et al., **Technische Universität Wien (Austria) and Infineon**, Elec. Lett. 1999, 35(25), p. 2195]

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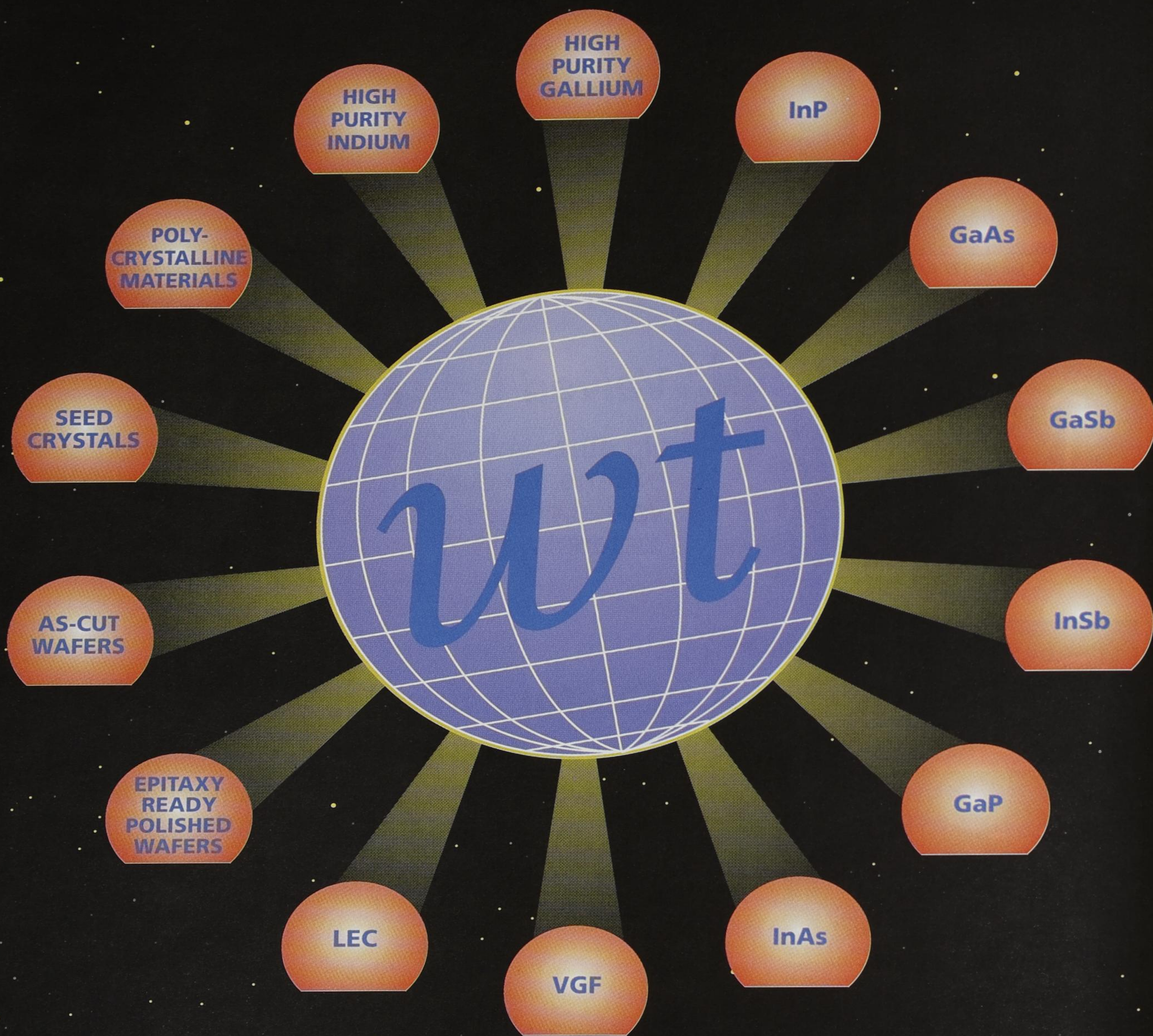
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Optoelectronic Devices

High Efficiency LEDs with a Radial Outcoupling Taper

A major factor limiting the performance of LEDs is their low external efficiency caused by total internal reflection of light. Various solutions already exist, including resonant cavity LEDs, devices with a back side mirror, and transparent substrate devices. This paper describes a novel method for efficient light outcoupling from LEDs involving the use of a circularly symmetric structure with a lateral taper. The device is shown schematically in Figure 1. Light can only escape from the bottom semiconductor-air interface at a small incident angle. A small fraction of the generated light is emitted from the area directly below the active region, while most of the light undergoes total internal reflection and is directed out towards the taper, guided by the mirror. The taper is designed such that light is efficiently coupled out of the device around the outer edge of the structure.

Devices of this type with InGaAs QW active regions, emitting at 980 nm, have demonstrated record high quantum and wallplug efficiencies of 45% and 44% respectively for encapsulated devices.

Figure 2 shows the detailed device structure. Device layers (InGaAs QWs, GaAs cladding layers) were grown by MBE, and a circular pedestal was defined. A photoresist layer was added, and modified into a lens shape by treatment in a solvent atmosphere. After ion beam etching, the remaining photoresist was removed to leave a flat-topped surface surrounded by a tapered ring. A quarter of the ring was metallized to form the n-contact, while the p-contact was a small circle in the center of the top surface. After deposition of the polyimide layers and the gold mirror, the thickness of the top metallization was increased by galvanization to form a quasi substrate. The structure shown in figure 2 was glued upside down to a glass carrier, and the substrate was removed by wet etching as far as

the AlAs etch-stop layer. The device was encapsulated in a medium with a refractive index of 1.48 to further increase the efficiency values.

[W. Schmid et al, **University of Ulm (Germany)**, presented at Photonics West 2000, see Proc. SPIE 3938-07]

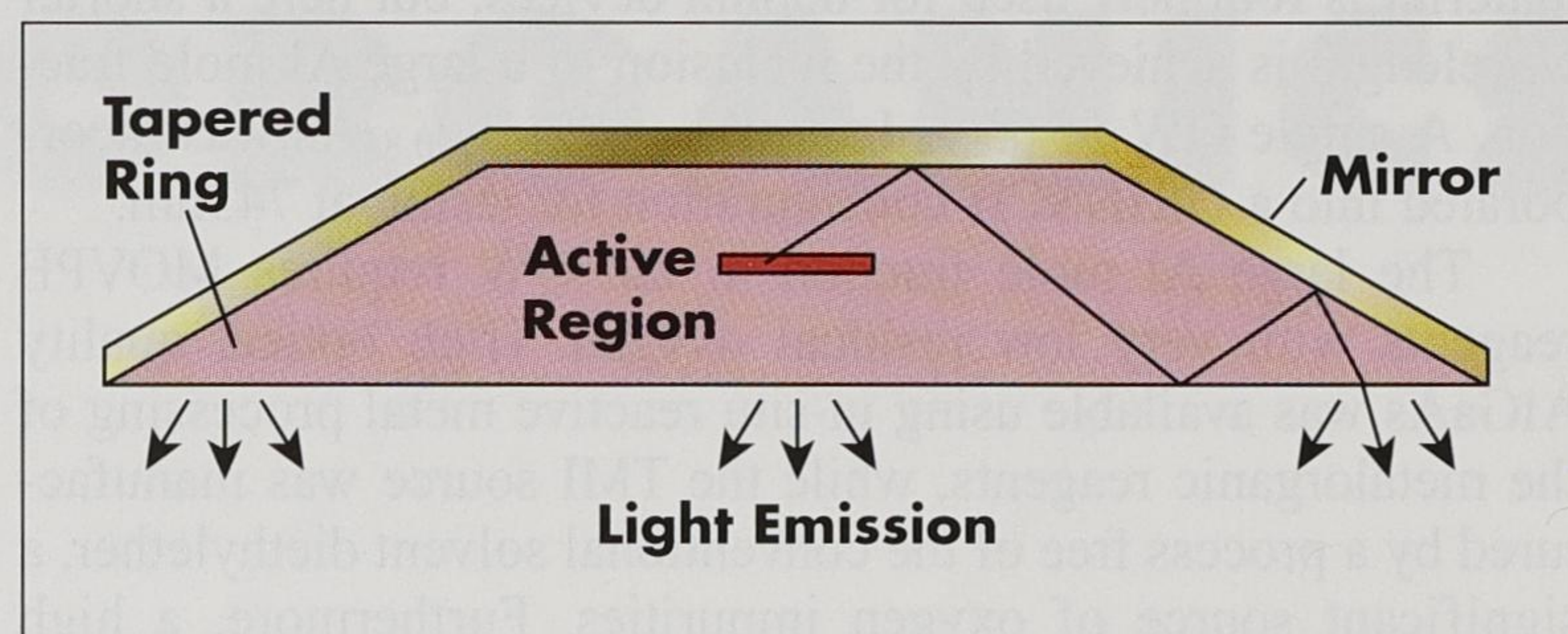


Figure 1. Simplified cross-sectional structure of the circularly symmetrical device, which is an extremely flat truncated cone covered by a mirror. Light is guided radially towards the taper, where it is directed out of the device.

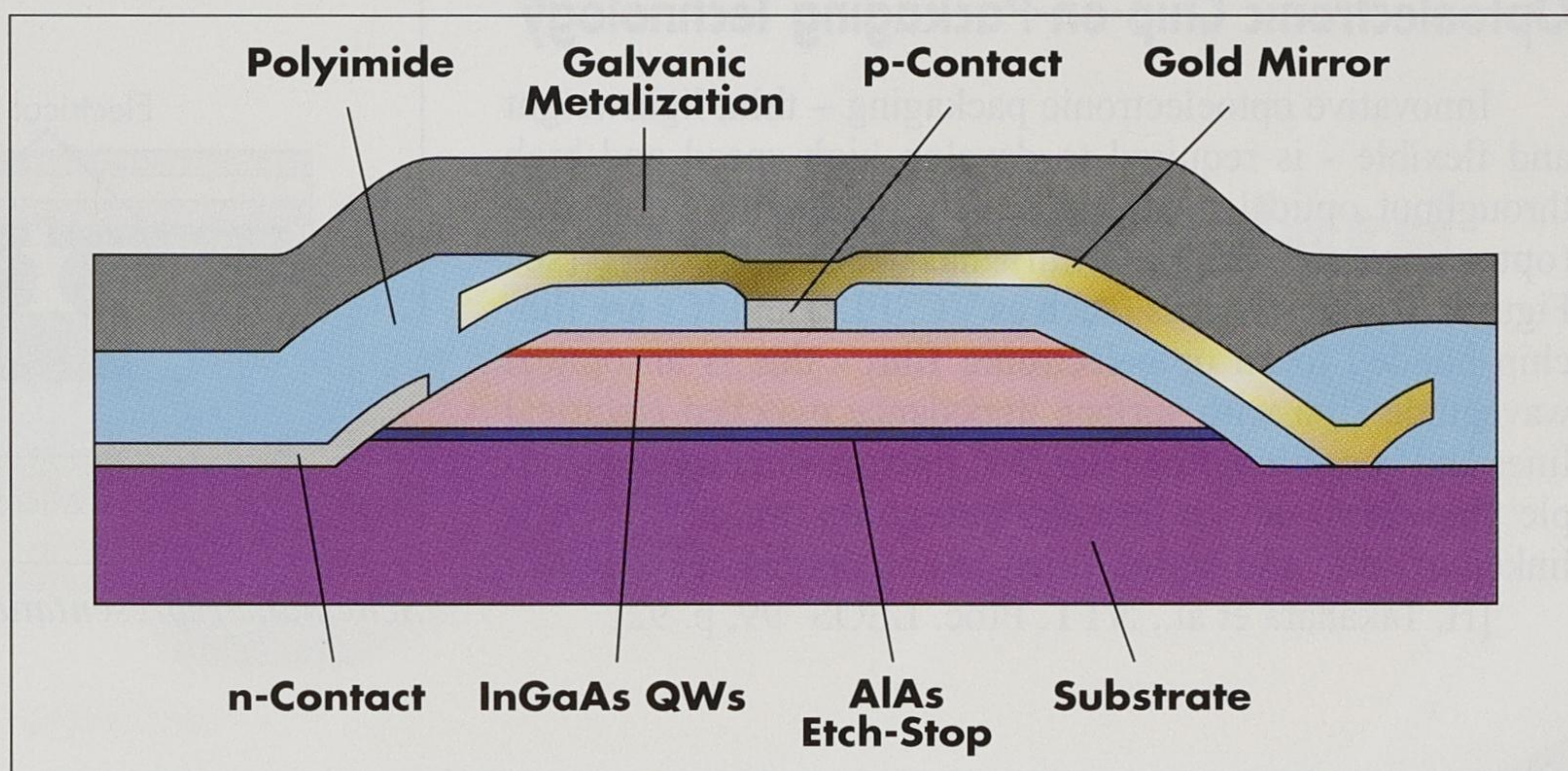


Figure 2. Schematic of the device structure. At this stage, the device is glued upside down on a glass carrier, and the substrate is removed by etching as far as the AlAs layer.

GaAs Solar Cells on Silicon

A passivation technique for single junction GaAs-on-silicon solar cells increased the efficiency (1 sun AM0 illumination at 27°C) from 15.8% to 18.6%. Devices were grown by conventional MOCVD and passivated at 250°C under a PH₃/H₂ plasma. This process provides H atoms to passivate the electrical activity of defects and impurity states, and P atoms to passivate the GaAs surface and suppress plasma-induced damage.

[G. Wang et al., **Nagoya Institute of Technology (Japan)**, Appl. Phys. Lett. 2000, 76(6), p. 730]

High Power Microstack Lasers

Many emerging applications of high power diode lasers require a low cost per Watt. A promising approach is the microstack laser in which two or more active regions are integrated vertically in the same monolithic structure. 808 nm devices containing two or three AlGaInAs/GaAs active regions separated by tunnel junctions were fabricated. A 200 x 600 μm² double stack laser exhibited a threshold current of 570 mA and an output power of 7 W under pulsed operation at room temperature.

[C. Hanke et al., **Infineon Technologies** and **Osram Opto Semiconductors**, Proc. LEOS '99, p. 80]

High power AlGaInAs 743nm Lasers

Laser diodes operating in the 700-770 nm wavelength range have potential applications for photodynamic therapy and optical pumping. However, the development of these wavelengths has been hindered by the range of possible QW gain regions. Some notable success has been reported recently for Al-free devices based on compressive- and tensile-strained QWs. In contrast, the gain region reported here is based on an AlGaInAs QW. This material is routinely used for 808nm devices, but here a shorter wavelength is achieved by the inclusion of a large Al mole fraction. A single QW of 65 Å $\text{In}_{0.15}(\text{Al}_{0.32}\text{Ga}_{0.68})_{0.85}\text{As}$ was incorporated into a GRINSCH configuration for lasing at 743nm.

The large Al mole fraction in the QW requires MOVPE reagents with very low residual oxygen. High optical quality AlGaAs was available using in-situ reactive metal processing of the metalorganic reagents, while the TMI source was manufactured by a process free of the conventional solvent diethylether, a significant source of oxygen impurities. Furthermore, a high

indium fraction of 15% was necessary to effectively pin dislocations propagating into the active region, where the principal degradation mechanism appears to correlate with bulk crystal defects.

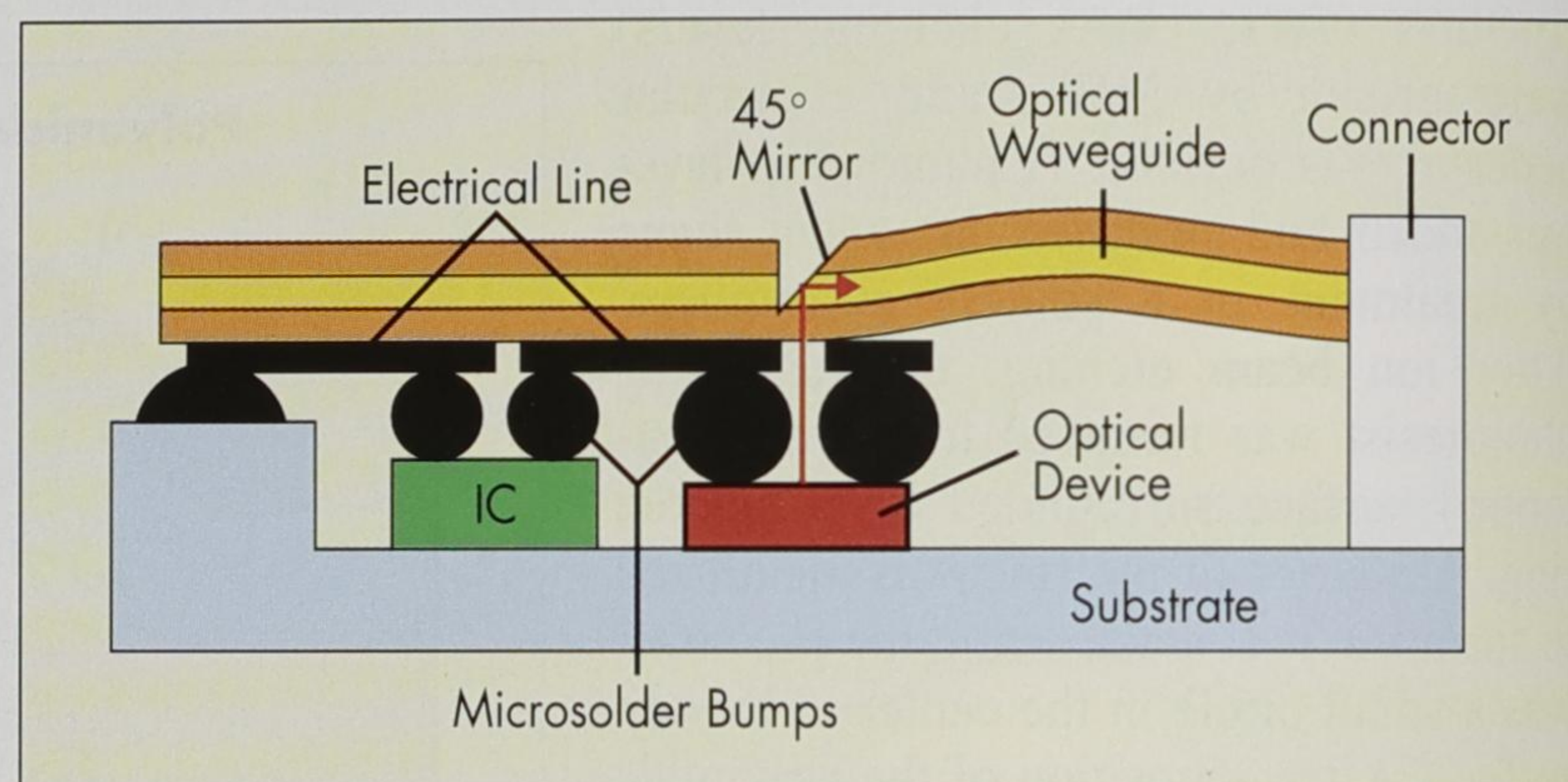
Facet coated, oxide defined stripe devices (1200 microns x 120 microns) were life tested at both 1.2 W and 1.5 W. The life-times of these devices at 15°C were 2000 hours and 700 hours, respectively. The degradation at 1.2 W was 12.4% in 2000 hours and the device failed after 2400 hours. Although the performance is not yet comparable to the more highly developed 808 nm laser, the high Al-content AlGaInAs QW system should meet the requirements of medical applications where dose periods, and therefore laser pulse lengths, are relatively short.

[J. S. Roberts et al., **University of Sheffield, PLT Technology Inc*** and **Epichem Ltd.**, presented at Photonics West 2000 - see Proc. SPIE 3947-08. *<http://www.plttechnology.com>]

Optoelectronic Chip-on-Packaging Technology

Innovative optoelectronic packaging – thin, lightweight and flexible - is required to develop high speed and high throughput optical modules. A new packaging technology (optoelectronic chip-on-film) has been proposed (see Figure). Optical devices (such as VCSELs) and ICs are flip-chip bonded to an optoelectronic film - this is an optical waveguide film with surface impedance matched electrical lines and bump-bonding pads. 45° mirrors were used to couple the optical device into the waveguide, which in turn is linked to input and output fibers via an optical connector.

[H. Takahara et al., **NTT**, Proc. LEOS '99, p. 92]



Schematic representation of optoelectronic chip-on-film packaging.

Wide Bandgap Materials

High Mobility AlGaIn/GaN on Silicon

Room temperature Hall mobilities exceeding 900 cm^2/Vs were obtained for AlGaIn/GaN heterostructures grown on Si(111) by single temperature flow modulation MOVPE. The 2DEG sheet carrier concentration was $1.3 \times 10^{13} / \text{cm}^2$ and the thin AlGaIn top layer had a surface roughness of 1.5 nm. State-of-the-art transistor structures grown on sapphire and SiC have mobilities exceeding 1500 cm^2/Vs at $10^{13} / \text{cm}^2$ sheet electron density.

[A. Schremer et al., **Cornell University**, Appl. Phys. Lett. 2000, 76(6), p. 736]

Low Threshold Current Density ZnCdSe Lasers

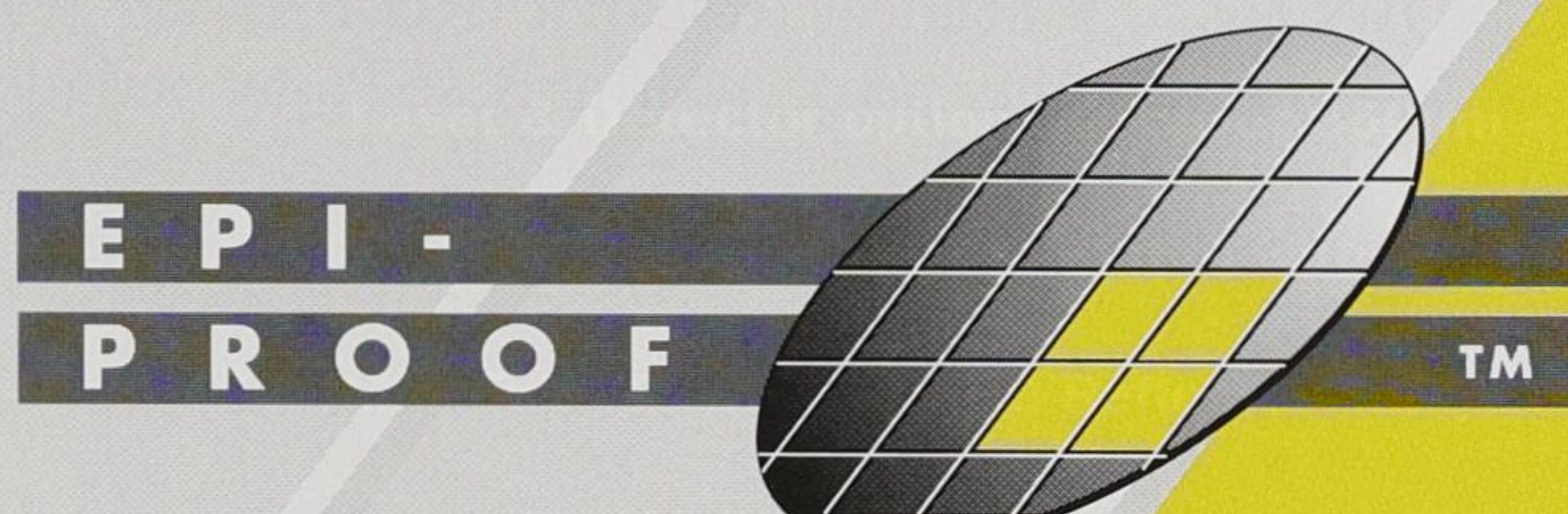
Green ZnSe-based lasers require improvements in lifetime, as well as reduced lateral current spreading through lateral waveguiding. Laterally selective implantation-induced disordering is used to fabricate index-guided ZnCdSe/ZnSSe lasers. The threshold current density was reduced by a factor of three from 276 to 96 A/cm^2 while the differential quantum efficiency was increased from 2.9 to 4.1%. The device lifetime under CW operation was increased by a factor of two.

[M. Strassburg et al., **Technische Universität Berlin** and Sony, Elec. Lett. 2000, 36(1), p. 45]

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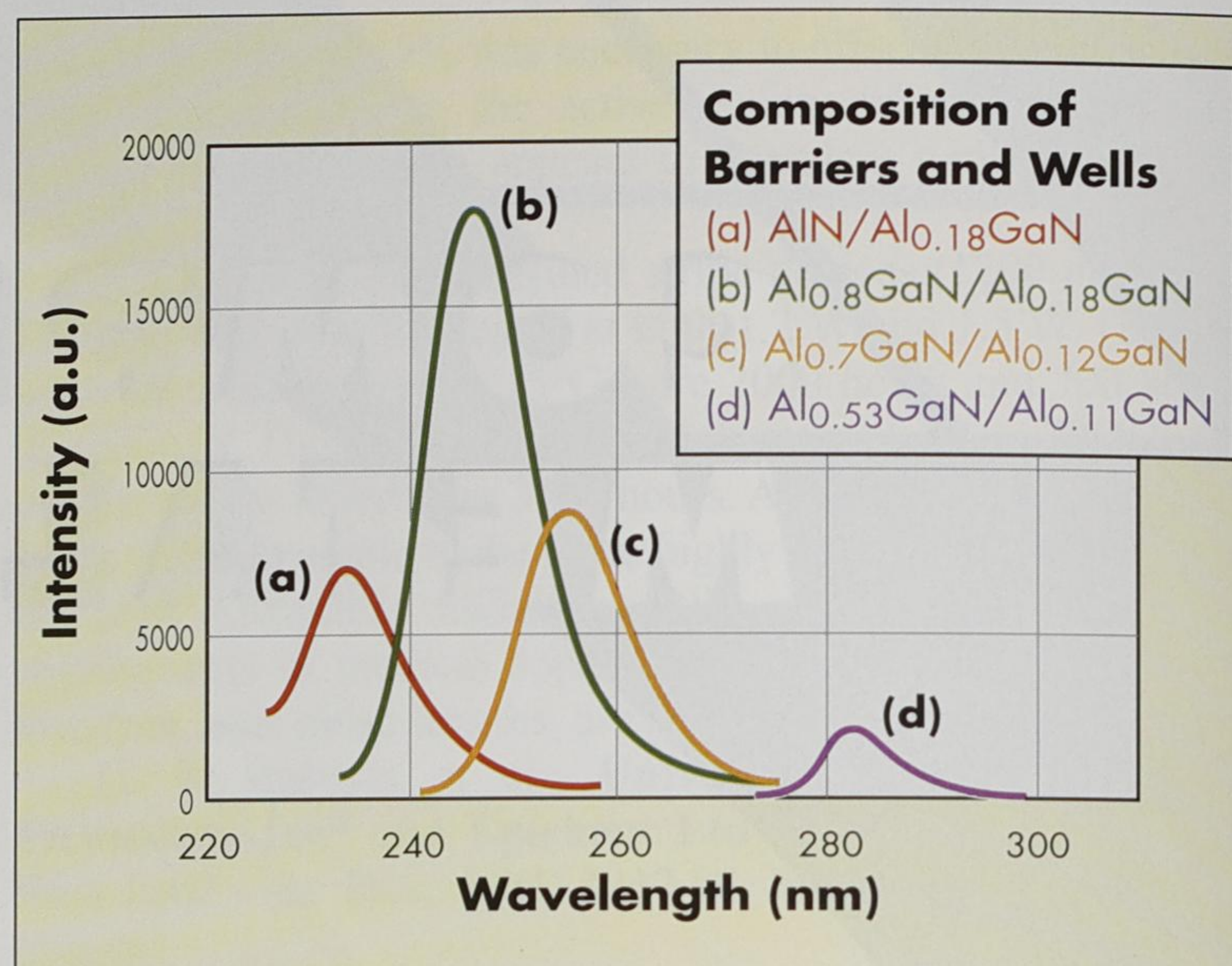
230-250 nm Photoluminescence from AlGaN QWs at 77 K

Ultraviolet laser diodes and LEDs are in demand for large capacity optical memories and compact UV measurement systems. However, some serious problems have to be overcome; one is the difficulty of obtaining efficient emission from AlGaN quantum wells (QWs), in contrast to InGaN QWs. The other major problem is achieving hole injection through AlGaN alloys with an Al content exceeding 30%.

This work describes the first intense UV photoluminescence (PL) around 230 nm from AlGaN multi-quantum-wells (MQWs) with high Al-content AlGaN or AlN barriers. Samples were grown by MOVPE on 6H-SiC substrates using a thin AlN buffer layer. After establishing the correct conditions for growth of high Al-content AlGaN, bulk AlGaN films with a high Al content (up to 95%) were grown. PL emission from near the band edge was observed at wavelengths as short as 218 nm for $\text{Al}_{0.95}\text{Ga}_{0.05}\text{N}$. More recently, near band edge emission was obtained from bulk AlN at 208 nm.

Samples containing AlGaN MQWs with wide bandgap AlGaN (53-100% Al) barriers were also fabricated. Efficient 77 K PL emission was obtained at 234 nm from $\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}$ MQWs with AlN barriers and at 245 nm from $\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}$ MQWs with $\text{Al}_{0.8}\text{Ga}_{0.2}\text{N}$ barriers. The optimum value of well thickness was approximately 1.5 nm. The emission intensity from the AlGaN MQWs was several tens of times higher than that of bulk AlGaN. The most efficient PL was obtained at around 240 nm from AlGaN MQWs with an $\text{Al}_{0.8}\text{Ga}_{0.2}\text{N}$ barrier (see Figure). More efficient emission is expected from AlN/AlGaN QWs by improving the crystal quality of the barriers and the AlN buffer layer.

It was also found that the PL intensity of AlGaN QWs is as strong as that of $\text{In}_{0.02}\text{Ga}_{0.98}\text{N}/\text{In}_{0.20}\text{Ga}_{0.80}\text{N}$ QWs at 77 K, and much stronger than that of $\text{Al}_{0.12}\text{Ga}_{0.88}\text{N}/\text{GaN}$ MQWs. However,



Comparison of PL intensity at 77 K of samples with 5 AlGaN QWs.

at room temperature, the emission from AlGaN and GaN QWs is much weaker in comparison with InGaN QWs. The next target for this work is to obtain efficient UV emission at room temperature. The group is also attempting to achieve stimulated emission at 230-250 nm from AlGaN QWs.

[Hideki Hirayama et al., **The Institute of Physical and Chemical Research (RIKEN)** and **Waseda University**, Japan. This paper won a Best Poster award at the 1999 Fall MRS Meeting.]

AlGaN/GaN MOS-HFETs

A novel device structure has been fabricated consisting of an AlGaN/GaN heterostructure FET (HFET, or HEMT) grown on sapphire, with a SiO_2 gate oxide. The gate leakage of this MOS-HFET was several orders of magnitude smaller than that of an equivalent HFET without the gate oxide. The MOS-HFET gate current remained low even at elevated temperatures up to 300°C.

[M. Asif Khan et al, **U. South Carolina, Sensor Electronic Technology Inc.**, and **Rensselaer Polytechnic Institute**, Elec. Dev. Lett. 2000, 21(2), p. 63]

Low Noise AlGaN/GaN HEMTs

The microwave performance of AlGaN/GaN HEMTs grown on SiC was measured. The minimum noise figure for 0.25 μm gate length devices was 0.77 dB at 5 GHz, and 1.06 dB at 10 GHz. These figures are comparable to those exhibited by GaAs-based FETs.

[A. Ping et al., **U. Illinois, ATMI/Epitronics** and **U. South Carolina**, Elec. Lett. 2000, 36(2), p. 175]

Mg-doped GaN UV Photodetectors

UV photodetectors were fabricated from microcrystalline Mg-doped hydrogenated GaN (GaN:H) films grown at 380°C by dual remote-plasma MOCVD under hydrogen-rich conditions. IR spectra showed N-H and Ga-H vibration bands but not a Mg-H band. The spectral photoresponse of an Al/ Mg-doped GaN:H/ Au sandwich-type cell showed a peak responsivity of 0.11 A/W at 360 nm, with a dark current of 10^{-11} at -1 V bias.

[S. Yagi, **Fuji Xerox Co.**, Appl. Phys. Lett. 2000, 76(3), p. 345]

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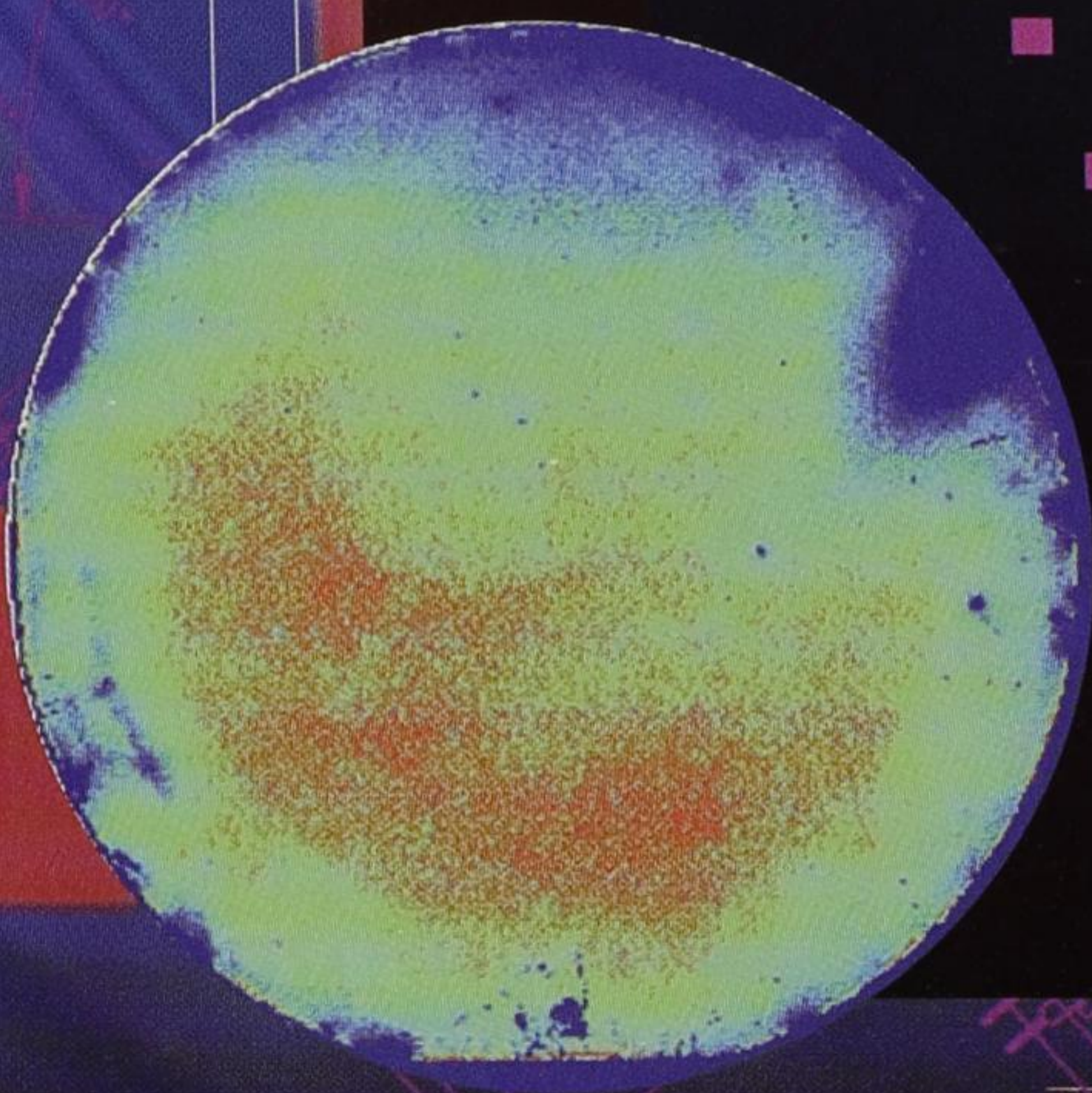


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ONR Semiconductor Electronics Roadmap: An Interactive Web-based Resource for Rationalization of Federal R&D Investment.

COLIN E.C. WOOD

Office of Naval Research, Electronics Division
Arlington, Virginia

and

GARY R. WESTLING

Computer Systems Center Inc.,
Springfield, Virginia

Over the past 5 - 10 years, a surprisingly successful compound semiconductor industry has emerged. It is particularly visible in the United States. Many of the products and technologies that make up the infrastructure of this industry are the direct result of science and technology investments made by the U.S. Federal Government years ago. GaAs technology, MMICs, and recent InP wafer improvements are examples of established products initiated or accelerated by defense research funding. A "virtuous cycle" has resulted:

- 1) Federal research funding drives fundamental semiconductor and device development to the point of commercial manufacturing,
- 2) Industry develops improved processes to make marketable products for the commercial sector, and as a result,
- 3) Military-specific as well as commercial procurement benefits from the cost reductions that result from these processes.

Today, the scientific and technical community finds itself in an era of both increasing requirements for technology and decreasing R&D funding in electronics. Advances in commercial products such as cellular phones, wireless LANs and LED displays usually do not directly address the military's technology needs. These highly profitable commercial products overwhelm the industry's investment agenda to the exclusion of high-end, but low production quantity, military specific circuits and devices.

The silicon semiconductor industry has benefited greatly from the roadmapping activities sponsored by SEMI and the SIA. However, there are no comparable organizations for the compound semiconductor industry. ONR is making an effort to fill this gap in furtherance of its mission to foster advanced technologies. However, this effort is not limited in scope or interest to just companies involved in traditional defence contracting.

Power Amplifier Modules - Requirements

Produce year	2000	2003	2006	2009	2012
Power(W)	7	20	25	25	40
PAE (%)	30	40	60	62	80
Gain(dB)	6	10	12	18	20
F operating(GHz)	10	12	14	20	30
Gate Width (mm)	2	3.5	3.5	3.5	4
Power Density (W/mm)	3.5	5.7	7.1	7.1	10

Colorcode:

Solutions Exist

Solutions Being
Pursued

No Known
Solution

Table 1. An example of a requirements projection - in this case, for a power amplifier. The ONR Roadmap is focused on projecting requirements for functional capability and device performance, and then relating these factors back to R&D challenges that need to be met.

Recognizing the need to focus scarce research dollars, the U.S. Office of Naval Research (ONR) is creating a comprehensive Compound Semiconductor Roadmap. The purpose of the Roadmap is to better coordinate strategic investment in the electronics technology needed by government and industry.

We hope this cooperative tool will be adopted as a U.S. institutional reference source and an aid to deciding future investment directions, as well as a forum on subjects relating to semicon-

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ductors, devices, and components. To this end, we invite those in government and large and small industrial and academic institutions to contribute to the Roadmap's design, function and direction and to help populate and refine Roadmap content.

Why ONR?

ONR's mission is to maintain a close relationship with the research and development community to support long-range research, foster discovery, nurture future generations of researchers, produce new technologies that meet known naval requirements, and provide order-of-magnitude innovations in fields relevant to the future Navy and Marine Corps.

The Information Science and Electronic technology programs seek to exploit the results of research to enhance surveillance capabilities, communications, command and control, new concepts for electronic devices, application of information sciences to complex problems including human-computer interaction, and electronic warfare.

The basic research program in semiconductor devices investigates electronic properties of wide bandgap and silicon-based semiconductors and novel devices. The program is focused on novel high power microwave and switching devices for broadband radar, EW, communications, and multifunctional systems applications and for high power control applications.

Basic semiconductor materials research at ONR investigates the synthesis and growth of semiconductor materials, both bulk and epitaxial. Of particular emphasis are wide bandgap semiconductor materials such as diamond, silicon carbide, and the Group III nitrides. Of particular importance is the compliant substrate technology for emerging semiconductor crystals for which there are no native substrates. ONR is also sponsoring development of the fundamental theory necessary for understanding the electronic properties of various epitaxial materials, and for understanding the mechanisms and processes for the growth of a variety of solid state electronic materials including Group IV, III-V, and II-VI materials.

Why a Roadmap?

The silicon semiconductor industry has benefited greatly from the roadmapping activities sponsored by

SEMI and the SIA. However, there are no comparable organizations for the compound semiconductor industry. ONR is making an effort to fill this gap in furtherance of its mission to foster advanced technologies. However, this effort is not limited in scope or interest to just companies involved in traditional defence contracting.

Since the end of the Cold War the favored federal acquisition approach is to specify commercial off-the-shelf systems and components, and to rely heavily on industry 'offerings'. This challenges the nation's ability to keep a technological and warfighting lead over even small nations willing and able to purchase commercially available offensive technology off that same shelf.

But this policy becomes problematic when industry doesn't have confidence that advanced components will be ready in time for deployment in defense systems. The Navy's industry partners will then conservatively design systems with lower than possible performance but high chance of success. The Navy's task is to reduce risk for industry to insert technology in modern ships and aircraft. It has done this by funding materials and device development in the 5-20 year timeframe, and component development in the 3-5 year timeframe. To take full advantage of this risk reduction, systems suppliers need to be able to predict, with a high degree of confidence, advances in the performance levels of components and circuits over time.

Taking a cue from the SIA silicon roadmap, we focus on projecting requirements for functional capability and device performance, identifying research and development challenges, and relating those challenges to potential solutions in semiconductor processes.

Semiconductor Material Potential Solutions										
SiC	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06	FY07	FY08
Bulk Growth										
Wafer Size (dia.,mm), 4H, 6H	50mm									
Wafer Size (dia., mm), 4H	75	75								
		100	100							
		150	150	150						
Defect Density										
micropipe (μpipes/cm ²) 4H	<15	<1	<1							
dislocations (/cm ²)	10E10	10E5	10E5							
dislocations (/cm ²)		10E3	10E3	10E3						
dislocations (/cm ²)			10E1		10E1	10E1				
Background impurity level										
Doping level control										
Wafering										
Cut										
Polishing										
■ Research Required ■ Development Underway □ Pre-Production										

Table 2. A major feature of the ONR Roadmap is the illustration of potential solutions for key challenges. This table is a sample of the format for such a projection page for Silicon Carbide.

Roadmap Approach

The Roadmap is web-based and interactive. It is intended to cover high-end compound semiconductor devices and materials. It reflects the realization that customers buy electronics for functional capability, and that semiconductor material processes enable the devices that deliver that capability. Taking a cue from the SIA silicon roadmap, we focus on projecting requirements for functional capability and device performance, identifying research and development challenges, and relating those challenges to potential solutions in semiconductor processes. Menus for functions (e.g., power amplifiers), devices, and semiconductors (e.g., SiC, GaN) lead to individual pages. Hyperlinks on each page lead to requirements, technology projections and challenges. For example, see Table 1, which shows an example of the projection for power amplifier requirements.

Identifying the challenges that need to be met is a major part of the roadmap -

and ONR is actively seeking the input from experts throughout the industry. The roadmap web site is set up so as to encourage input from diverse sources. Examples of topics include:

- What stops us from making devices today with performances needed tomorrow?
- What design improvements are necessary?
- What semiconductor growth or process hurdles are to be leaped?
- What other challenges need to be met?

The Compound Semiconductor Roadmap holds a "challenges database." This database identifies and collects research challenges and relates them to devices, semiconductors and functions. Users in the R&D community will be able to access and search this database on line, and are invited to submit challenges. A companion research database is being

built to relate ongoing and proposed research efforts to the challenges they are intended to meet.

Table 2 shows a sample of the format for presenting the projections - in this case, for Silicon Carbide.

How To Participate

ONR is in the process of identifying 'page owners' to adopt, populate and maintain portions of its semiconductor Roadmap. Readers are invited to visit the site's home page, make comments, and enter their research challenges into the Challenges Database.

Log onto <http://enterprise.csciv.a.com/semiconductor-roadmap/index.htm> with the user name "public" and password "roadmap." To develop the science and technology for the future, ONR needs active participation today from those who will produce the products of tomorrow.

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FIBER-OPTICS

Conexant Launches 10 Gb/s Device Family

Newport Beach, CA. Conexant Systems has announced a comprehensive family of devices for 10 Gb/s (OC-192) fiber-optic systems, based on the company's GaAs HBT and SiGe BiCMOS processes. The new devices include front-end transimpedance and limiting amplifiers, laser and modulator drivers, clock data recovery (CDR) devices and parallel-to-serial and serial-to-parallel converters. The products complement Conexant's recently introduced crosspoint switches, and the company plans further OC-192 offerings later this year with a second generation of highly-integrated, low power solutions.

On the receiver side, the CX60057 transimpedance amplifier and CX60083 limiting amplifier are designed for single-mode, long-haul fiber applications. CDR devices, clock multiply units and parallel-to-serial and serial-to-parallel converters are manufactured using Conexant's GaAs HBT technology.

On the transmit side, Conexant offers two devices for driving laser diodes or external modulators. The CX20480 driver is designed for medium-range OC-192 fiber applications, and is a SiGe BiCMOS device priced at \$289 in volumes of 50,000. The CX60080 long-range laser/modulator driver is a GaAs HBT device that is priced at \$850 in similar quantities.

OC-192 Driver Amplifier from Celeritek

Santa Clara, CA. Celeritek has announced a medium power driver amplifier for external fiber optic modulators targeting high-bandwidth 10 Gb/s (OC-192) applications. The CMM3020-BD delivers 23 dBm of gain and operates from 30 kHz to 20 GHz with a linear 10 dB gain response. A low internal jitter makes it suited to high speed digital data applications, and the typical output voltage is 7.5 V peak-to-peak. This GaAs PHEMT device can be used to drive lithium niobate external optical modulators, where a high extinction ratio is necessary.

OPTO DEVICES

New Lasers from SLI

Binghamton, NY. Semiconductor Laser International (SLI) has introduced a range of new high power lasers. For applications involving marking, cutting, welding and optical pumping, SLI offers a 7 W single-chip diode laser operating at 808 nm supported in a high heat load package. It also offers a 2 W version in a TO-3 package operating at 808 and 980 nm wavelengths. Other products include water-cooled versions of an 808 nm 30 W fiber coupled laser and 60 W diode laser mounted bar.

Thomson-CSF High Power Laser Diodes

Orsay, France. Thomson-CSF has recently announced new 300 W CW stacked laser diodes and a 30 W CW fiber coupled laser. Operating at in the wavelength ranges 795-860 nm and 940-980 nm, the AlGaAs-based TH-C17xx-M1 multi-bar stack features water-cooled micro-channel heat sinks and contains a $10 \times 16 \text{ mm}^2$ emission area. The total efficiency is 43% and beam divergence measures $10^\circ \times 35^\circ$. Wavelength variations are 0.26-0.3 nm/°C and the spectral width is <4 nm.

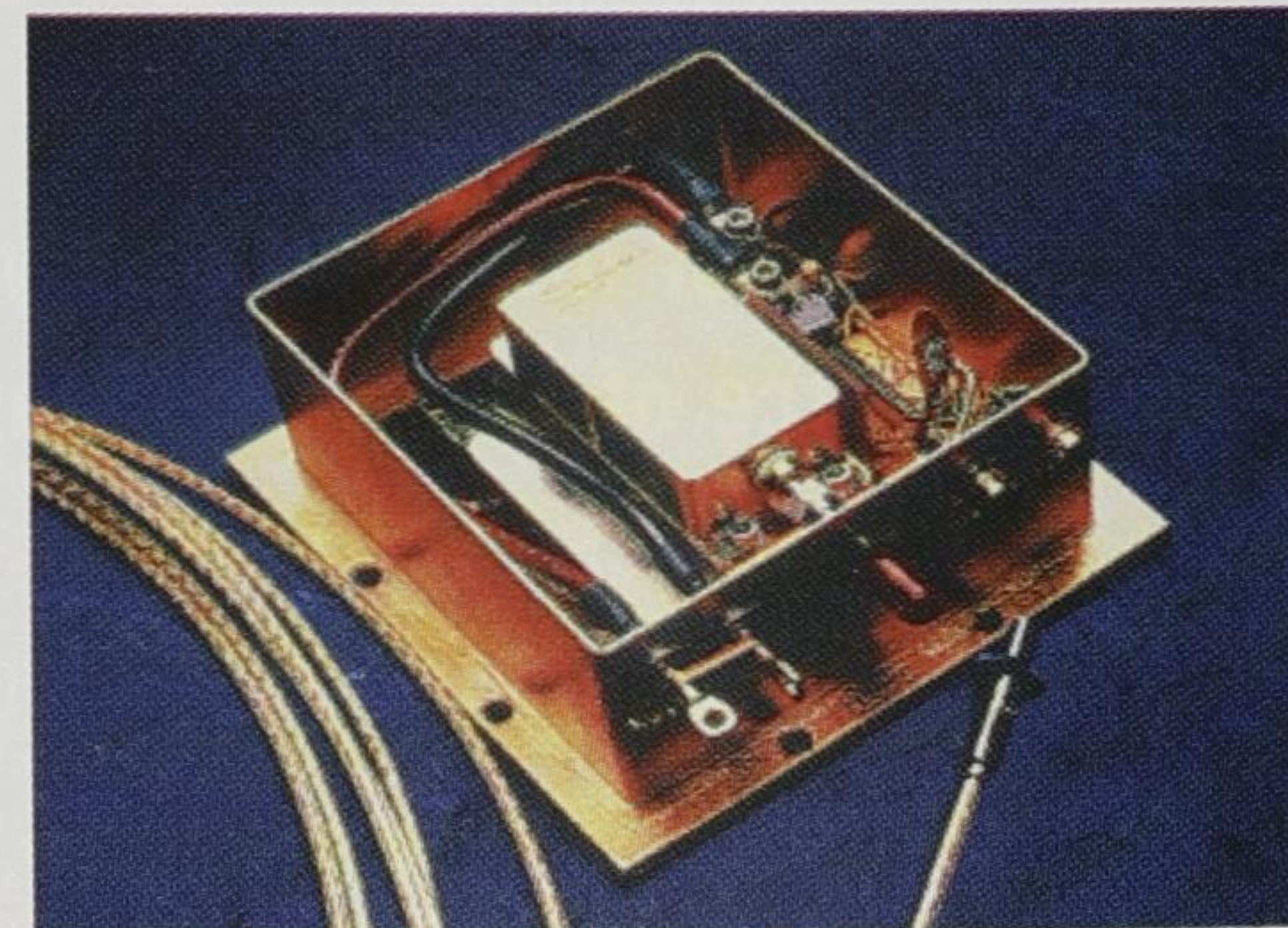
The TH-C1830-F6 fiber coupled laser diode delivers 30 W, making it suitable for DPSS lasers, soldering, materials processing and micro-machining. The conductively cooled package is connected to a 1.5 m long 600 μm diameter fiber (0.22 NA). The standard wavelength is 840 nm (spectral width <3.5 nm FWHM), and other wavelengths are available in the range 795-860 nm.

Coherent 940 nm Diode Lasers

Santa Clara, CA. Coherent Semiconductor Group has unveiled a new series of 940 nm high-power laser diodes, based on its Al-free active area InGaAsP/InGaP technology. These 20 and 35 W bars and 16 W fiber array packaged (FAP) bars represent a 940 nm laser family suitable for integration into a host of Yb:YAG solid-state laser pumping applications, as well as direct-diode thermal applications in the medical and industrial markets.

Mounted on a $25 \times 25 \text{ mm}^2$ conduction-cooled package, Coherent's 1 cm long, 20 W component and 16 W FAP are based on a 30% fill-factor bar, while the 1 cm long 35 W device

employs a 50% fill-factor bar. The spectral width of all devices is <3 nm FWHM, and the beam divergence is $38^\circ \times 10^\circ$. The FAP delivers its energy via an 800 μm diameter (0.16 NA) fiber bundle.



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WIRELESS

Digital Attenuators from Alpha

Woburn, MA. Alpha has introduced new GaAs-based 5-Bit digital attenuators. Designed for base stations, wireless data, and wireless local loop gain level control circuits (0.5 – 2 GHz range), the AA101-80 has an LSB of 1 dB and a total attenuation of 31 dB. The AA102-80 has an LSB of 0.5 dB, a total attenuation of 15.5 dB, and is designed to extend from 0.5 to 2.5 GHz. Manufactured in a SSOP-16 package, both attenuators feature single positive control (+3 to +5 V).

New GaAsTEK Devices

Roanoke, VA. GaAsTEK has introduced a new PA, and families of digital attenuators and switches. The two-stage ITT6402HB is a GaAs-based PA designed to work in the 5-6 GHz frequency range, and is appropriate for the emerging Unlicensed National Information Infrastructure (U-NII) in the US and for International Hiperlan applications. Featuring a power output of 30 dBm at 7 V and 28 dBm at 5 V, the PAE is typically 39% at P1dB.

GaAsTEK's eight new GaAs switches are designed for wireless handsets, LANs, data, and base stations. The ITT501 AJ switch, for example, is a SPDT high power transmit/receive (T/R) switch that operates from +3 to +10 V. It features positive control and a 1dB compression point of 35dBm at +5V. Four new attenuator are also available for cellular, radio, and wireless LANs. The ITTA504AE is a 5-bit digital attenuator featuring 1,2,4, 8, and 16 dB bits for a maximum attenuation of 31 dB in 1 dB steps. Its usable frequency is 0–2.5 GHz.

Fujitsu's New Frequency Divider

Yamanashi, Japan. The FMM1103VJ frequency divider from Fujitsu extends the range of the company's previous 2-10 GHz divider out to 12 GHz. Featuring a –5 V (or +5 V) DC single power supply, this GaAs microwave device divides an input signal by 8 for synthesizer and phase locked oscillator applications, and is available in a 10 pin SMT-10 package.

Dual-Band LNA from RFMD

Greensboro, NC. RF Micro Devices (RFMD) has introduced a new dual-band LNA engineered for use as a front-end for 950 MHz GSM and 1850 MHz DCS applications. The RF2363 is a GaAs HBT-based device featuring low-noise and high linearity at a supply current of 3 V. The 900 MHz LNA is a single-stage amplifier, while the 1900 MHz LNA is a two-stage amplifier, and both deliver 18 dB gain at these frequencies.

Celeritek Announces InGaP HBT WCDMA Amplifier Modules

Santa Clara, CA. Celeritek has announced two new 6 mm² PA modules for 2.5G and 3G high bandwidth WCDMA wireless data markets. Available in May, these new InGaP HBT amplifier modules are part of the TrueTriangle product line and are designed to maximize linear efficiency for wireless data applications.

The CHP0230-PM is a 824-849 MHz, multi-mode, 2-stage PA for 1X cellular handsets and wireless local loop (WLL) subscriber units. It offers 40% linear PAE, 60% analog PAE, with +28.5 dBm output power (1X WCDMA mode). The CHP2230-PM is a linear efficient, 3-stage PA developed for WCDMA 3G cellular handsets and infrastructure systems (1920-1980 MHz). It offers 30% linear PAE at 28 dBm under 3X WCDMA modulation. Common features include operation as low as 3.2 V from a single positive supply, and 30 dB gain at operating output power.

NEC Introduces HBT-based LNA

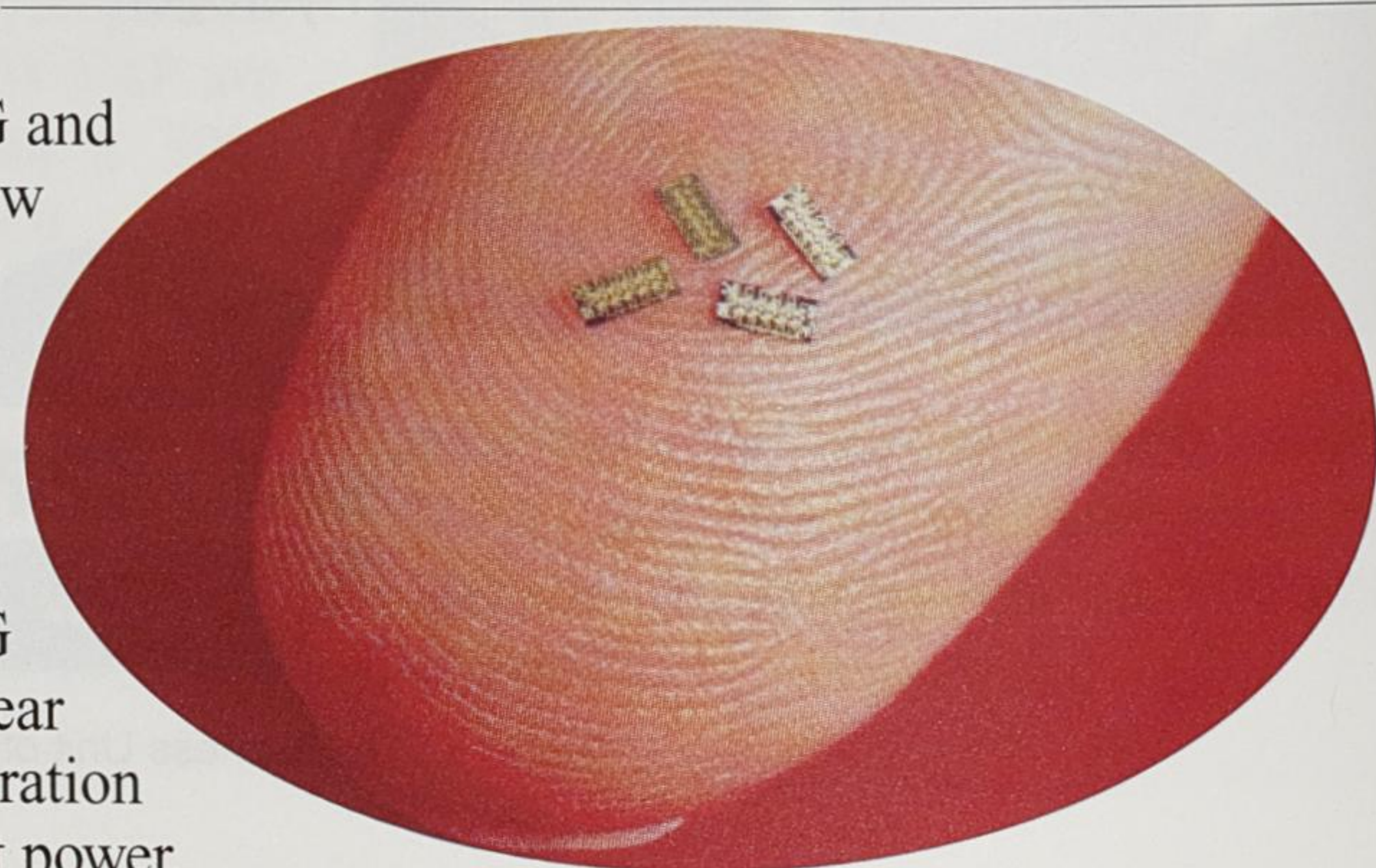
Santa Clara, CA. CEL has announced a GaAs HBT-based LNA for the L and S band. Manufactured by NEC and featuring a typical NF of 1 dB and gain of 15 dB (at 2 GHz), the NE52118 is designed for use as an LNA in applications such as TDMA handsets, and requires only a single power supply.

Anadigics Unveils PHEMT Switches

Warren, NJ. Anadigics has unveiled a new range of 3 V switches based on its new 6-inch PHEMT process. The AWS5505, -5507, and -5512 are single-pole double-throw (SPDT) switches with insertion losses as low as 0.4 dB at 900 MHz. The -5508 is a SP4T device featuring 0.8 dB loss at 1 GHz. Other products include dual band SP4T PHEMT switches for AMPS/TDMA 800 and 1900 MHz handsets.

M/A-COM's New SPDT Switch

Lowell, MA. Demand is growing for switches that offer higher isolation for synthesizer and local oscillator switching in base stations. The SW-439 GaAs SPDT switch is available with positive control voltage in a low-cost, MSOP plastic package covering the DC to 3 GHz range. These switches can also be used for general purpose switching in applications up to 0.25 W.



RF Micro Devices and Qualcomm Enter CDMA Alliance

RF Micro Devices and Qualcomm have entered an alliance to provide advanced power amplifiers for the CDMA market. Initially, the companies will develop CDMA PAs for inclusion in present and future Qualcomm CDMA chipsets.

"Combining Qualcomm's CDMA system, design and software expertise with RFMD's design and process technology will allow Qualcomm to offer the best performing and most cost-effective PAs for the CDMA market," says Johan Lodenius, senior VP of marketing and product management for Qualcomm CDMA Technologies. "Qualcomm will continue to offer manufacturers the most integrated and advanced products available."

"RFMD is the world's largest supplier of GaAs HBT RFICs and CDMA has been one of our most successful markets," says Jerry Neal, executive VP of sales, marketing and strategic development of RFMD. "With our own wafer fabrication plant now in full production, and with a second wafer fab under construction, RFMD has the capacity to fulfill all of Qualcomm's foreseeable GaAs HBT requirements."

The joint development, utilizing the expertise of both companies, is expected to yield products that will provide higher levels of integration and, with advanced packaging technology, will enable handset manufacturers to produce phones with smaller form factors and increased talk-time capabilities.

Qualcomm has already announced the first products to emerge from the alliance: a new family of PA modules that complete Qualcomm's total chipset solution for CDMA handsets. The PA3100 module, together with the RFT3100 chip, comprise the

entire radio portion of the transmit chain for IS-95B compliant handsets. The initial release of the PA3100 series will include PAs for the 824-849 MHz cellular band, and the 1850-1910 MHz and 1750-1780 MHz PCS bands.

Also, Qualcomm and software giant Microsoft Corp. plan to work together to develop advanced wireless devices. The alliance will focus on developing hardware reference designs for mobile devices, including so-called smart phones based on the Microsoft Mobile Explorer wireless communications platform, and wireless pocket personal computers using Qualcomm's CDMA chipset and system software.

RFMD to Supply PAs for Ericsson's First CDMA Handset

RF Micro Devices has received production orders to supply GaAs HBT-based PAs for use in Ericsson's A1228c cellular CDMA handset. The new phone signals Ericsson's entry into the fast growing CDMA market. "This represents an important milestone in our business relationship with Ericsson and we are pleased to be a part of their first handset for the CDMA market," says Jerry Neal. "We anticipate that our business relationship with Ericsson will continue to expand, particularly with the mobile phone groups."



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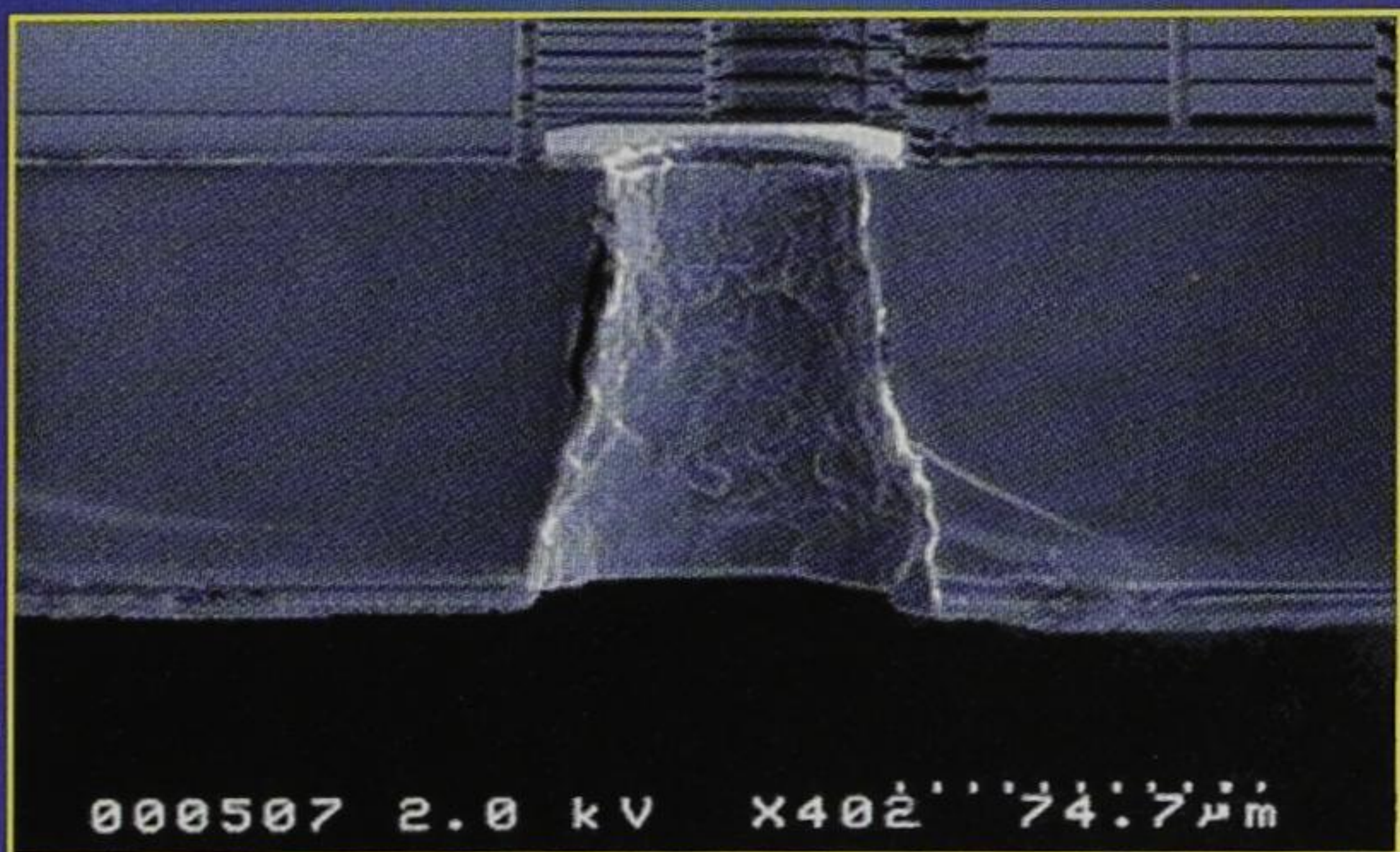
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M/A-COM Acquires GaAsTEK Business

M/A-COM is to increase its GaAs IC fabrication capacity by acquiring the GaAsTEK business unit of ITT Industries. GaAsTEK, located in Roanoke, Virginia, is a module-level systems supplier of RF, microwave and millimeter-wave ICs for commercial and defense markets. The unit will operate as part of M/A-COM, a subsidiary of Tyco Electronics, and the purchase is expected to close in early March.

M/A-COM now has three GaAs fabs – one at its headquarters in Lowell, MA, one at Colorado Springs, CO, and now a third at Roanoke, VA – and the company plans to continue operating all three. “This acquisition strengthens our position in both companies’ major markets, namely wireless and defense,” says M/A-COM’s president Rick Hess. “It provides us with increased wafer fabrication capacity and a strong MMIC power amplifier design and manufacturing capability. We’re delighted to have the GaAsTEK team joining M/A-COM.”

“GaAsTEK is an excellent complementary fit to M/A-COM’s existing businesses,” adds Paul Gralnick, president of GaAsTEK. “We are excited about the combination of our two companies, and are looking forward to helping M/A-COM achieve greater growth in its major markets.”

GaAsTEK employs a patented GaAs MMIC process, known as Multifunction Self-Aligned Gate or MSAG, which process allows the integration of multiple circuit functions onto a single MMIC [see CS 5(8), p. 50]. In addition to providing M/A-COM with additional capacity, the acquisition of the GaAsTEK fab and MSAG process strengthens M/A-COM’s product capabilities for multifunction and power ICs in both the wireless and defense markets.

Alpha Industries Buys Network Device Inc.

Alpha Industries (Woburn, MA) is to acquire privately-held Network Device, Inc. of Sunnyvale, CA. Network Device provides GaAs IC design and fabrication services for HBTs and other process technologies relevant to wireless telephony and other wireless markets.

“Network Device is going to be an important element in our long-term strategy to increase Alpha’s share of the wireless market,” says David Aldrich, Alpha’s president and COO. “The company brings valuable advanced process capabilities, especially for high-efficiency HBT power amplifiers for use in wireless telephone handsets. Network Device’s GaAs InGaP HBT process is production-ready, while PHEMTs and MESFETs are already in production.”

“Network Device has capacity available today, and we will increase their output significantly, positioning us to meet rapidly-growing market demand, both in the short and long-term,” continued Aldrich. “By balancing production between Network Device’s fab and our recently expanded fab in Massachusetts, we will be able to accelerate conversion of our fab to six-inch GaAs wafers, which will more than double its production capability. Network Device’s fab has already been qualified as a second source for some of Alpha’s highest-volume RFIC products, and having fabs in two locations will make Alpha more attractive to major handset OEMs who are beginning to require this dual-fab capability.”

“We are very pleased to join Alpha,” says Ding Day, president and CEO of Network Device. “The HBT has emerged as a critical GaAs process technology and we are focused on ensuring that Alpha will have the next-generation HBT GaAs products for wireless, fiber-optics and high-speed networking markets. Network Device will form the nucleus of a West Coast design center for Alpha, giving the company access to the region’s top engineers in RF semiconductor technologies.”

\$8.5 M of Handset PAs Orders for Celeritek

Celeritek has announced follow-on orders worth \$8.5 million from a major U.S. handset manufacturers. The orders are expected to ship during 2000. The new orders were fueled by continued dramatic growth in CDMA subscriber numbers, which reached almost 50 million at the end of 1999. Celeritek designs and develops products using GaAs MES-FET, PHEMT, and HBT processes.

"We are proud to provide ongoing support to our customer's subscriber business. We view the increase in orders as strong reinforcement of our strategy to lead the market with cost effective 3.0 V linear efficient power amplifier prod-

ucts," stated Bill Hoppin, VP of semiconductor sales and marketing. "We are especially pleased to have been selected to support several sockets on handsets targeted for high-volume, data-enabled consumer applications."

"Further investments in our factory, augmented by the \$27 million recently raised in a private placement and combined with strengthened relationships with our subcontractors have been an integral part of our increased capacity plans," said Tamer Hussein, president and CEO. "We are continuing to anticipate needs in a fast moving wireless market and preparing accordingly," he concluded.

Conexant Develops "Smart" PA Technology

Conexant Systems has unveiled its advanced power-management technology that will significantly improve the efficiency of power amplifiers for mobile handsets and third-generation (3G) wireless terminals. The SmartPA(TM) technology, for which patents are pending, is expected to provide handset designers with a convenient, single-chip solution for giving consumers up to triple the battery life possible with current handset designs. Conexant will embed the SmartPA technology in a new family of CDMA power amplifiers which will begin general sampling in the second calendar quarter of 2000, with volume production scheduled for the second half of the year.

PAs are the handset's biggest determinant of battery life and talk time, and until now have not been capable of running at the optimum dynamic load in response to changing power output conditions. This has significantly reduced power efficiency over time. In developing its SmartPA technology, Conexant has exploited a combination of specialized mixed-signal integrated circuit (IC) design expertise and the company's leadership in 50 GHz GaAs HBT process

technology and multichip module IC (MMIC) packaging techniques.

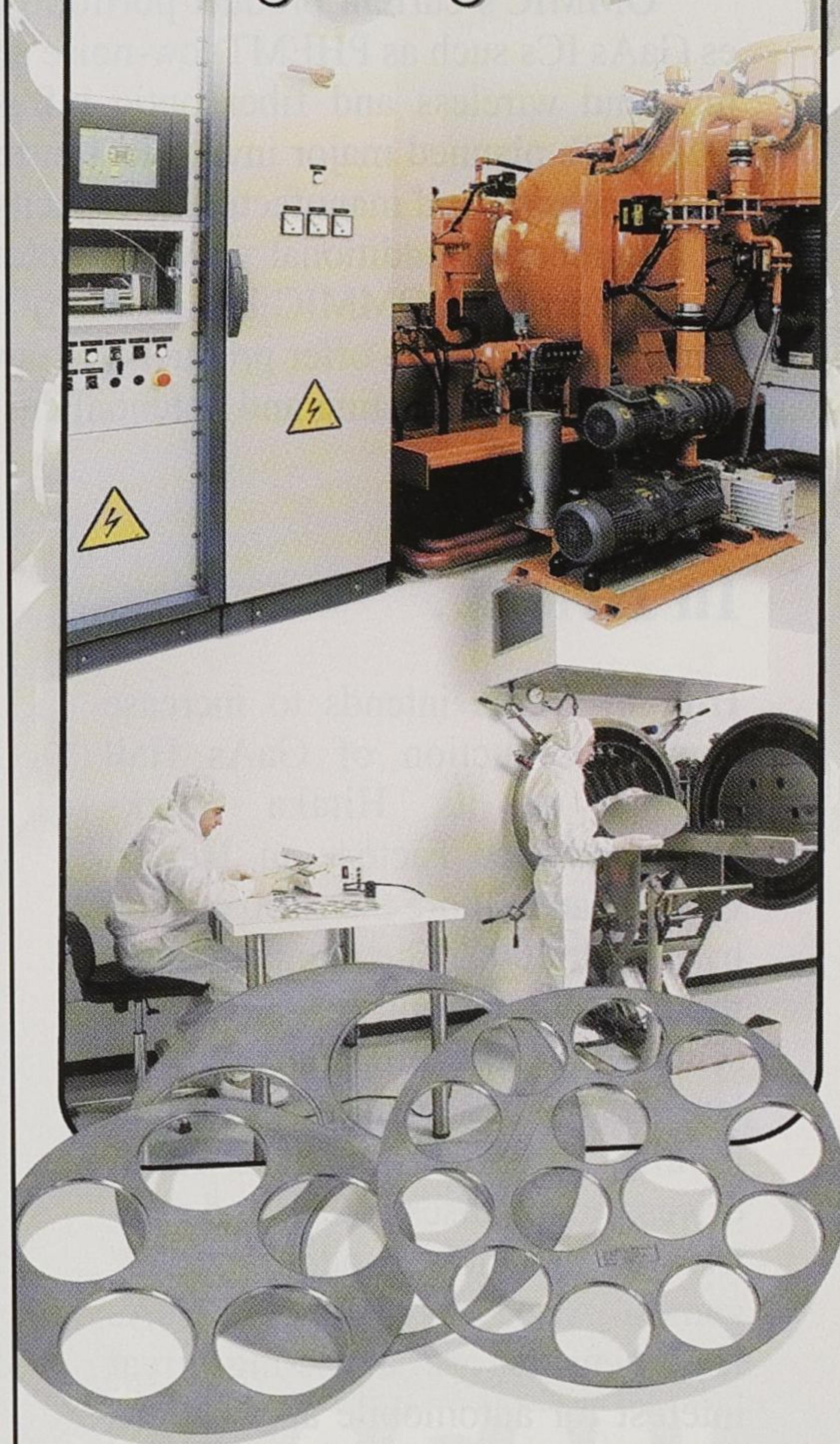
The technology uses innovative switching techniques so that a mobile handset's power consumption can be optimized at various power levels. The SmartPA architecture is particularly effective at low power ranges where handsets operate 90% of the time. Using this advanced architecture, Conexant's PAs will be able to dramatically increase the power efficiency of a handset design, independent of the rest of the handset system.

"Conexant has spent years analyzing power efficiency issues that we believe represent the single most important challenge for mobile handset designers," says Moiz Beguwala, senior VP and general manager for Conexant's Wireless Communications Division. "SmartPA technology offers a universal solution to the problem, and gives designers an extremely easy-to-implement technology that will be embedded directly into our power amplifiers. It will provide significant advantages for both IS95 CDMA handsets and for future 3G terminals that will demand even better power management for supporting voice and data applications."

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Philips Microwave Limeil Becomes OMMIC

A new company dedicated to the research, development and manufacture of GaAs semiconductor devices – OMMIC – has been created from the former Philips Microwave Limeil (PML). Based in Limeil-Brévannes on the outskirts of Paris, PML is one of the world's leading GaAs MMIC foundries, and has an impressive track record for the development of compound semiconductors (see box). OMMIC, a wholly-owned Philips company, will continue to have its headquarters in the same location. According to a press statement, the new company is "self-reliant with enhanced flexibility to fulfil its plans in expanding further in specialized applications, primarily with high-frequency devices and systems for the telecommunications market."

In addition to capitalizing on PML's comprehensive portfolio of products and services, OMMIC intends to expand its competencies in both foundry-produced MMICs and MOVPE-grown devices. OMMIC has more than 15 years proven experience in the growth of PHEMTs using MOVPE and holds more than 100 patents in GaAs production technologies and processes.

OMMIC's current product portfolio primarily comprises GaAs ICs such as PHEMT low-noise amplifiers for use in high-end wireless and fiber optic infrastructures. Part of OMMIC's planned major investment in technology, production processes and manufacturing capacity is the acquisition of a number of additional growth reactors in the next few years. Currently, OMMIC has a base of about 40 key customers, and plans to offer products for new applications and markets to both existing and potential customers.

Selected achievements of the former Philips Microwave Limeil (PML):

- 1968 – First production of Gunn diodes as an industrial unit of Philips.
- 1972 – Began research into GaAs MMICs, digital ICs and epitaxy as part of Philips Research Laboratories.
- 1980 – Advanced R&D of III-V devices and ICs based on GaAs PHEMTs, InP FETs, GaInAs/InP PIN and avalanche photodiodes, and quantum-well lasers.
- 1983 – Began production of GaAs FETs, digital ICs and MMICs.
- 1986 – Constructed world's first 5 x 3-inch MOVPE planetary reactor, a technology subsequently licensed to Aixtron.
- 1988 – World record of 720,000 cm²/Vs (1.5 K) for quantum Hall resistance standards.
- 1990 – Formed Philips Microwave Limeil to consolidate activities in R&D and the manufacture of compound semiconductors.
- 1995 – Introduced a unique enhancement depletion 0.18 µm PHEMT process to handle analog and digital functions on the same chip up to 70 GHz.
- 1998 – Installed 8 x 4-inch MOVPE reactor with robot and individual rotation control, providing a capacity of 25,000 wafers/year.
- 1999 – Market release of a 10 Gb/s transimpedance amplifier with the most optimal sensitivity ever achieved.
- 1999 – Introduced a 0.15 µm power PHEMT process for 40 Gb/s driver ICs.
- 2000 – Forms OMMIC.

In Brief...

Hitachi Cable intends to increase annual production of GaAs Hall sensors at its Hitaka Works Semiconductor Factory in Hitachi City, Japan to more than 100 million by March 2000. The company cites the growing demand for GaAs Hall sensors for room temperature brushless DC motors found in such commodity products as CD-ROM drives, floppy discs, VCRs and electric current meters, in addition to TV games. Also, says Hitachi, GaAs Hall sensors are attracting great interest for automobile applications because of their excellent temperature characteristics.

Applied Micro Circuits Corp. (AMCC) has unveiled the industry's first, highly-integrated SiGe 10 Gb/s (OC-192) transceiver for use in SONET/SDH and DWDM applications. The transceiver implements the front-end of SONET equipment, which consists of the serial transmit and receive interfaces. The new two-chip chipset consumes a total of 4.5 W of power. "These devices address critical system design issues for our customers by being an easy to use, low power and highly manufacturable chipset that exceeds industry standards requirements," says Ken Prentiss, director of marketing for telecommunication products.

TriQuint and Agilent have announced the availability of the TQTRx foundry process design kit, which includes TriQuint's TOM3 advanced non-linear GaAs FET models. Integrated into Agilent's Advanced Design System electronic design automation (EDA) software, TriQuint's design kit provides RFIC designers with electrical and physical models for both passive (spiral inductors, capacitors, resistors, transmission lines) and active (FETs and diodes) devices. The EDA software provides developers with an integrated, end-to-end communication-signal-path solution for products such as cellular and portable phones, pagers, wireless networks, and radar and satellite communications systems.

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Endwave Corp. Formed by Merger of TRW Milliwave and Endgate

Endgate Corp., a manufacturer of "first-mile" wireless broadband access products, is to merge with TRW Milliwave Inc., creating a new company, Endwave Corporation. TRW Milliwave, a subsidiary of TRW Space & Electronics Group, is a manufacturer of high-performance MMIC-based modules for commercial telecommunications system developers. The union creates a leading supplier of broadband access equipment, including specialized antennas, transceivers and outdoor units (ODUs) - units that transmit and receive radio signals and serve as the "engines" of broadband wireless Internet access systems and cellular backhaul.

"Endwave's products will provide the cost-effective wireless solutions customers are demanding for the expansion of e-business," says Edward Keible, president, CEO and director of Endgate Corp., who will become Endwave president and CEO. "We are strategically positioned in a rapidly growing industry segment, and we will also have a strong customer base that includes Nokia, Hughes Network Systems and other major broadband system developers."

"The formation of Endwave strongly affirms TRW's GaAs business strategy of addressing the broader telecommunications market," says Dwight Streit, director of TRW Telecom Products. "Endwave has guaranteed access to TRW's GaAs HEMT and HBT product line, enabling the new company to bring to the marketplace the highest performance GaAs products in the industry. Endwave's future growth will in turn provide expanded opportunities for TRW's GaAs chip business."

Current broadband access technologies based upon existing wire line infrastructure, such as XDSL and T1, are limited to a few hundred kb/s up to a few Mb/s. Fiberoptic technology provides virtually unlimited bandwidth but is expensive (costing up to \$600K per km), and can take months or years to install. Broadband wireless technology using millimeter-wave frequencies above 15 GHz is relatively inexpensive, quick to install, and today provides data rates up to 155 Mb/s (OC-3). The transceiver technologies for broadband access systems are also used for wireless infrastructure connectivity ("backhaul" systems) in cellular networks. As the density of cellular users continues to increase and 3G systems are implemented, this trend represents a strong growth opportunity for Endwave, according to Keible.

Endgate Corporation recently announced commercial availability of its AllegrA millimeter-wave transceivers, the industry's first family of standard-architecture transceivers for first-mile broadband wireless Internet access. The AllegrA transceiver family provides a fast, easy and low cost solution in the 21-40 GHz range, enabling the industry to build next-generation point-to-point and point-to-multi-point radios for broadband Internet access to businesses and cellular handsets.

The closing of the merger is subject to regulatory approval. Endwave will be owned approximately 50 percent by TRW and 50 percent by Endgate's current shareholders. The new company will be headquartered in Sunnyvale, and maintain design and manufacturing facilities in Sunnyvale, Santa Clara and Diamond Springs, Calif.

Teledyne Provides MMIC PAs for Wireless Access Networks

Teledyne Technologies Inc. will provide Adaptive Broadband Corp. with 75,000 MMIC PAs for the AB-Access U-NII (Unlicensed National Information Infrastructure) band radio. AB-Access is a broadband fixed wireless access network for Internet, data, video, and voice applications spanning the 2-42 GHz frequency range. The first products will operate in the U-NII band from 5.25 to 5.825 GHz.

Teledyne's Microwave Electronic Component (MEC) site in Mountain View, CA is a partially vertically integrated operation that designs and supplies GaAs MESFET-based MMIC PAs and assemblies for wireless microwave applications, RF filter products for fixed access applications, and electromechanical switches for communications, space, and defense applications.

Anadigics Receives Multi-Million Orders for RF Switches

Anadigics has received an order for more than 10 million RF switches, and has begun production shipments to one of the largest U.S. based manufacturers of wireless handsets. The single supply 3 V RF switches will be used in the 800 MHz digital CDMA/AMPS dual-mode phone, which is enjoying increased cellular market penetration, particularly in the US.

"This high-volume order validates Anadigics' continuing efforts to penetrate the RF switch market," says Bami Bastani, president and CEO of Anadigics. "This production win is an important milestone in expanding our wireless communications customer base beyond power amplifiers, and demonstrates our strong entry into the RF switch marketplace."

"Anadigics' ability to meet demanding price and performance requirements, combined with our continued capacity expansion in a tightening RF component market, have led to our success as a preferred supplier for RFIC products," remarked Glenn Fraser, VP of Wireless Communications Products at Anadigics.

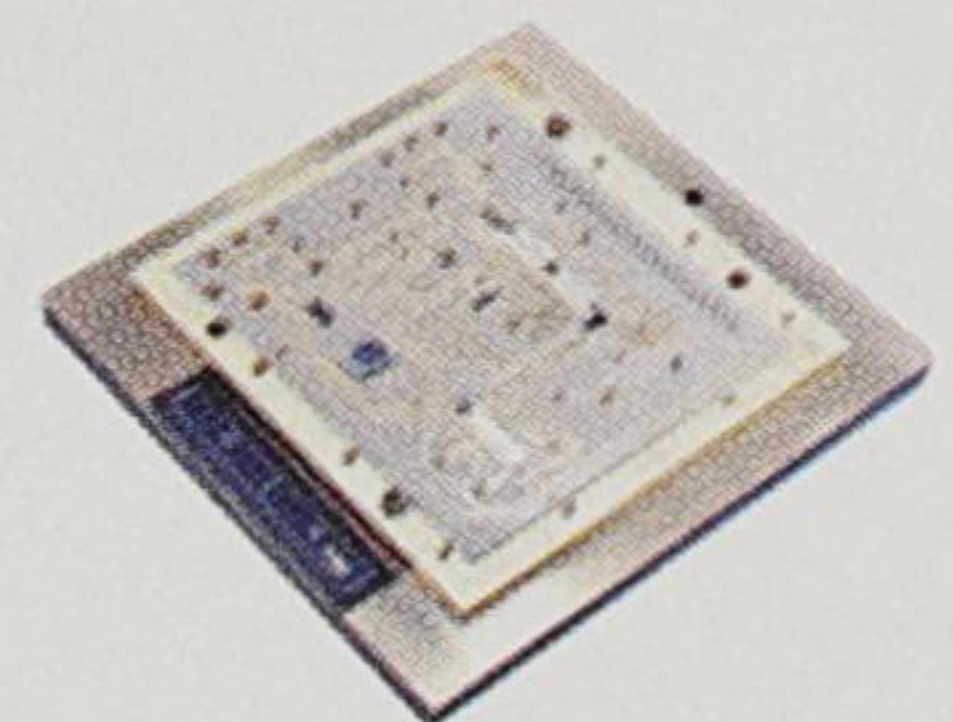
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Business Opportunities and Technology Trends— Millimeter-wave Modules for Sensor Products and Broadband Wireless Communications

PATRIC HEIDE

Siemens AG*

The availability of commercial microwave and millimeter-wave modules is a key growth factor for innovative products in various fields: broadband millimeter-wave communications, automotive distance warning systems and industrial sensors. According to forecasts published recently by Strategies Unlimited, Allied Business Intelligence and Frost & Sullivan, this technology is going to generate a market volume of more than US\$ 1 billion in the near future (see Figure 1).

The success in these volume markets strongly depends on the ability of suppliers and system integrators to find novel technical solutions that are attractive in terms of production simplicity. As cost remains the major inhibitor, it is absolutely necessary to move away from former military-type solutions and step into commercial solutions.

One decade ago, microwave modules were sophisticated and costly devices (> \$1000 per unit). An evolutionary commercialization of microwave components started with less cost-sensitive products such as point-to-point (PTP) millimeter-

Worldwide Revenues for
Commercial Millimeter-wave Equipment

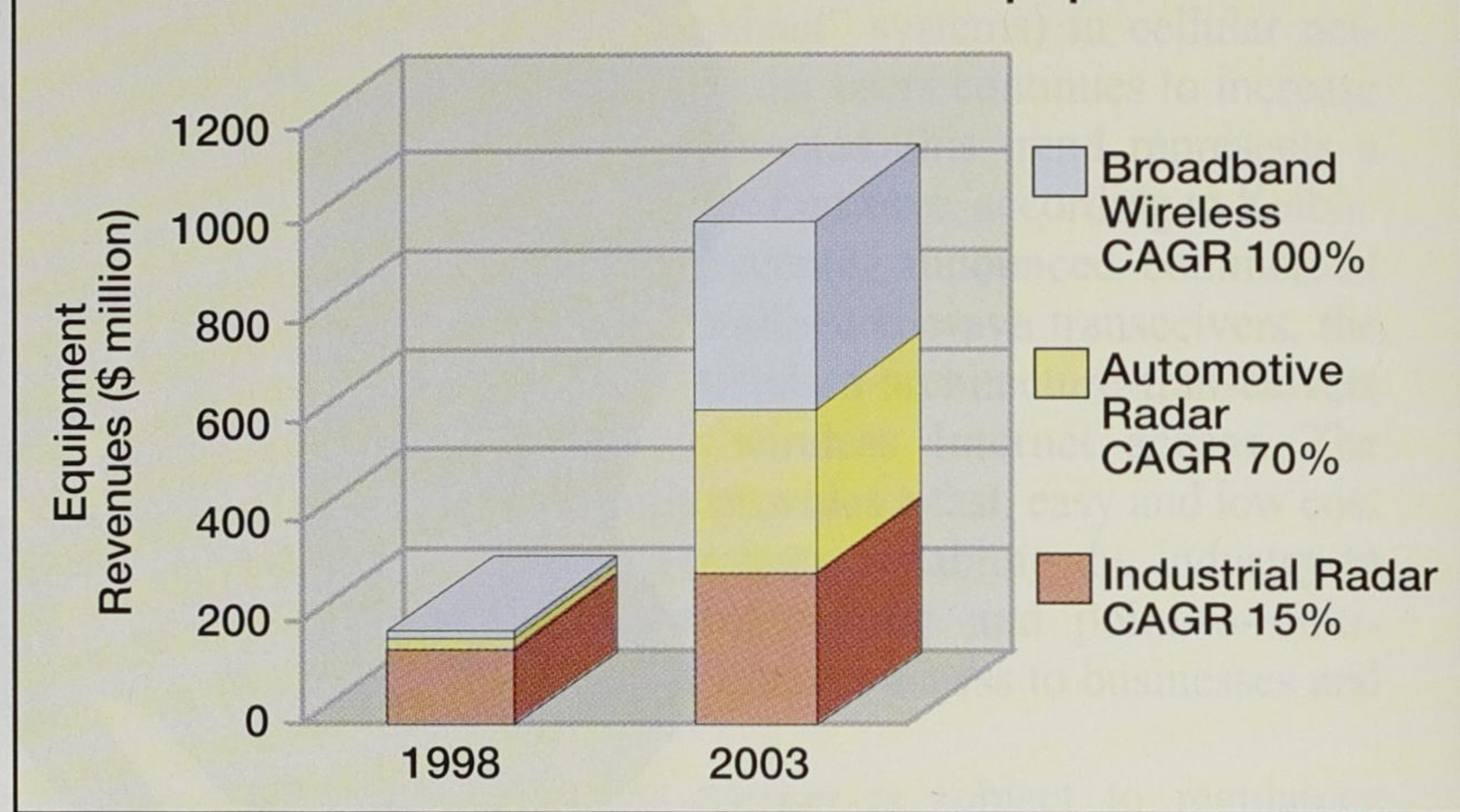


Figure 1. Millimeter-wave market forecast. Data compiled from market studies by Frost & Sullivan, ABI Inc. and Strategies Unlimited.

wave radios and industrial sensors. With respect to the requirements of high-volume products like automotive radars, point-to-multipoint (PTMP) transceivers and wireless local area networks (WLANs), millimeter-wave module production technology seems to be still at the beginning of a revolutionary change. The product roadmap in Figure 2 gives an idea of the ongoing significant market movement.

Advanced Production Technologies

A successful market launch of millimeter-wave products strongly depends on the availability of efficient production technologies. In the past, there have been two separate production worlds. The first is the microwave world, i.e. a sophisticated high-tech approach using bare chip placement with fine-pitch requirements (mostly chip-on-board techniques with wire bonding). The second is the standard electronics

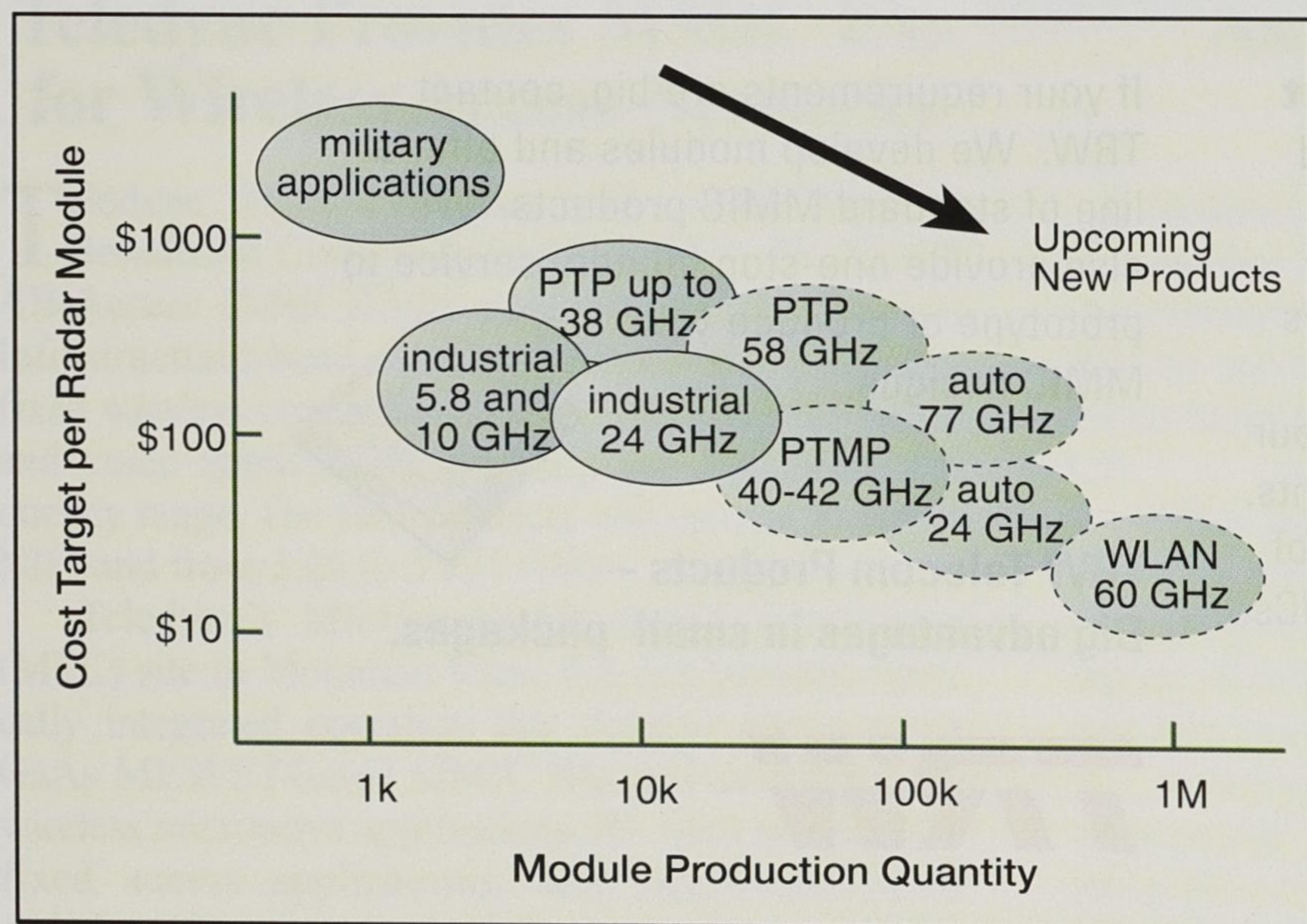


Figure 2. Millimeter-wave product roadmap.

*Patric Heide is the Manager of the Microwave Systems Center at Siemens Corporate Technology, located in Munich, Germany. He can be reached via email at patric.heide@ieee.org.

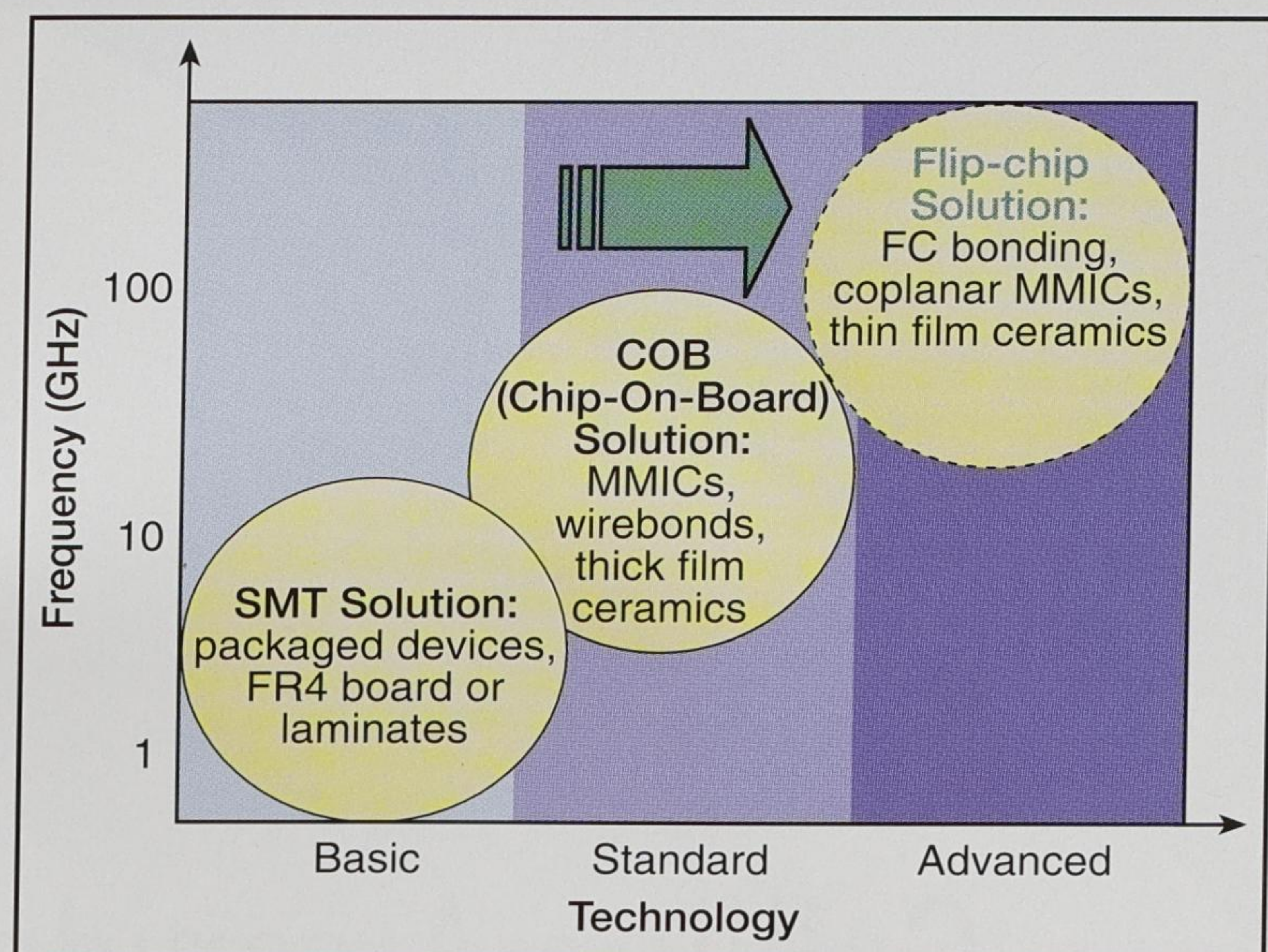


Figure 3. Flip-chip technology is a key for millimeter-wave modules.

world. While the microwave world focuses on the optimization of RF performance, the standard world, while using mostly packaged devices, has ever had its focus on the minimization of manufacturing time and cost. The complexity of electronic systems is increasing rapidly and with the corresponding higher integration, the size of semiconductor packages has been dramatically reduced. Related to this trend to micro-integration, the border between standard electronics and microwave electronics is eroding.

The mobile phone business has promoted a significant progress in the commercialization of microwave components. Surface mount technology (SMT) is currently used for board assembly at least up to 10 GHz. The pick-and-place process is now becoming feasible even for ultra small SMT devices. At the Productronica 1999 exhibition, major vendors claimed the capability of their SMT production machines to handle '0201' packages within a qualified pick-and-place process.

The next step beyond today's SMT devices is leading to flip-chips. The flip-chip is actually a very small SMT-like device that has no package around it. While flip-chip technology has

been discussed for decades, it is now starting to ramp-up. And because of the excellence of flip-chip in terms of RF performance, there is no doubt that flip-chip is a key technology for future microwave and millimeter-wave modules. The technical progress has increased the upper frequency limit that can be reached with conventional production means. Nowadays, up to 30 GHz can be handled with state-of-the-art SMT pick-and-place machines while about 50 GHz can be achieved with the traditional Chip-on-Board (COB) approach. However, flip-chip technology provides excellent results even far beyond 100 GHz (see Figure 3).

Concerning the flip-chip (FC) process, two assembly procedures have to be considered: thermocompression FC bonding and solder FC. Solder flip-chip is likely to be the favorite process for mass production, as it can provide high-speed chip mounting with self-alignment, but this process is not yet qualified for the extreme pitch requirements of millimeter-wave devices. Thus, for the near term, thermocompression FC bonding is a good alternative in terms of flexibility and maturity.

A comprehensive expertise in flip-chip technology up to 100 GHz has been built up at Siemens. Millimeter-wave modules have been manufactured using state-of-the-art flip-chip bonders. The semiconductor suppliers are prepared to include solder or gold bumps on their chips, such that no further bumping step is required. However, for prototype quantities, stud bumps are more flexible as they can be placed onto any off-the-shelf MMIC to make it compatible to flip-chip mounting. Figure 4 shows a typical flip-chip MMIC with about 20 stud bumps (left), an enlarged view of a stud bump with a diameter of 50 μm (center) and a flip-chip mounted MMIC (right).

For a production-oriented millimeter-wave module design, the choice of coplanar waveguides on ceramic substrates is a good solution. Siemens is developing second generation modules for different commercial products, for example the 77 GHz automotive sensor module shown in Figure 5. State-of-the-art MMICs and flip-chip technology are used. All semiconductor devices and even selected passive components are mounted in a flip-chip configuration. The implemented substrate approach is completely uniplanar (no via holes, no backside metallization, no transitions) and thus very attractive in terms of production simplicity and cost.

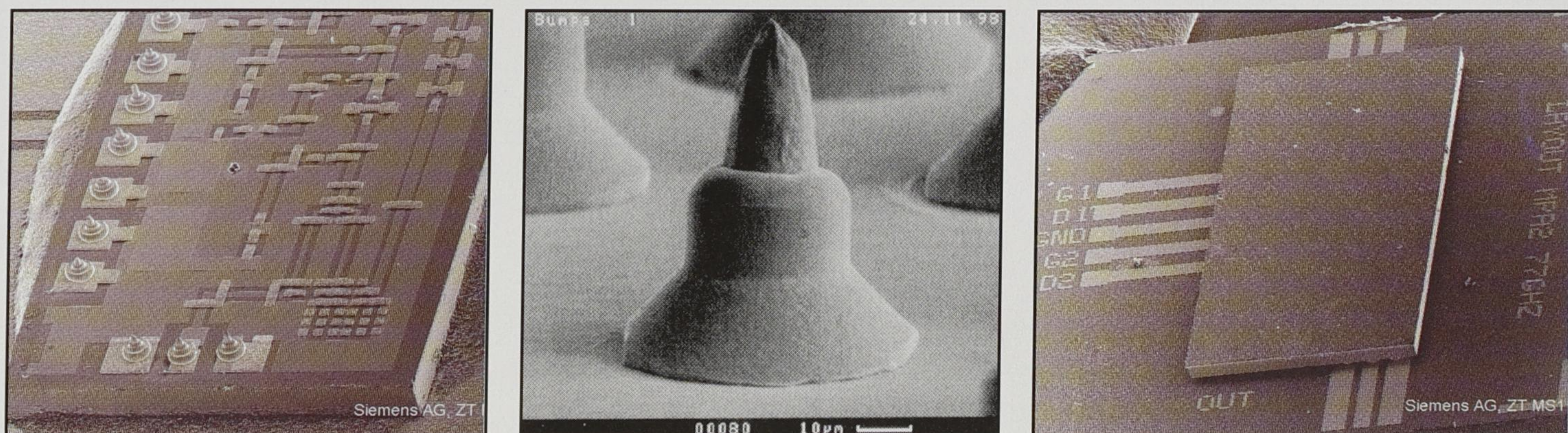


Figure 4. Flip-chip MMIC assembly, showing (left) a MMIC with stud bumps; (center) close-up view of a stud bump and (right) a flip-chip assembled MMIC.

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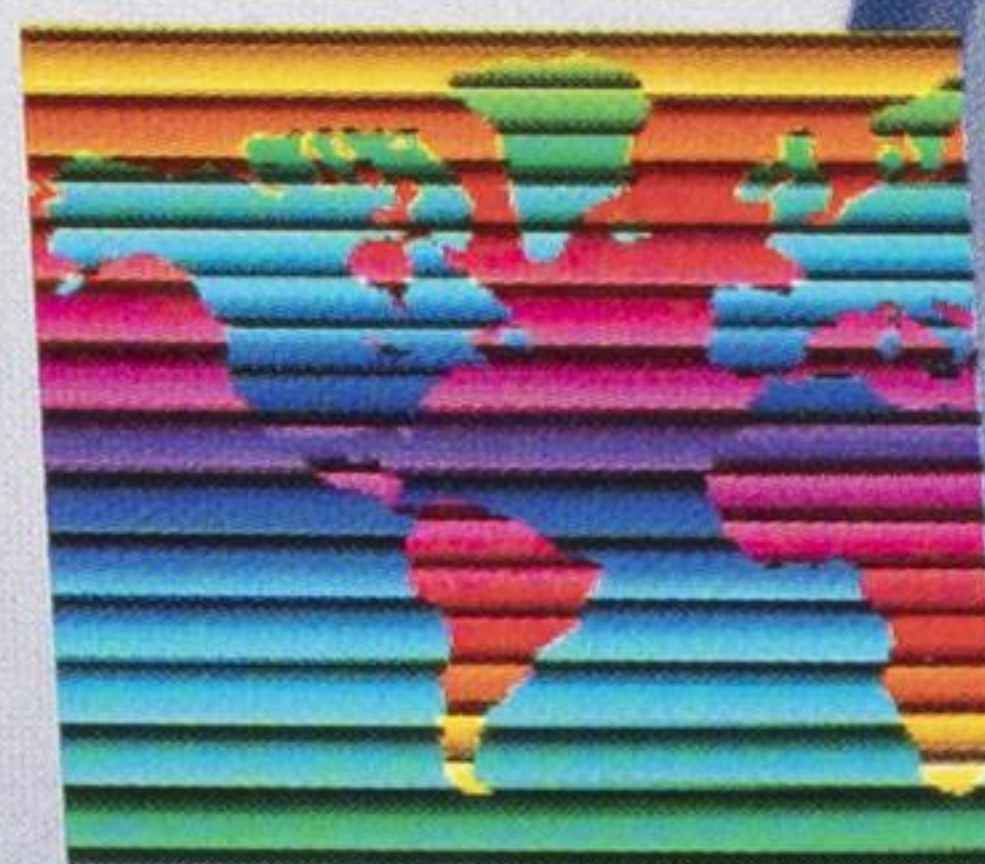
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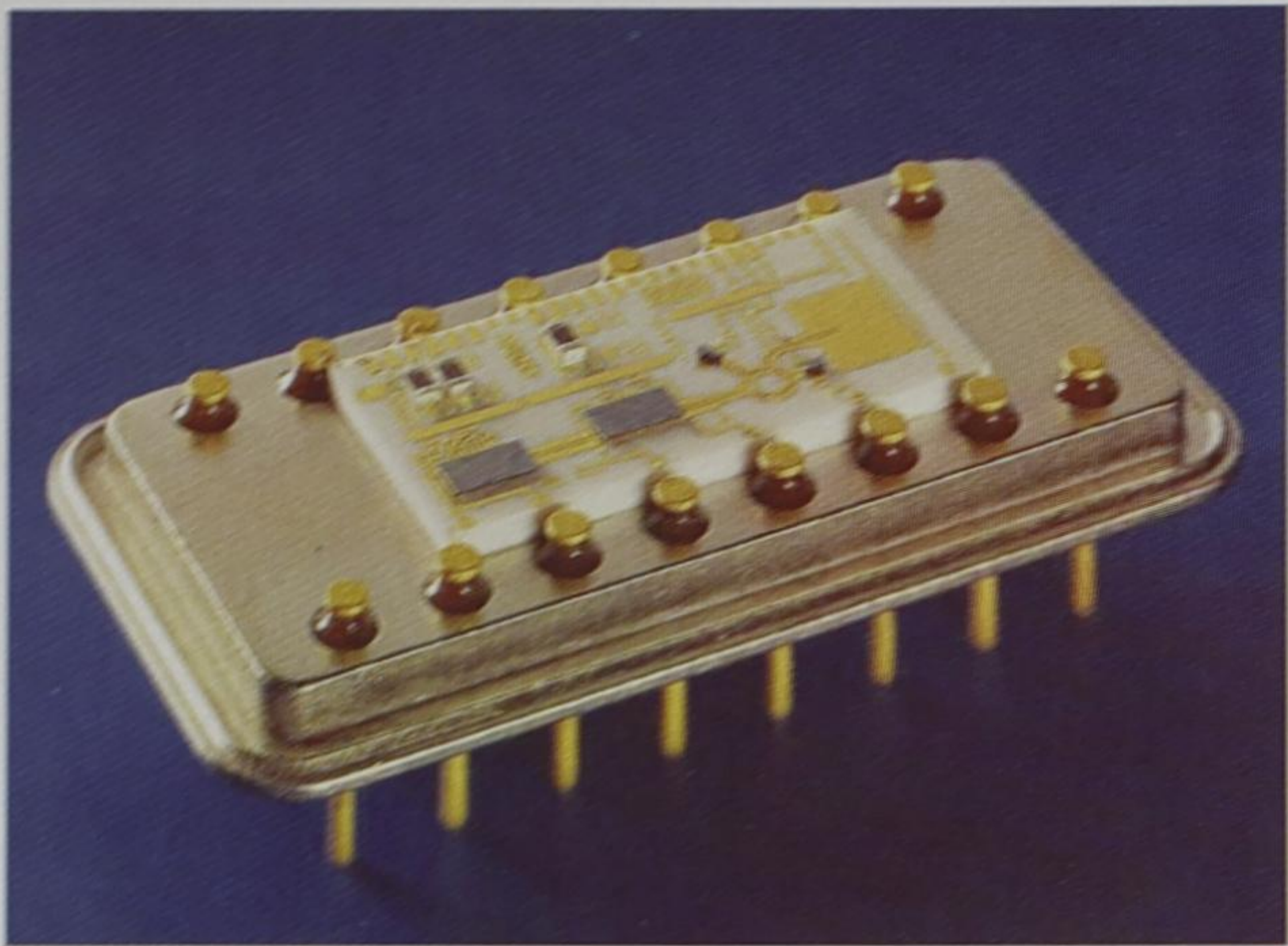


Figure 5. Flip-chip module for second generation 77 GHz automotive radar.

Fully-Automated MM-Wave Module Production: The Value Chain

The value chain of a millimeter-wave system product is illustrated in Figure 6, an important part of which is module production. The chain starts at the basic component level, where suppliers are providing semiconductors (MMICs) and substrates. From these generic parts, a specific module is built within an advanced production process, including fine-pitch flip-chip assembly and quality testing. At the end of the chain, the millimeter-wave module becomes part of the system, ideally as a drop-in component.

As far as Siemens understands the value adding steps, the competitive advantage of a millimeter-wave system product is generated at the module level rather than the chip level. When targeting inno-

vative products, being generic at the chip level reduces cost and minimizes risk and time-to-market, since multiple sourcing of the basic product ingredients becomes feasible. A close co-operation across the whole chain is recommended, as the suppliers need to know about the technical and economic influence of their technology on the system. As packaging and assembly of the millimeter-wave section tends to be the most sophisticated task, there is ongoing effort towards higher integration of active and pas-

sive functions into the generic parts. Examples are MMIC-based subsystems or multilayer substrates based on low temperature co-fired ceramics (LTCC). But in spite of the attractiveness of ICs, it is widely accepted that the module business is going to become an essential value-adding step between the component level and system level business.

Siemens has put much effort into the development of low-cost modules and MMICs suitable for automated high-volume production. Complete microwave assemblies can be realized as a compact sandwich-type PCB, being established by lamination of different layers of dielectrics and metal. Flip-chip subassemblies are included as drop-in devices. Due to simple mechanical constructions, there is no need for further board-to-board solder interconnections, expensive milled metal housings or other complicated manu-

facturing steps. This technological approach, already in production, is used as a common platform for Siemens' 24 GHz industrial and automotive sensor products (see example in Figure 7). The ongoing developments will extend Siemens' module platform up to 100 GHz.

Automotive Radar Sensors

Radar technology has strong support from the automotive industry, and enables numerous functions that are currently under consideration (see Figure 8). Automotive distance warning systems are using radar sensors around the car to monitor the distance and speed of adjacent objects and alert the driver in case of potential collision with an obstacle. First generation 77 GHz adaptive cruise control (ACC) systems have recently been introduced in Mercedes-Benz S-class cars.

As a further expansion of the auto radar market, the next generation of products is likely to bring short-distance sensor functions into the car, for example lane-change aid, parking distance control, pre-crash detection, blind spot sensing, side-crash detection and stop-and-go radar. It is not yet clear if these functions will be realised at 24 or 77 GHz. Parking distance control systems have been implemented using ultrasonic technology, but these are likely to be replaced by low-cost microwave sensors. As a major customer benefit, the microwave modules can be mounted invisibly behind plastic bumpers.

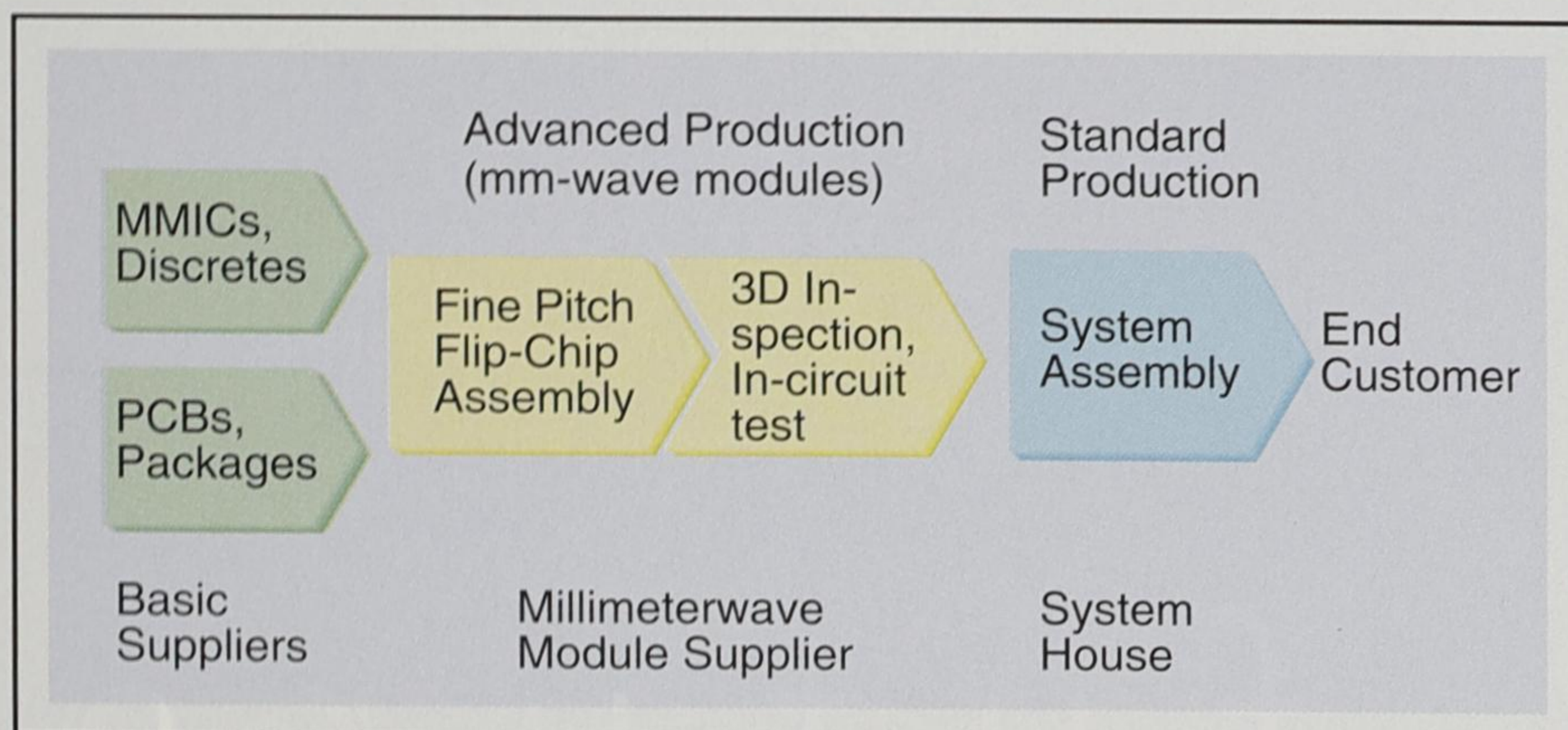


Figure 6. Value chain for millimeter-wave system products.

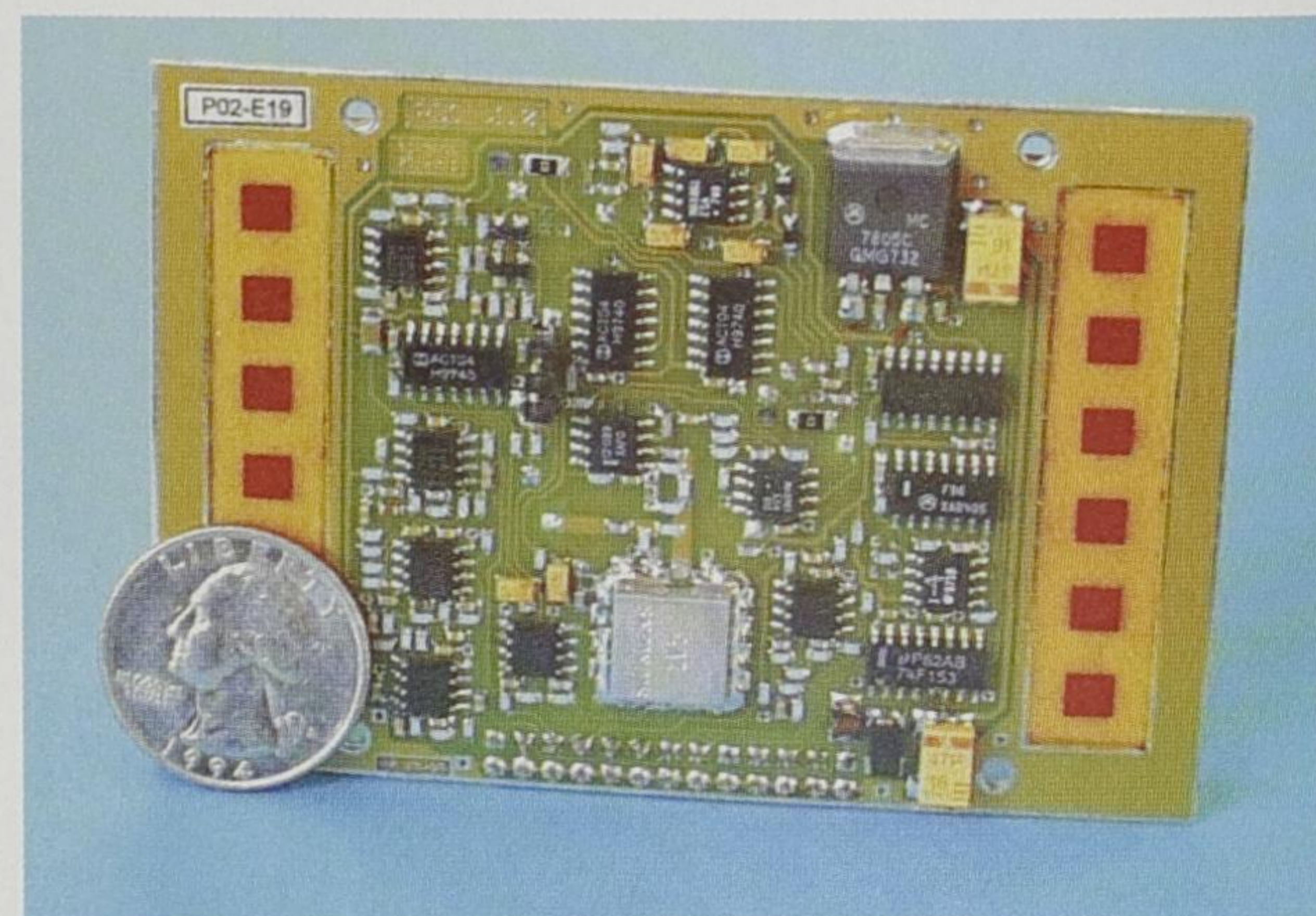


Figure 7. 24 GHz radar module for short distance automotive sensor functions.

Radar pre-crash detection should greatly enhance the safety of a vehicle and its occupants. One possible new function is the "smart airbag", which is inflated adaptively according to sensor information about the collision and the situation of the occupants. The radar pre-crash sensor, used as a add-on to acceleration or pressure sensors, helps to improve the reliability of the airbags (especially the side airbag). Radar pre-crash sensors could also be used to activate reversible safety systems like pneumatic airbags and electronically activated safety belts, neck restraints and knee pads.

Industrial Sensors

The measurement of level in tanks is a significant industrial market. The process control industry needs to monitor the level of a wide range of different products stored in tanks throughout chemical and pharmaceutical plants, power plants, oil refineries, pulp and paper mills and cement mills. Traditional level instruments (e.g. float gauges, capacitance probes and difference pressure transmitters) require a mechanical contact to the process and thus have limitations regarding to the diverse process conditions (e.g. corrosive media and changes in density, pressure, dielectric constant, temperature).

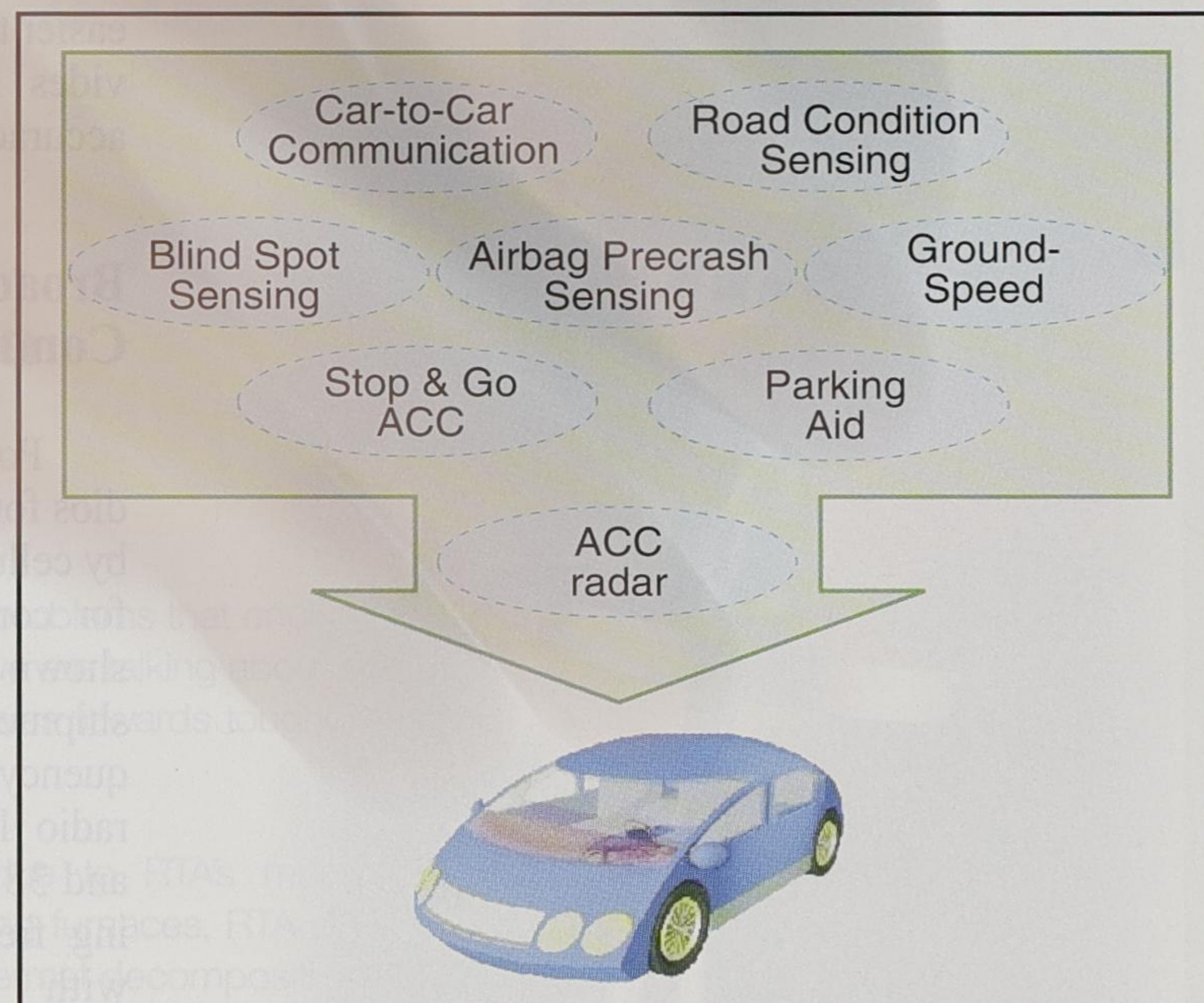


Figure 8. Radar functions around the car.

Microwave technology has proved to be well suited for tank level detection, due to non-contact sensing, reliability over a wide measuring range and robustness against temperature, pressure,



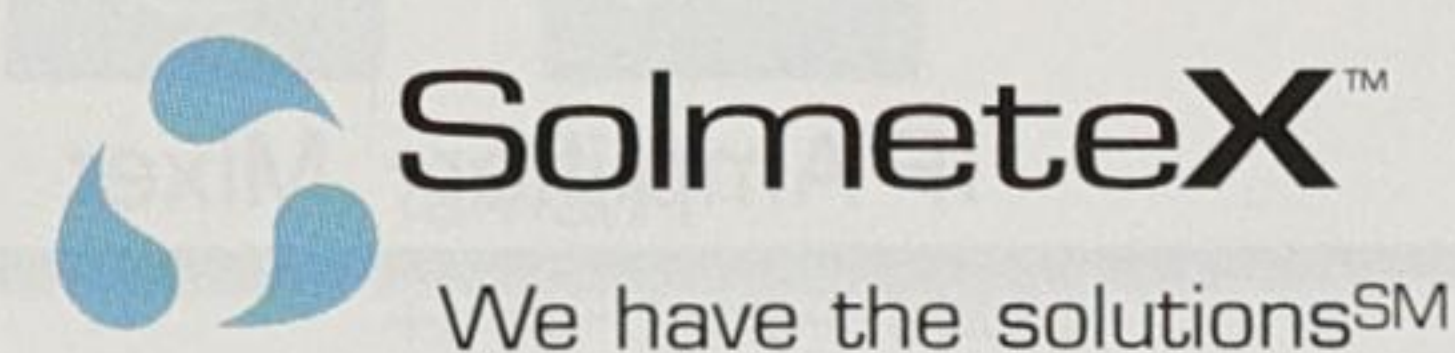
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Figure 9. Industrial tank level gauge (Siemens SITRANS-LR).

steam and dust. The market share of radar level gauges increases steadily. Most of today's systems operate at 5.8 GHz or 10 GHz. However, the next product generation uses 24 GHz technology, like the new radar level gauge shown in Figure 9, which was introduced by Siemens at the Interkama 1999 exhibition. With 24 GHz technology, the level gauge is smaller and

easier to handle, and also provides higher reliability and accuracy.

Broadband Communications

Point-to-point (PTP) radios for use as backbone links by cellular phone providers or for corporate networks have shown a steady growth in shipments. A variety of frequency bands are allocated to radio links (e.g. 18, 23, 26 and 38 GHz), and the operating frequency has increased with growing capacity requirements. As the spectra are usually very crowded in city areas, providers are starting to use picocells with a coverage of 0.5-1 km as the basis of radio links in the 58 to 64 GHz range. As 60 GHz

transmission is limited by atmospheric losses, a re-use of frequencies is possible.

Besides the well-established PTP business, there is a high market potential related to last mile solutions offering a flexible way for providers to deliver broadband multimedia bi-directional services to private homes. Point-to-multi-

point (PTMP) radios have been evaluated for several years, but the market has not yet taken off. Although a variety of test systems have been deployed, PTMP radios are facing strong competition from conventional alternatives already in place like satellite systems and fixed wired networks. At least in undeveloped areas, radio links are accepted as the most flexible and economical approach. Nevertheless, in view of the rapidly growing capacity requirements and tight time-to-market schedules of new services, it is very likely that broadband wireless communications will become a reality also in metropolitan areas, and even for low-cost consumer applications like indoor and outdoor multimedia access and WLANs.

The ingredients required for communication transceivers are very similar to those for radar sensors: a local oscillator, up- and down-converters, amplifiers etc. (see Figure 10). However, the implementation of a communication system imposes specific technical challenges concerning the local oscillator quality (phase locked loops are required), low spurious emissions (high-quality filters needed for radio approvals) and good antenna gain and sidelobe performance. But at the bottom line, the production infrastructure of the communication and sensor business is almost the same, such that a major part of the required investments in production equipment is a budget that can be shouldered by multiple products.

Conclusion

Millimeter-wave technology is rapidly moving towards commercial use. Siemens is convinced that flip-chip technology is the most promising for large volume millimeter-wave module production. A clear market demand is now recognized rather than a technology push, with the main drivers for new products being the fields of communication and sensors. Both volume markets will use similar technology—a good chance for a shared investment with regard to the required production lines.

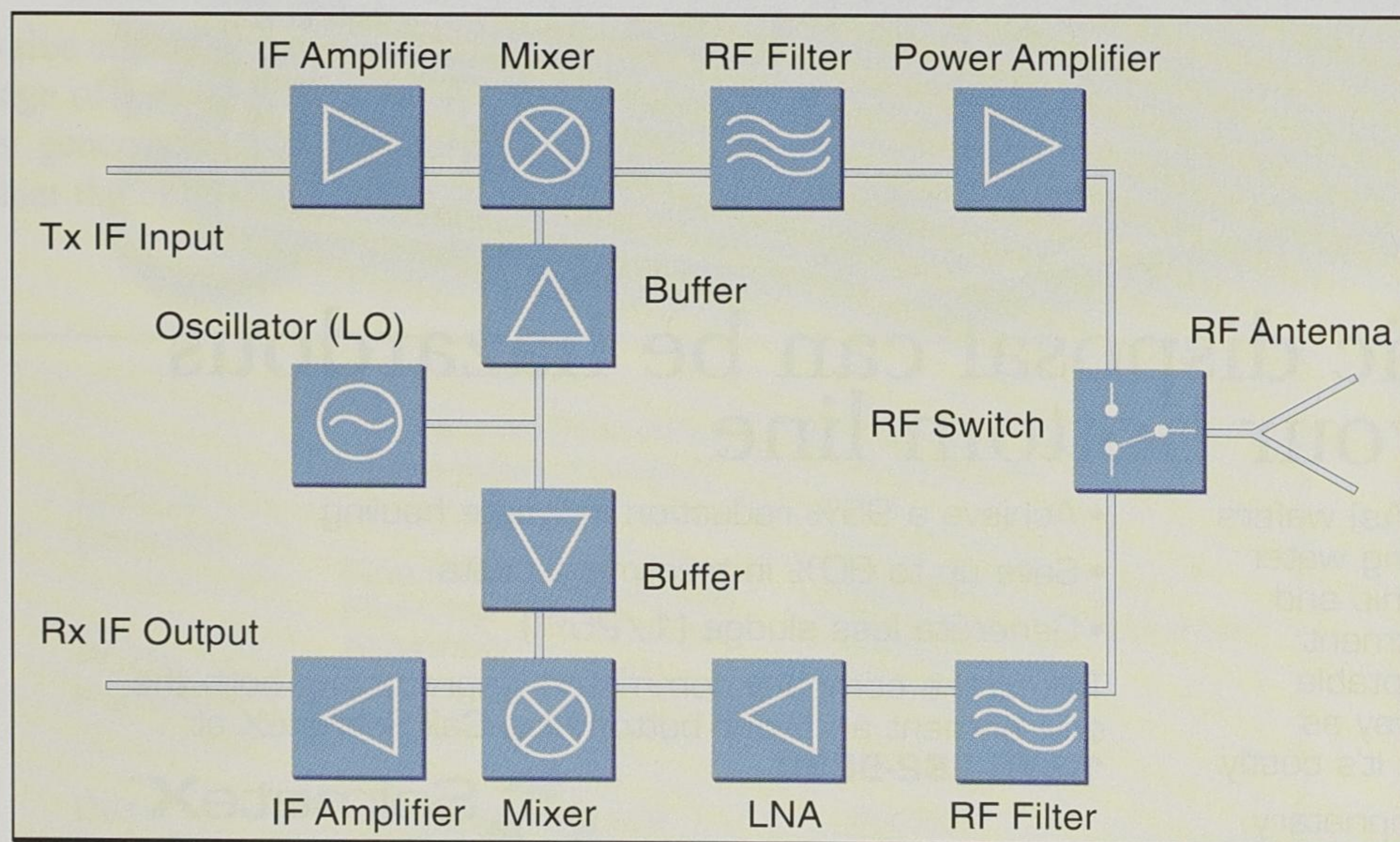


Figure 10. Schematic of a transceiver for millimeter-wave radio links.

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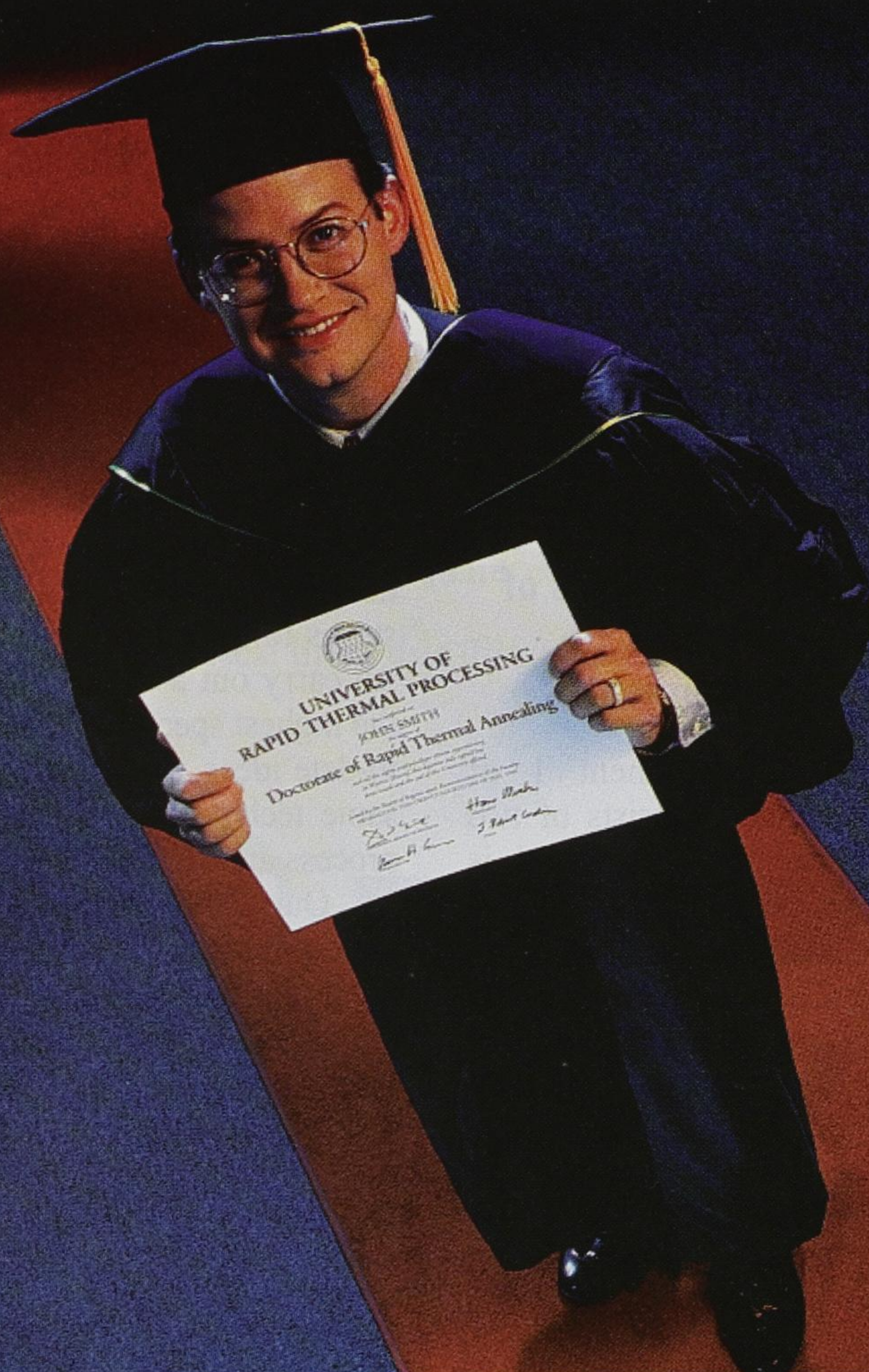
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Development of GaAs HBTs by Teratec Corporation

KENJI UCHIDA*, HIROYUKI MATSUURA, TSUYOSHI YAKIHARA,
SHINJI KOBAYASHI and AKIRA MIURA
Teratec Corporation

Teratec Corporation is a research and development consortium under the control of the Japan Key Technology Center that will be operational for a limited duration, from March 1992 to March 2001. The objective is the development of ultra-high-speed electronic measuring technology by fusing device fabrication technology and system construction technology.

Teratec is funded by the Japan Key Technology Center and six private enterprises associated with the measuring instrument business: Yokogawa Electric Corporation, Advantest Corporation, Ando Electric Co., Ltd., Anritsu Corporation, Agilent Technologies Japan, Ltd., and Iwatsu Electric Co., Ltd. Teratec consists of the head office and six sepa-

ately located departments. The development of GaAs heterojunction bipolar transistors (HBTs) is being pursued by Department 1.

Of the available ultra-high-speed devices, such as high electron mobility transistors (HEMTs) and metal-semiconductor field-effect transistors (MESFETs), HBTs are the most suitable for our requirements because of their low noise characteristics and device stability. These properties are indispensable in order to achieve the consortium's objectives. The low base impedance of HBTs decreases the influence of intrinsic noise sources caused by the imperfection of wafers, which are notable in compound semiconductors. Essentially, the infinite gate impedance of HEMTs or MESFETs

is easily influenced by the noise sources, and the circuits using these devices tend to exhibit irregular delay characteristics and high phase noise characteristics which are called gate lag and back gate effect.

The Circumstances of GaAs HBT Development

Department 1 of Teratec consists of two sections - Section 1 is engaged in GaAs HBT fabrication and Section 2 is engaged in IC design. Both sections constantly exchange

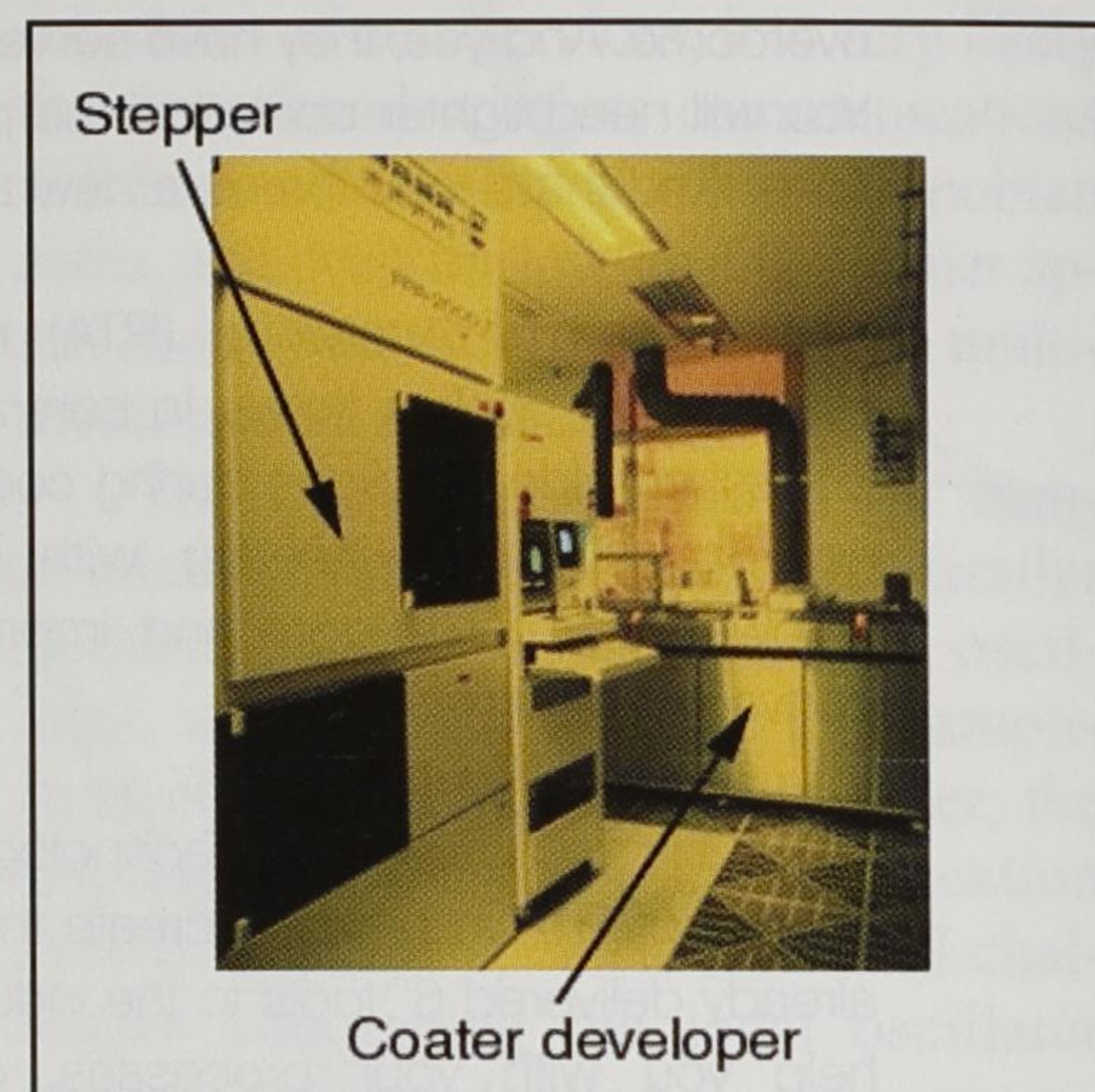


Figure 2. The stepper and the coater-developer in the clean room of Department 1 of Teratec.

information with each other, and GaAs HBT prototype wafers are fabricated using the inputs of both sections in a short time period.

The target in the case of GaAs HBT development is to attain a 300-GHz technology. To achieve this target, we define two process specifications, the circuit research specifications and the ultra-high-speed specifications. In the former case, we optimize process parameters in the device fabrication and extract precise device parameters in the circuit design stages for practical use. In the latter case, we carry out a thorough investigation of the highest speed HBT possible using up-to-date ideas. As both processes have the same technical basis, the results of one process are used in the other process.

Our GaAs HBT devices and circuits are currently in the research and development phase, and are used mainly for the purposes of Teratec and related companies. However, we hope to commercialize

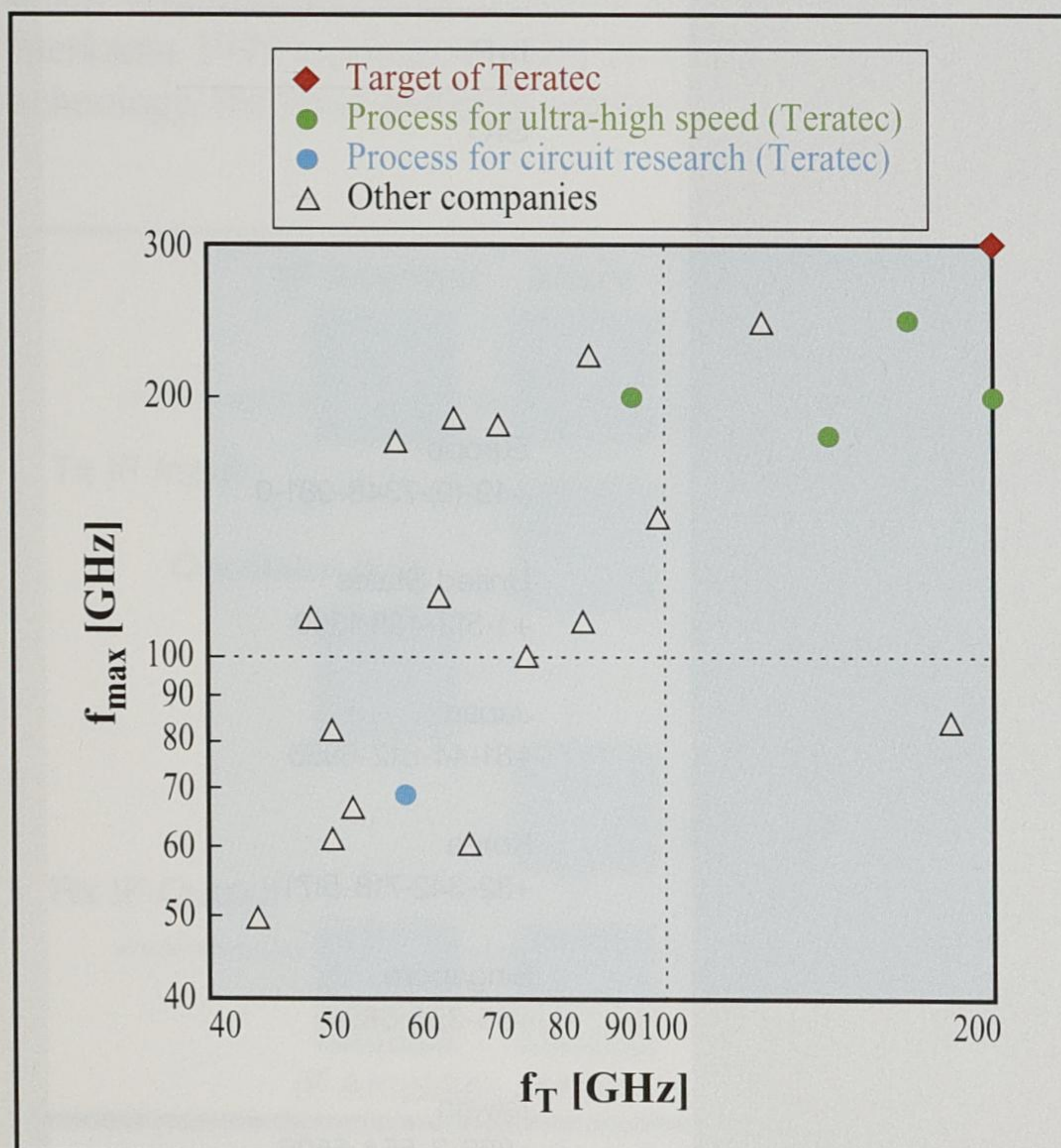


Figure 1. The performance of GaAs-based HBTs fabricated using Teratec's processes, compared to research results from other companies.

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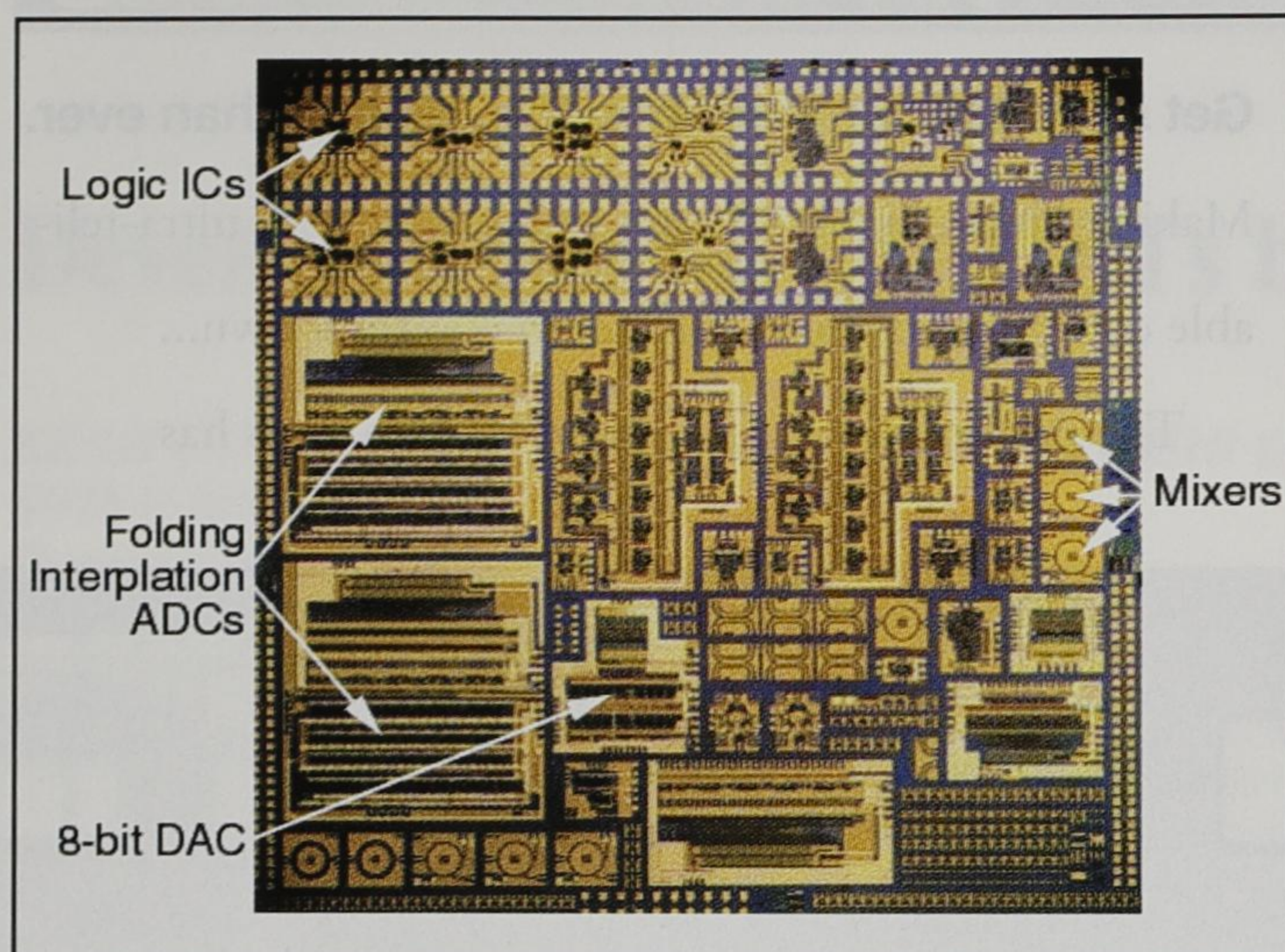


Figure 3. A typical multi-project-type IC layout (measuring 15 mm x 15 mm) fabricated using Teratec's GaAs HBT process.

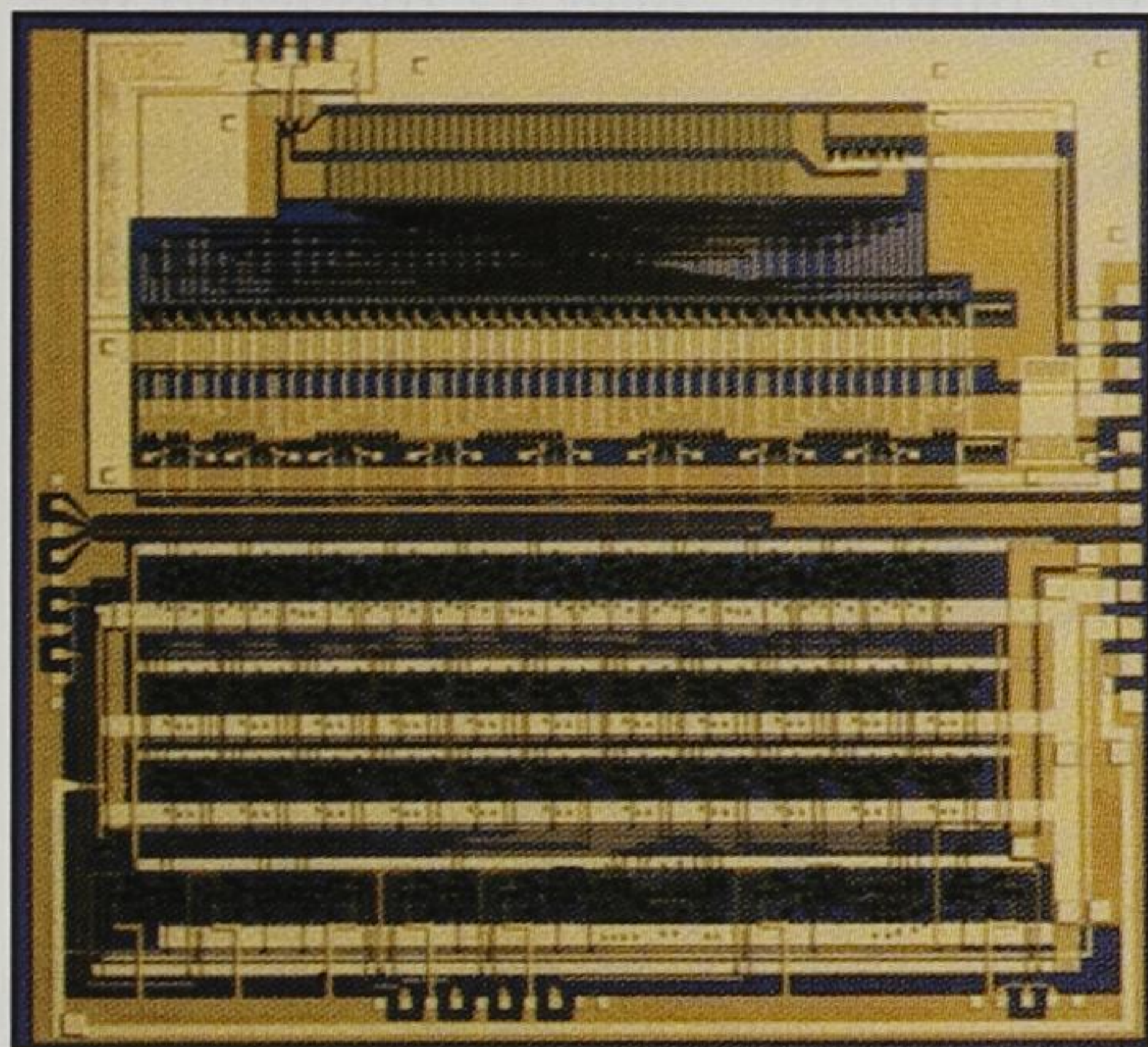


Figure 4. A 6-bit folding/interpolation analog-to-digital converter (ADC) measuring 4.4 mm x 4.0 mm. This architecture enables high-speed action with relatively small chip size.

For an oscillator fabricated using different design parameters, an oscillation frequency of 104 GHz was measured with a phase noise of -95 dBc/Hz at a 1 MHz offset [2]. The phase noise characteristic is approximately 20 dB lower than that of HEMT oscillators around this frequency. The result confirms our prediction that HBTs are highly suitable devices for use in high-speed measuring applications.

Improving the Reliability of GaAs HBTs

In the initial stages of development, the lifetime of ultra-high-speed GaAs HBTs was less than several minutes at a high current density. We investigated the reason for this through reliability tests and transmission electron microscope (TEM) image observations, and discovered two defects: the spike of Au-Ge alloy in the emitter, and the lattice destruction on the base-emitter interface. To prevent the occurrence of these defects, we employed refractory metal in the

this technology in the future. Figure 1 shows the current gain cutoff frequency (f_T) and the maximum oscillation frequency (f_{max}) of our GaAs HBTs along with the research results of other companies.

Teratec carries out epitaxy and photolithography in-house: the facilities of Department 1 include a multi-chamber MBE system, an i-line stepper and an automatic coater-developer (see Figure 2).

The Circuit Research HBT Process

As part of the development of a process for circuit research, we have been designing and fabricating GaAs HBT ICs twice a year since 1994. The process yields f_T and f_{max} values of around 50 GHz. The mask design is what is called the multi-project type, and various types of ICs are arranged together over an area of 15 mm x 15 mm, as shown in Figure 3. The multi project type layout is an efficient style for us to fabricate and test different types of HBT-based ICs and test element groups (TEG).

One of the targets for the process is the development of a high-speed analog-to-digital converter (ADC). We attempted fabrication of a 6-bit folding/interpolation ADC, as shown in Figure 4. The folding/interpolation architecture enables high-speed action with relatively small chip size. The ADC consists of 845 HBTs, 19 schottky barrier diodes (SBDs), 487 resistors, and 20 capacitors, and handles more than 1 giga-sample per second (GS/s). The power consumption is 4.0 W with the chip size of 4.4 mm x 4.0 mm [1].

Using this process, Teratec is now developing track-and-hold circuits with an interleave architecture. These ICs are key components for measuring instruments and wireless communication systems.

The Ultra-High Speed HBT Process

Teratec has also developed a GaAs HBT process for ultra-high-speed ICs. As shown in Figure 1, very high performance devices have been fabricated, including HBTs with $f_T = 190$ GHz and $f_{max} = 230$ GHz. Recently, we have also demonstrated excellent device stability under high current density operation, as described below. As a result of these process improvements, we have succeeded in developing a 146.7 GHz fundamental-mode oscillator at a current density of 134 kA/cm². To our knowledge, the oscillation frequency is the highest frequency ever realized using bipolar technology. Figure 5 shows a micrograph of the oscillator.

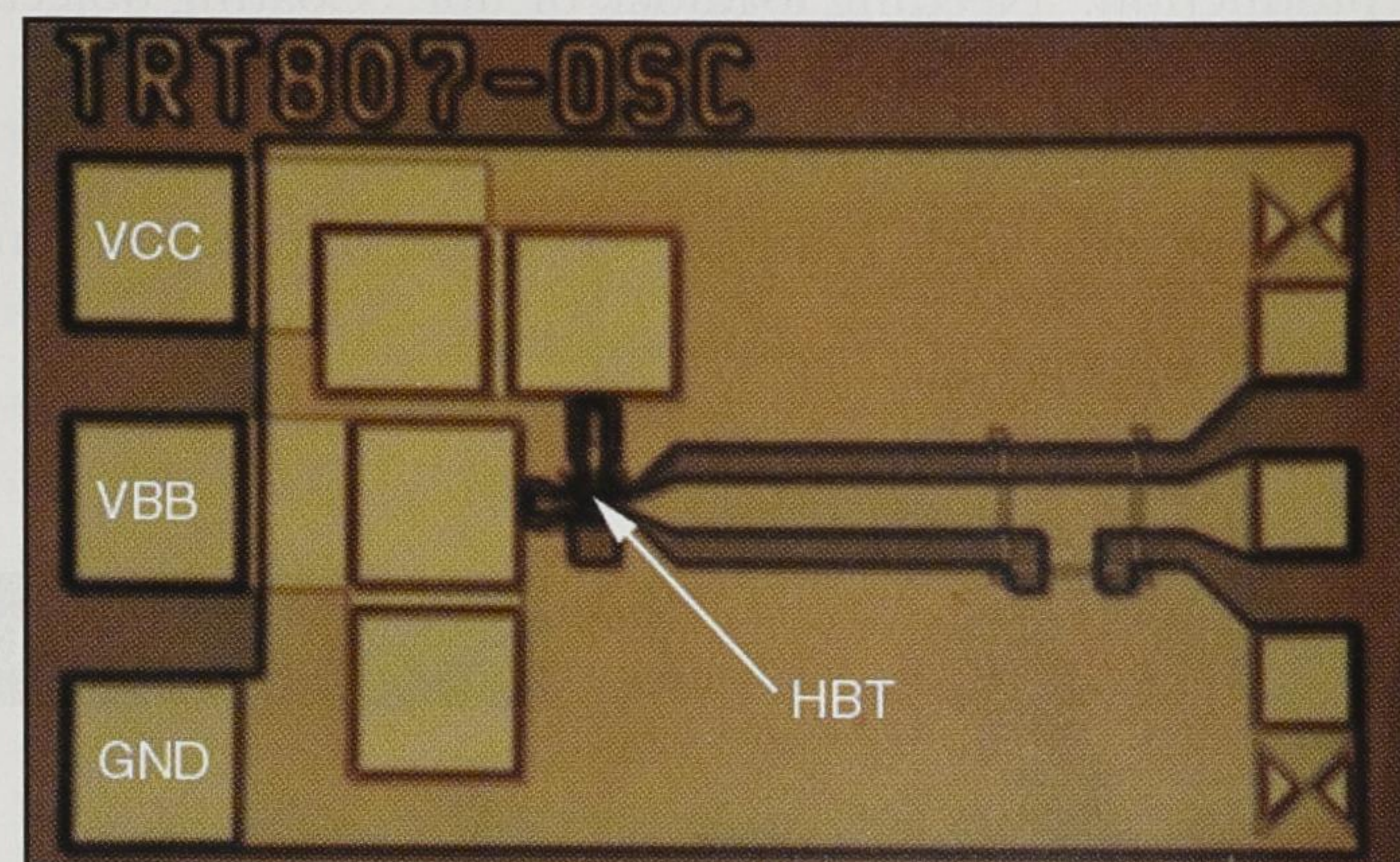


Figure 5. Micrograph of the 146.7 GHz fundamental-mode oscillator fabricated using Teratec's ultra-high-speed GaAs HBT process. The oscillator measures 732 μ m x 411 μ m.

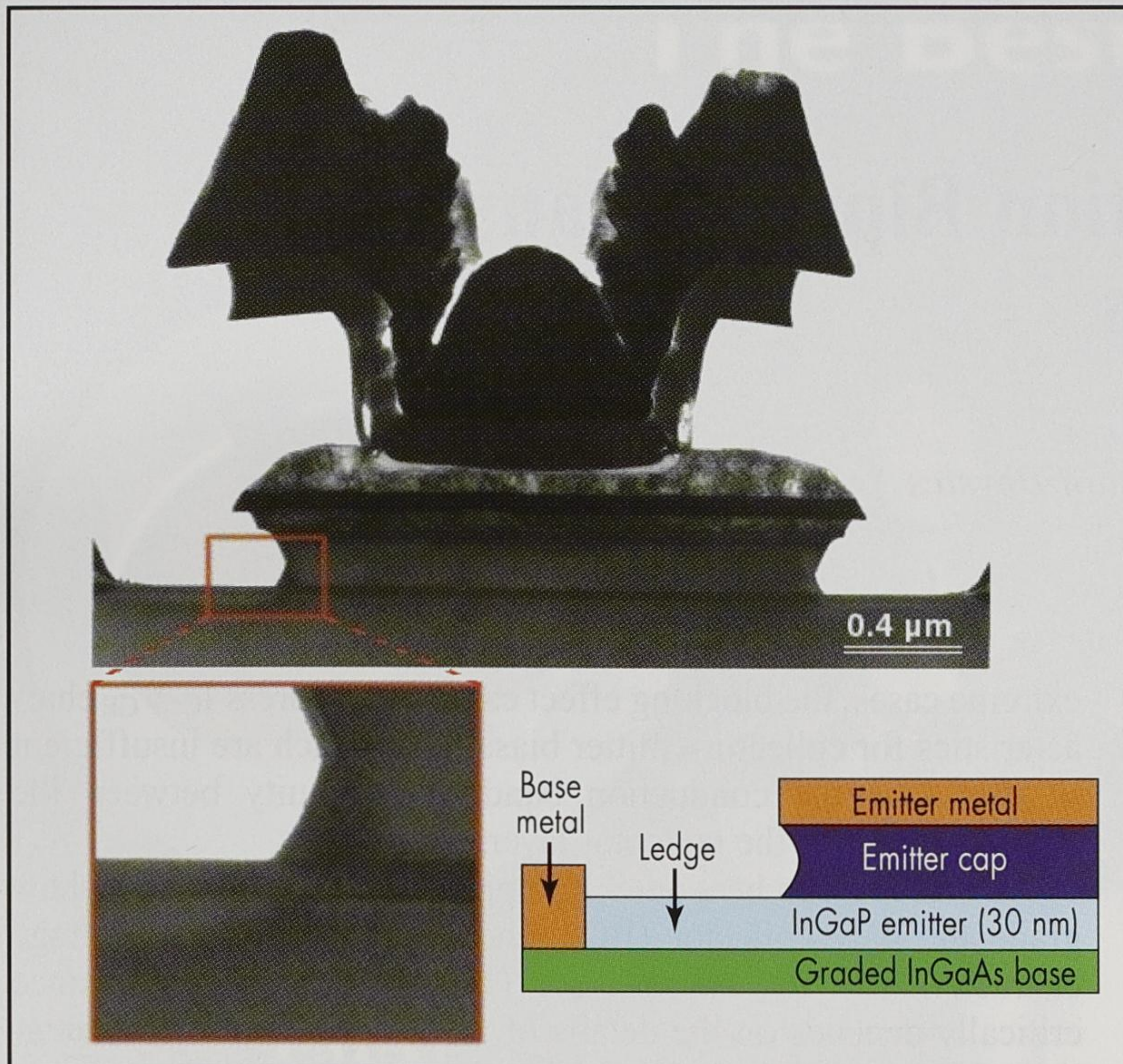


Figure 6. TEM image of Teratec's HBT device, with a close-up of the ledge structure. The schematic shows the position of the emitter ledge that protects the base-emitter interface.

ohmic contacts and changed the emitter material from AlGaAs to InGaP. We also implemented a 30-nm thick InGaP ledge to protect the base-emitter interface. Figure 6 shows the cross-sectional view of the HBT with the ledge.

After applying these measures, the reliability of the HBT was greatly improved. The HBT can withstand a 1000-hour reliability test with a current density (J_C) of 50 kA/cm², an ambient temperature (T_a) of 125°C, a junction temperature (T_j) of 200°C, and a collector-emitter voltage (V_{CE}) of 3.5 V. We believe that the test reveals the HBT to be sufficiently reliable for practical application.

We express our gratitude to Mr. Hisao Nakamura, the Senior Vice President/Managing Director of Teratec, for valuable suggestions.

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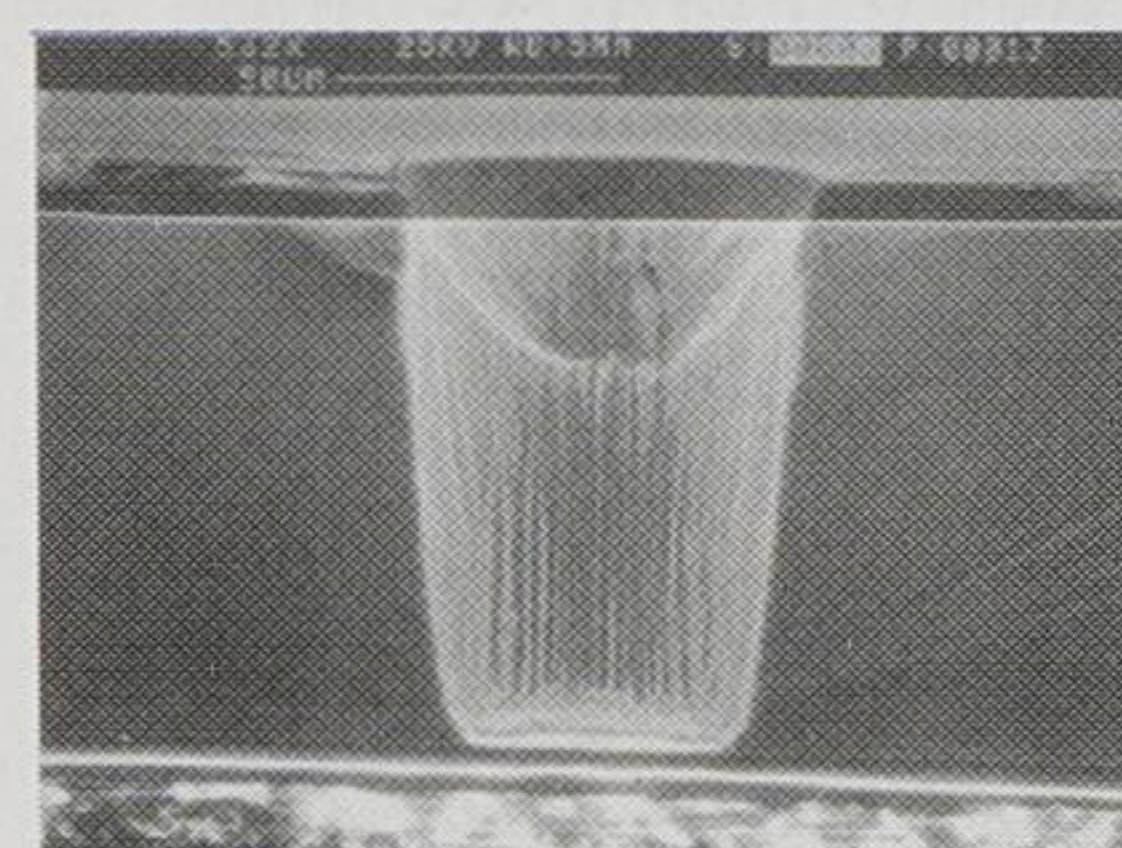
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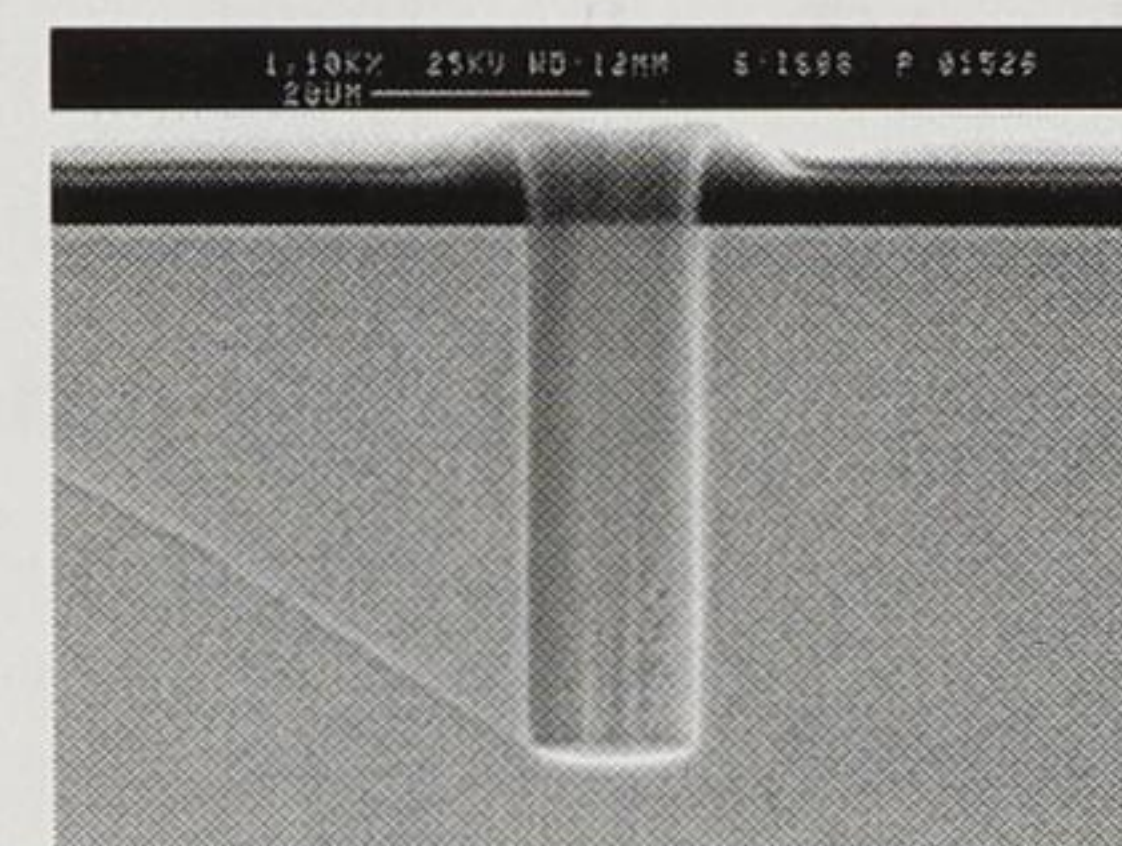
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InP-Based Double Heterojunction Bipolar Transistors: It May Not Have to Be GaInAs

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InP/GaInAs- and AlInAs/GaInAs-based single heterojunction bipolar transistors (SHBTs) have demonstrated outstanding properties with cutoff frequencies well in excess of 200 GHz because of the superior electron transport properties of GaInAs. Like other narrow bandgap materials, GaInAs features high mobilities and peak electron velocities, but can only sustain low electric fields (<200 kV/cm) before the onset of carrier multiplication by impact ionization. In the context of HBTs, impact ionization at low fields results in low collector breakdown voltages and high output conductances.

It has long been recognized that the collector breakdown characteristics of SHBTs can be improved through bandgap engineering by inserting a widegap collector layer between the base and the heavily doped GaInAs sub-collector. Unfortunately, the large conduction band discontinuity ΔE_C between GaInAs and AlInAs (~ 0.5 eV), which proved so enabling in the realization of millimeter-wave AlInAs/GaInAs HEMTs, becomes a major liability in the DHBT context. This is because of its retarding effect on the transport of minority carrier electrons trying to exit the base as shown in Figure 1. The so-called collector current blocking effect reduces the effective electron exit velocity from the base and increases electron storage in the base layer, resulting in a dramatic drop in cutoff frequency in comparison to SHBTs. In

extreme cases, the blocking effect can even suppress I_C - V_{CE} characteristics for collector-emitter biases V_{CE} which are insufficient to overcome the conduction band discontinuity between the GaInAs base and the collector layer.

Device researchers quickly appreciated the need to somehow grade the base-collector (BC) junction to restore low voltage characteristics (for example see [1]), but device performance critically depends on the details of the BC grading implementation. Of course, if the bulk of the collector material is intended to be InP one only needs to grade the conduction band with an AlGaInAs quaternary alloy (or an AlInAs/GaInAs "chirp" superlattice with a variable duty cycle to engineer minibands that mimic a graded quaternary alloy) to overcome the discontinuity between GaInAs and InP (~ 0.25 eV). The BC junction grading can also be accomplished by step grading from GaInAs to InP by inserting a GaInAs spacer followed by a couple of GaInAsP layers with compositions, thicknesses, and doping levels engineered so as to minimize the trapping of electrons in the conduction band notches present at each interface.

Tiwari [2] first critically examined the effect of alloy grading at the collector-base junction of DHBTs. It was pointed out that unless care is exercised in device design and implementation the electron traveling space charge associated with high collector current densities J_C eventually exposes a retarding alloy potential at the BC junction *even* if the BC interface is properly graded to smooth out its conduction band discontinuity. In his analysis, Tiwari provided clear criteria which can be used to ensure current blocking effects due to the alloy potential would be suppressed at normal operating currents in given graded BC design. Once armed with concrete design criteria yielding prescriptions which fall well within the capabilities of modern epitaxial growth techniques, what could stop us from producing high-performance DHBTs on a large scale?

Grading Schemes

Various doping and/or compositional grading schemes have been developed to eliminate the BC current blocking effect, and some of the approaches are illustrated in Figure 1. For nearly five years now, excellent device performance reports have been released based on variations on the above grading and/or doping schemes for heterojunction collectors. In some cases the dynam-

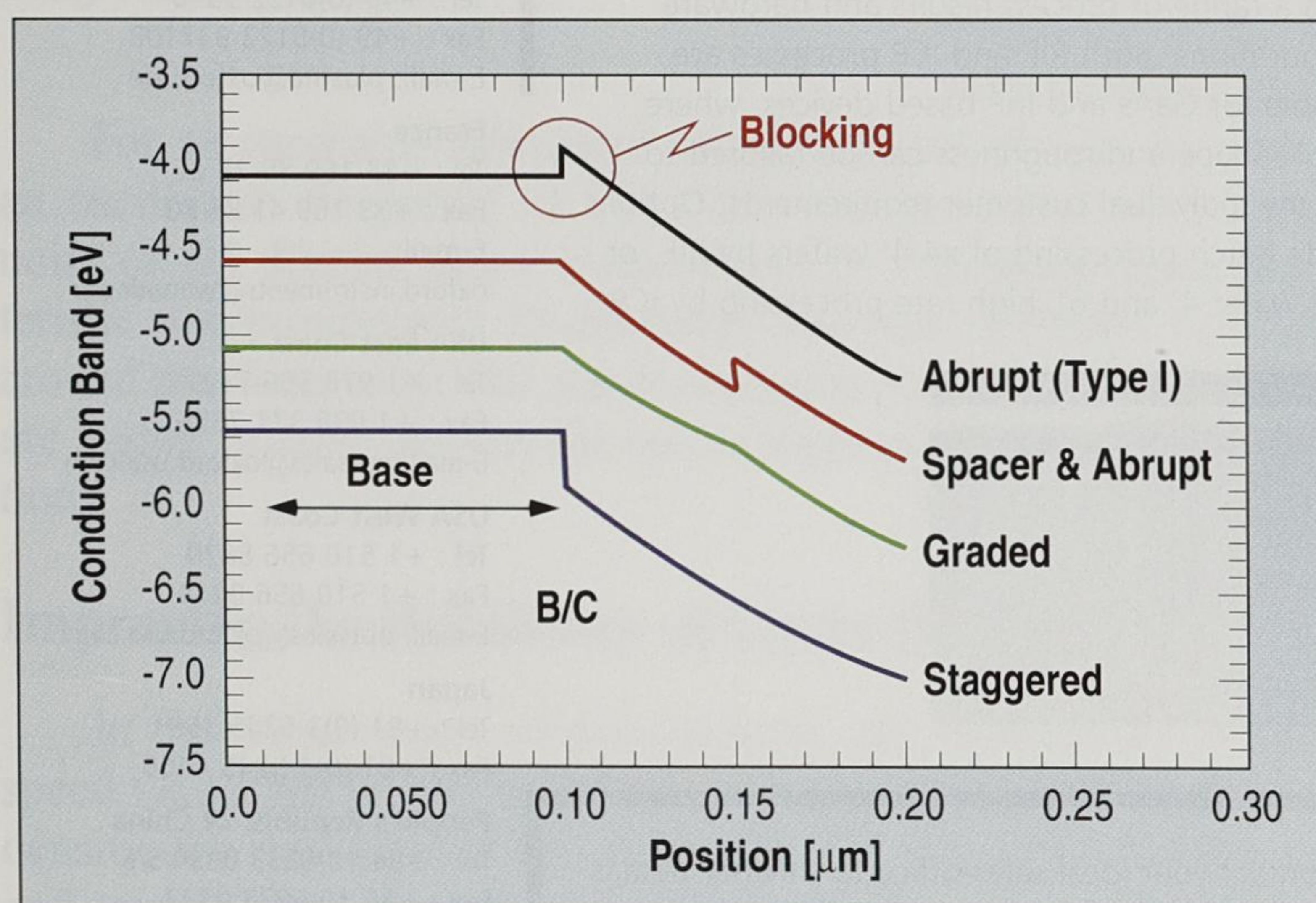
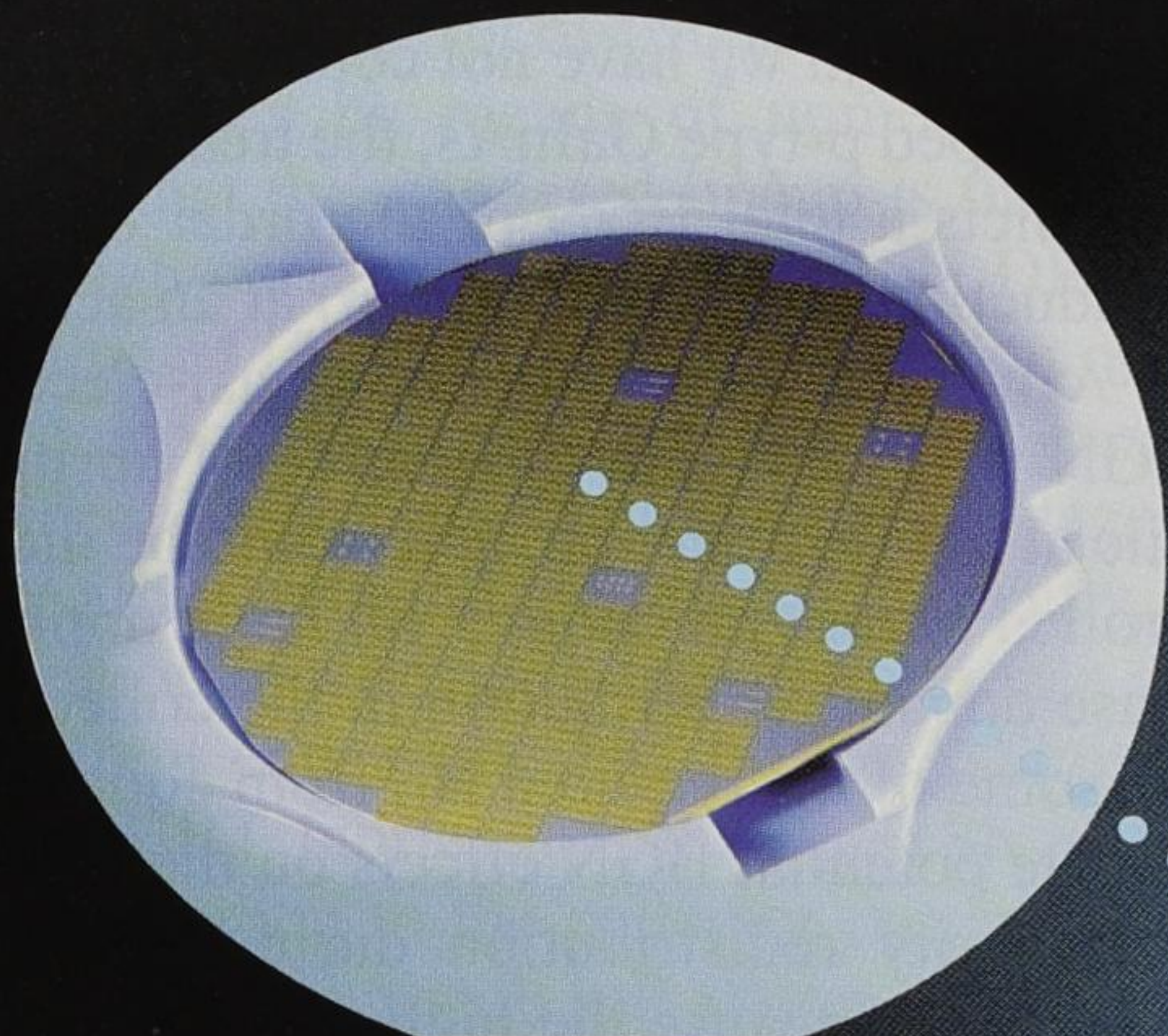


Figure 1. Conduction band profiles for a few design options available for the implementation of InP-based DHBTs. The staggered lineup is obviously free of potential collector blocking effects.

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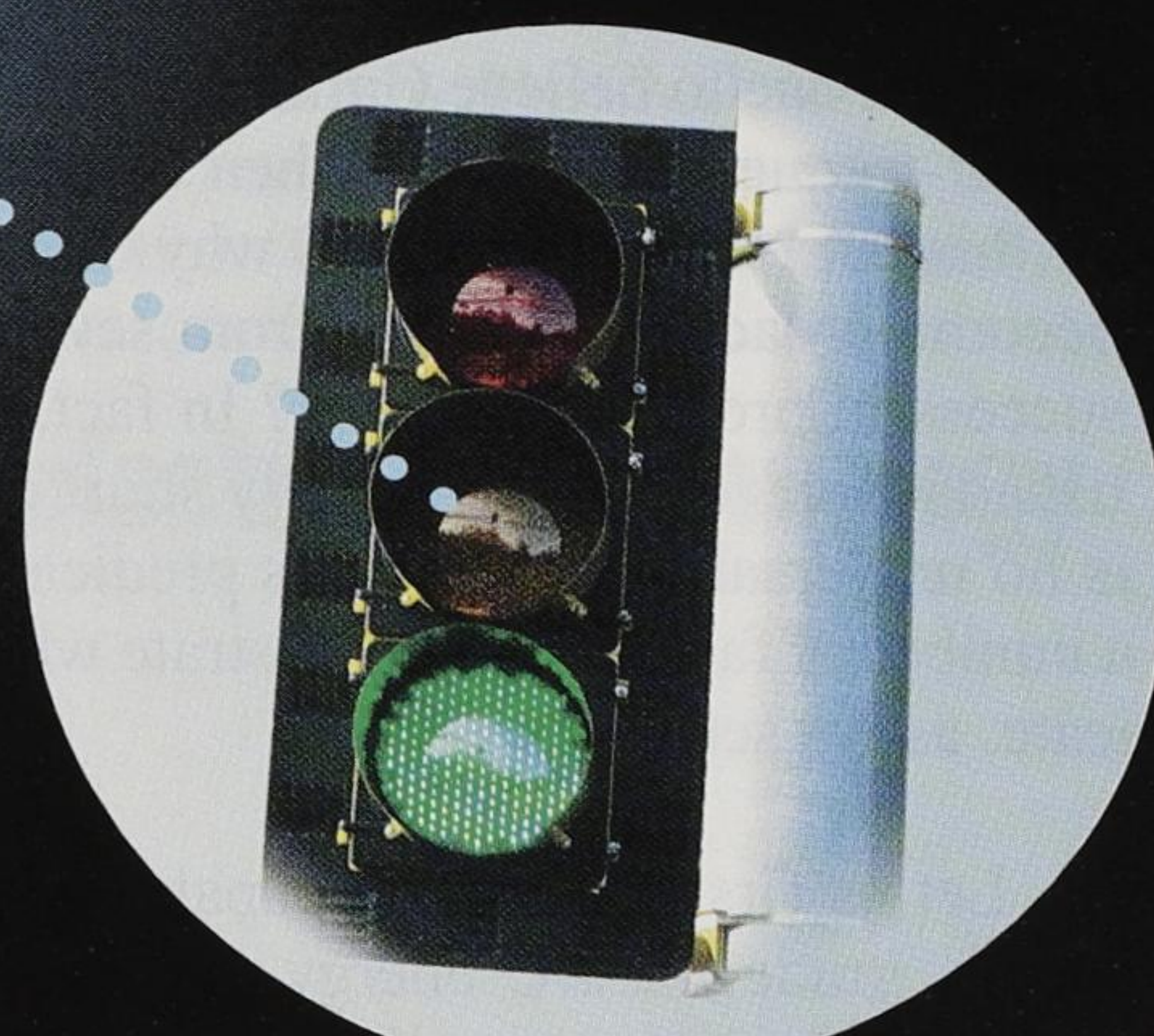
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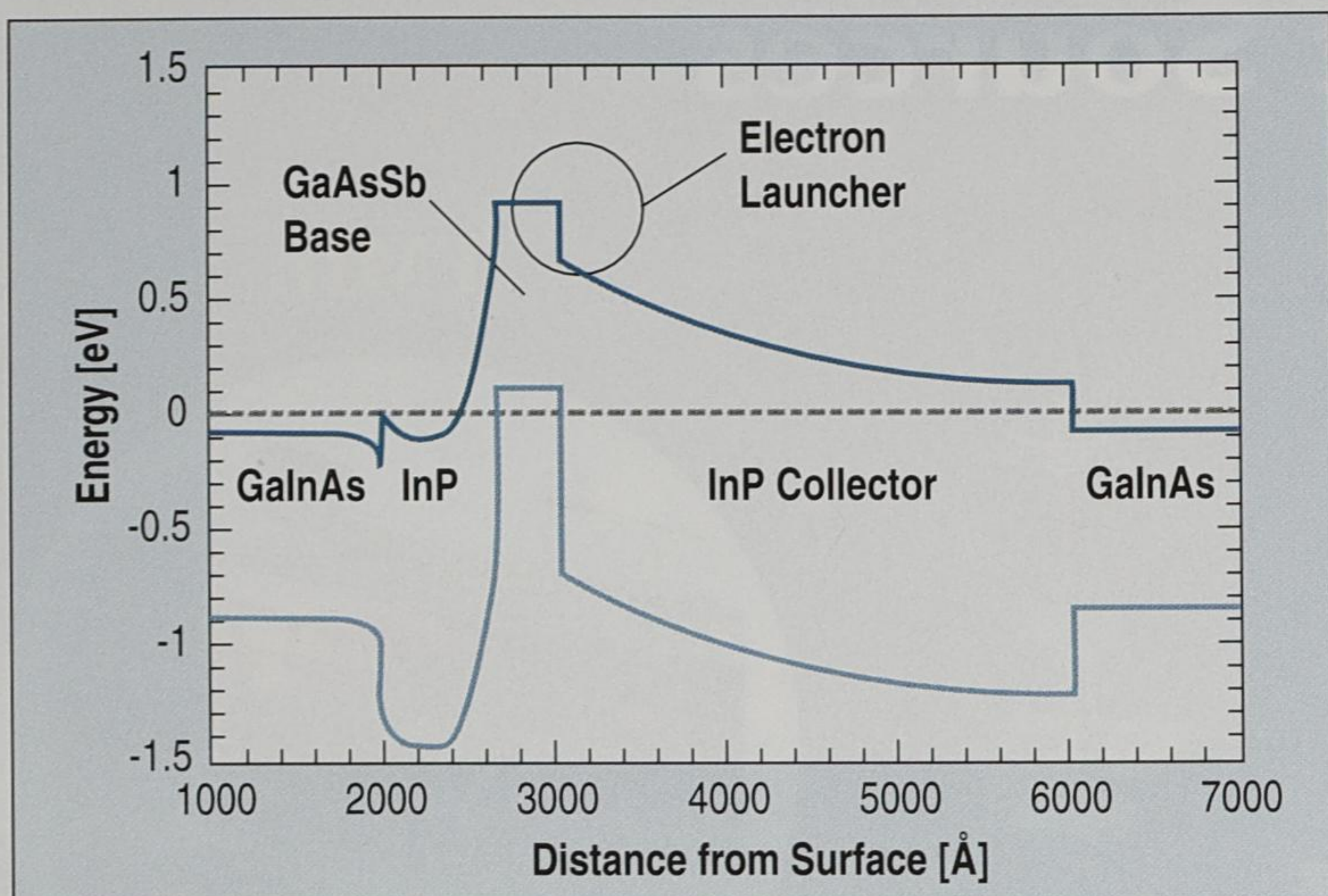


Figure 2. Equilibrium band diagram for an InP/GaAsSb/InP DHBT. The structure can be grown with abrupt EB and BC interfaces. Electrons are thermally injected into the base which they cross by diffusion. The use of an AlInAs emitter would enable hot electron injection.

ic performance of DHBTs was even found to be as good as that of high-speed InP/GaInAs SHBTs, with the added bonus of a much-improved power handling capability. The literature could thus lead one to believe GaInAs DHBTs provide a free gain in the power-frequency tradeoff when compared to the GaInAs SHBT. If this is really the case, why haven't InP/GaInAs DHBTs become broadly available - from several sources - after so many successful proofs-of-concept? In fact, attempts to duplicate published results can fall tragically short of the goal. There probably is no universal answer for this predicament but one can consider a number of factors which illustrate why the situation is quite delicate, as we see below.

Let us first assume the capability to controllably and reproducibly grade the BC energy gap over ΔE_C is in place —definitely doable, but no small engineering feat. Tiwari and Frank [3] pointed out that a linear grading to overcome ΔE_C over a length y_o , required a collector doping N_D to prevent collector blocking at a current density J_C such that.

$$N_D \geq \frac{\epsilon}{q y_o} \cdot \frac{\Delta E_C}{W(N_D, V_{BC}) - y_o} + \frac{J_C}{q \bar{v}} \quad (1)$$

Clearly larger conduction band discontinuities require either longer grading lengths, wider depletion regions W , and/or high doping levels —all these alternatives are not conducive to good dynamic properties if cutoff frequencies in excess of 160 GHz are desired. One also notes from the equation that the minimum collector doping level depends on the mean electron velocity in the collector through the second term in (1): clearly $\bar{v}$ can vary significantly from one material to another, from high values in velocity overshoot materials like GaInAs, to low values in AlInAs. One notes that the functional dependence of (1) suggests the minimal required doping density, and thus the lower junction capacitances, are achieved for a grading length equal to half the collector depletion region width. Again, it will probably be more

advantageous to get the electrons out of the graded regions, which are characterized by low velocities, and into the InP collector as soon as possible.

It is also interesting to ask whether or not the device design process should consider the potential impact of the base bandgap narrowing (BGN) on the conduction band discontinuity to overcome at the BC junction. Although we have not come across any published data for heavily-doped p-type GaInAs, the treatment of Jain and Roulston [4] predicts a total BGN of the order of 120 meV (with a 40 meV conduction band contribution) at an acceptor doping level of $10^{20}/\text{cm}^3$. The impact of the quasi-electric field associated with BGN will vary with the degree of abruptness of the doping profile at the BC junction, and would be most significant in well-controlled abrupt junctions with large doping gradients. In contrast, base dopant redistribution in the collector would partly compensate some of the required N_D from equation (1) on one hand, but mitigate potential BGN effects on the other.

The issue of base impurity redistribution during epitaxy needs to be carefully considered because the high doping levels used in modern HBTs could lead to a portion of the collector being converted to p-type material if a significant redistribution of acceptors were to take place near the BC junction. This issue is also relevant to SHBTs where any extension of the base region will increase the base transit time (or at best, result in ballistic collection phenomena under some biases). Acceptor redistribution can prove particularly deleterious in DHBTs because of its interference with the effectiveness of the BC grading design. The effect may therefore explain the large spread in performance experienced by different laboratories on nominally identical structures (variations in base impurity diffusion may make outsourcing of epitaxial DHBT structures a difficulty for manufacturers who have zeroed in on a "sweet spot" with a given internal/external primary source). Dopant redistribution phenomena can in principle be resolved through the use of low-diffusivity C acceptors in both MBE and MOCVD (at the risk of introducing H-passivation related device instabilities, if GaInAs is the base material). Also, Be diffusivity can be alleviated by optimization of growth parameters such as the use of low substrate temperatures, high arsenic overpressures, and/or the insertion of a spacer (or lower doped) layer near the BC interface. One begins to appreciate the challenge of DHBT implementation in "type I" heterojunction systems.

The use of quaternary or digital alloys near the base region in the collector of DHBTs also diminishes the base exit velocity. This results in increased carrier storage in the GaInAs base region because of the resulting exit velocity bottleneck. From an exit velocity point of view, GaInAs would be the best available collector material on InP if it were not for its low breakdown voltages. On the other hand, (Al,Ga,In)As exhibits poor transport properties that appreciably slow the base exit velocity with increasing Al contents. InP, with its large intervalley separation and large drift velocities in high electric fields, would appear to be a good choice for the collector material. Unfortunately, the option of injecting electrons directly from the GaInAs base into the InP collector is simply a non-starter without the use of a transition layer of some sort as discussed above.

Staggered Lineup InP/GaAsSb/InP DHBTs

A staggered lineup BC design such as the one shown in Figure 2 is evidently free from the difficulties that plague GaInAs DHBTs. Strangely enough, this configuration received no theoretical attention until Niu and Cressler [5] investigated the effect of band offset distribution and base profile optimization in SiGe HBTs by means of numerical simulation. The authors found that the staggered lineup is the optimal configuration for the high current operation of NpN DHBTs. The other principal finding of [5] was that the application of "careful optimization" of compositional grading can yield excellent transistor performance (i.e. approaching that of the staggered configuration) for any arbitrary band alignment. Evidently, achieving careful optimization in a device simulator and in a growth chamber are two different endeavors. The InP/GaAsSb/InP system is a "natural" for DHBT fabrication: the GaAsSb alloy base provides an elegant solution to the collector current blocking problem because its band lineup with InP allows electrons to be injected from the GaAsSb conduction band edge into the InP conduction band at abrupt InP/GaAsSb heterojunctions. Essentially, the necessary degree of production control in epitaxy is reduced to that of controlling the composition, doping, and thickness of the ternary base region inserted between two binary InP layers. Consideration of the various factors above as well as the difficulty in decoupling the effects involved prompted our investigation of InP/GaAsSb/InP DHBTs. In the present section, the basic

advantages and some of the remaining challenges associated with the InP/GaAsSb system for DHBTs are outlined.

Fundamentals

MOCVD grown $\text{GaAs}_{0.51}\text{Sb}_{0.49}$ is lattice-matched to InP and is characterized by a room temperature energy gap of 0.72 eV and a conduction band offset $\Delta E_C = 0.15$ eV with respect to the conduction band of InP [6]. The narrow base energy gap implies that InP/GaAsSb/InP NpN DHBTs should feature low base-emitter turn-on voltages, and they do indeed turn-on at $V_{BE} = 0.4$ eV for a current density of 1 A/cm² [7]. The combination of low turn-on, low collector offset, and high breakdown voltages make InP/GaAsSb/InP DHBTs extremely attractive for low-voltage long talk-time wireless applications because the devices can easily be operated on a single 3.6 V Li ion or 1.2 V NiCd or NiMH battery.

The InP/GaAsSb/InP DHBTs turn-on voltages are slightly lower than those found in abrupt InP/GaInAs SHBTs (~0.45 V) and markedly lower than those of GaInP/GaAs HBTs (~1.05 V) or Si BJTs (~0.65 V), also at 1 A/cm². The GaAsSb base alloy is readily doped p-type with low-diffusivity C with either CCl_4 or CBr_4 ; we have used both sources with success at SFU [7]. One of the very important advantages of GaAsSb is that, in contrast to GaInAs, p-type material can be grown by MOCVD without any H-passivation effects as already pointed out by others [8, 9]. In addition, p-type Ohmic contacts on GaAsSb bases fabricated in

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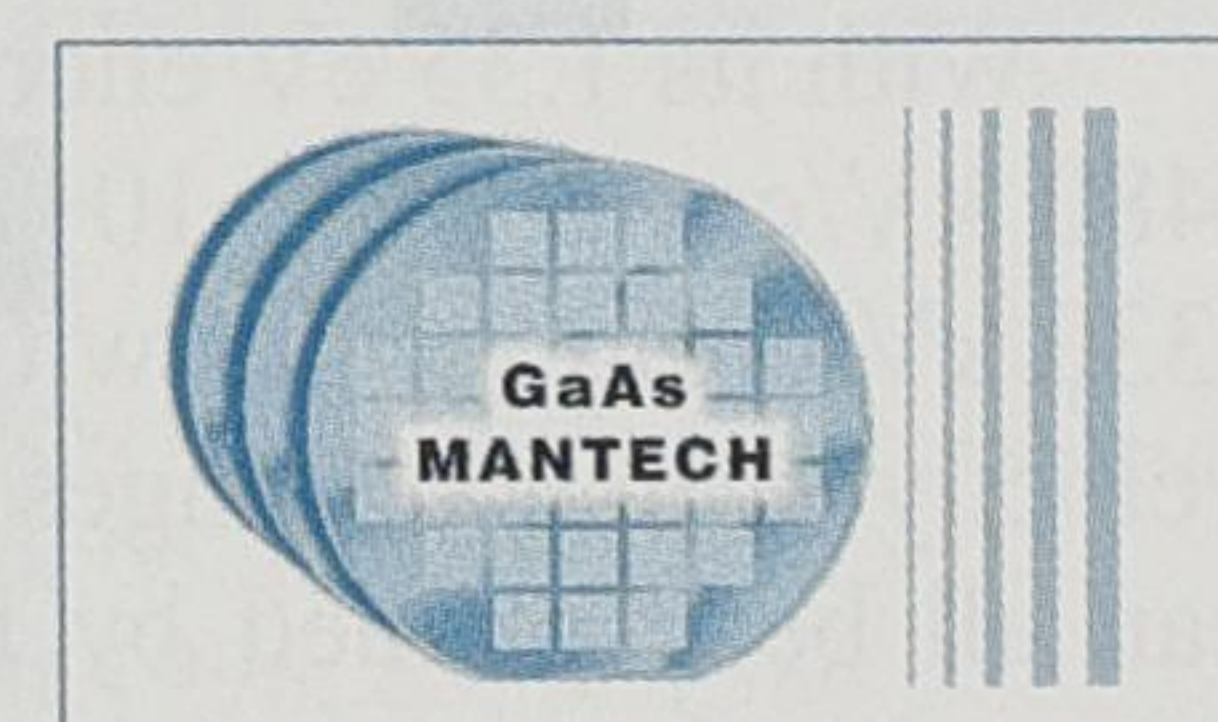
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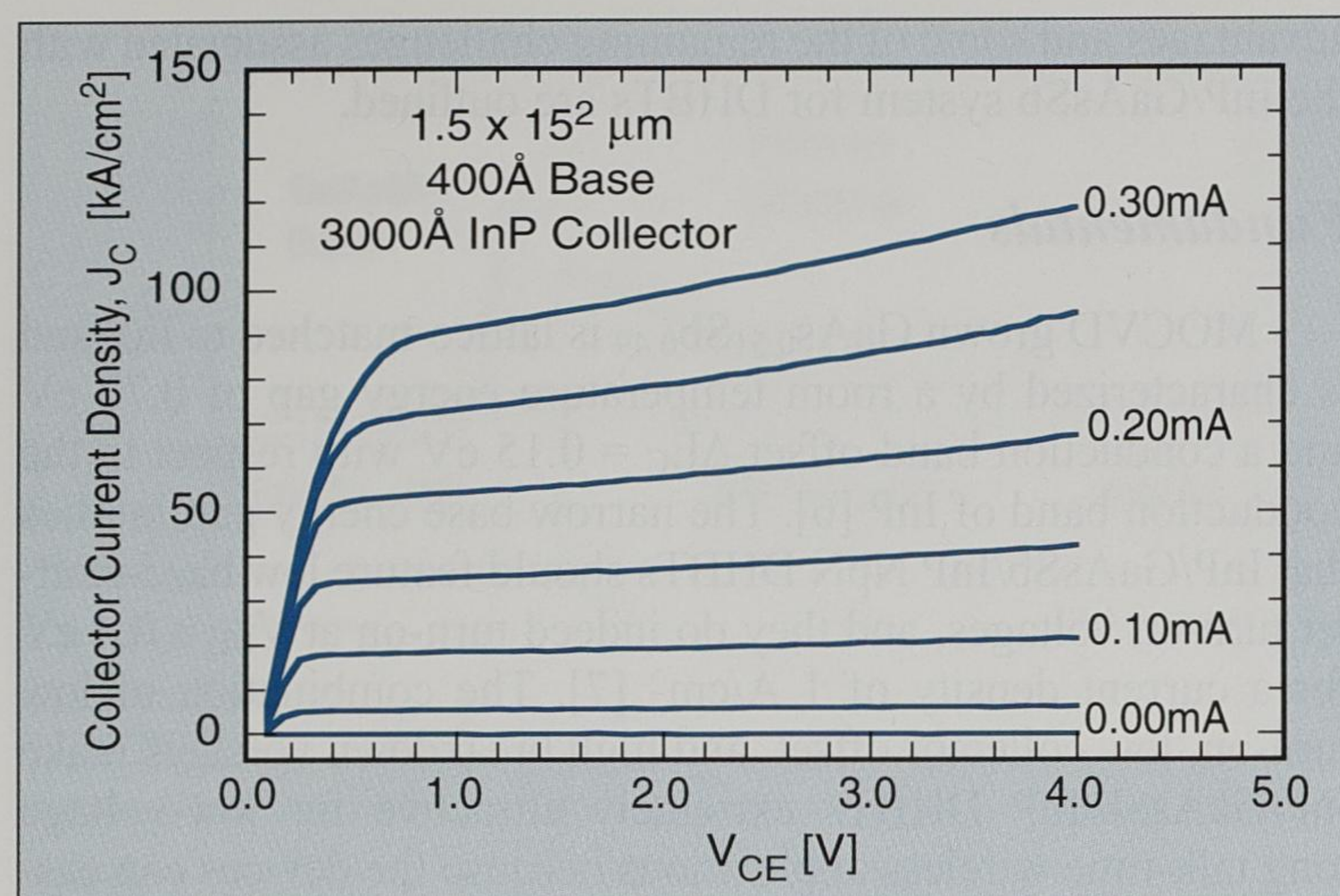


Figure 3. High-current common-emitter characteristics for a 3000 Å InP collector without any heatsinking.

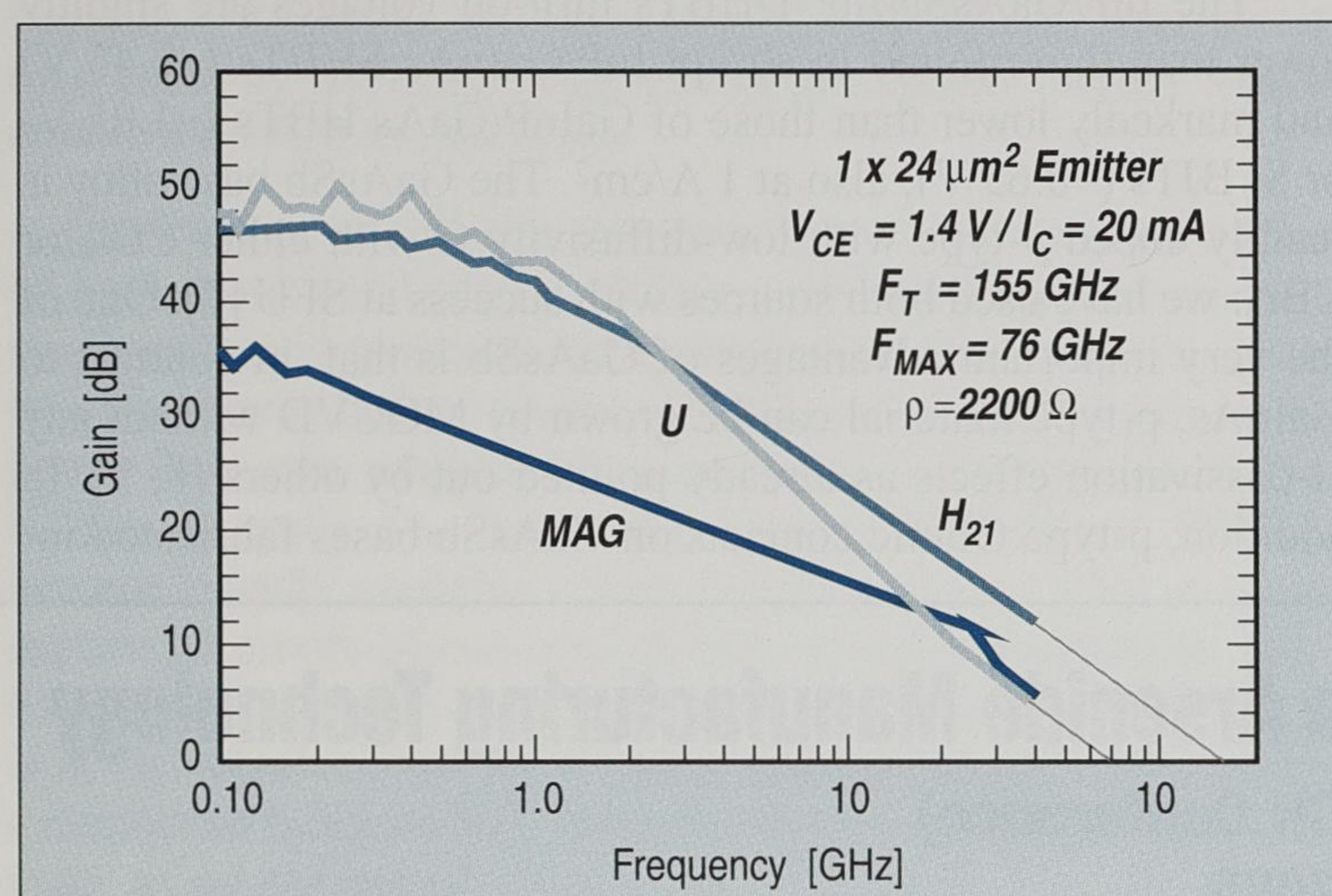


Figure 4. Microwave performance of a thin base transistor with a 2200 Ω/sq base sheet resistance.

our laboratory are far superior to those achieved on GaInAs, presumably because of the low Schottky barrier height on antimony-containing semiconductors. Whereas the Fermi level pins near the conduction band in GaInAs, antimonide surfaces generally show Fermi levels in the bottom half of the energy gap. Accordingly, our best base Ohmic contacts on GaAsSb feature a resistance of $1.1 \times 10^{-8} \Omega\text{cm}^2$ [10] with typical values of $10^{-7} \Omega\text{cm}^2$ on non-annealed contacts (whereas our best result for annealed contacts on Be-doped GaInAs bottomed out at $10^{-7} \Omega\text{cm}^2$, with typical values 3-5x higher). Very low contact resistances become a critical requirement in narrow emitter devices where a large fraction of the base resistance comes from the contact contribution.

With its 1.35 eV energy gap, InP exhibits a breakdown field (480 kV/cm at $\infty = 10^4$ /cm) that is superior to that of GaAs (330 kV/cm) together with higher carrier velocities and broader velocity overshoot ranges as a collector material. These features can all be explained by the reduced density of available final states for the scattering of hot electrons (including ionization events) because of the relatively large Γ -L intervalley separation in InP (0.6 eV). Interestingly, InP is second only to the narrow

gap semiconductors such as InSb, InAs, and GaInAs when it comes to peak carrier velocities. This is because the narrow energy gaps in these materials allow impact ionization processes to take place at energies lower than those required for intervalley transfer, and carriers thus remain in the high velocity Γ valley. A less favorable feature of InP is that electrons do not get accelerated very efficiently in this material. Fortunately, the staggered band lineup at the GaAsSb-InP heterojunction provides an initial kinetic energy of $\sim \Delta E_C$ focused toward the collector that would be expected to boost the initial velocity in the collector and reduce the collector signal delay. The latter is most sensitive to the carrier velocity nearest the BC junction, and turns out to be equal to half the collector transit time if a constant velocity is maintained while traversing the lightly-doped collector layer.

InP/GaAsSb/InP DHBTs also benefit from the high thermal conductivity of the InP collector in comparison to that of other alloys grown on InP - good heat conduction is maintained all the way to the BC junction where hot spots are likely to develop. This advantage may prove of some importance in reduced collector area devices because fewer heat flow paths are available in mesa-isolated InP HBTs than in implant-isolated GaAs HBT processes. The use of a thin GaInAs sub-collector (or even better, a simple n^+ InP sub-collector with a GaInAs etch stop) should lower junction temperatures and help reduce thermal non-uniformities and interactions in multi-finger power devices. These attributes will help InP/GaAsSb/InP DHBTs scale up in a more straightforward manner than conventional HBTs. Current InP/GaAsSb/InP DHBTs hold up well under high current operation as seen in Figure 3.

Remaining Challenges and Performance Prospects

The manufacturability advantages afforded by the InP/GaAsSb system for high-performance DHBTs do not come for free but rather at the cost of transport properties in the GaAsSb base layer. Generally, GaAsSb is characterized by a majority hole mobility of $\mu_p = 20 - 30 \text{ cm}^2/\text{Vs}$ for C-doped ($4 \times 10^{19} \text{ cm}^{-3}$) material grown in our MOCVD laboratory. These mobilities are lower than those found in GaInAs by a factor of two or so because of the dominance of alloy scattering for holes in Ga(As,Sb) alloys. From a device performance point of view, low hole mobilities call for attention to device geometry in order to achieve high maximum oscillation frequencies: narrow emitter stripes, self-aligned base contacts with small emitter undercuts, and reduced area BC junctions become necessary to achieve $f_{\text{max}} \geq f_T$ with high base sheet resistances. All the above requirements can be fulfilled to yield DHBTs with the performance of GaAs and the power consumption of GaInAs HBTs [10].

The minority electron mobility across the p-type GaAsSb base inferred from the collector saturation current values for several devices fabricated in our laboratory appears to be of the order of $700 \text{ cm}^2/\text{Vs}$ ($D_n = 18 \text{ cm}^2/\text{s}$). It is thus markedly lower than in p-type GaInAs ($\mu_n = 3000 \text{ cm}^2/\text{Vs}$, or $D_n \approx 78 \text{ cm}^2/\text{s}$). For purely diffusive transport, as one would expect from the band diagram of Figure 2, the base transit time scales as $W_B^2/2D_n$ and one can thus reproduce a given base transit time in GaAsSb by

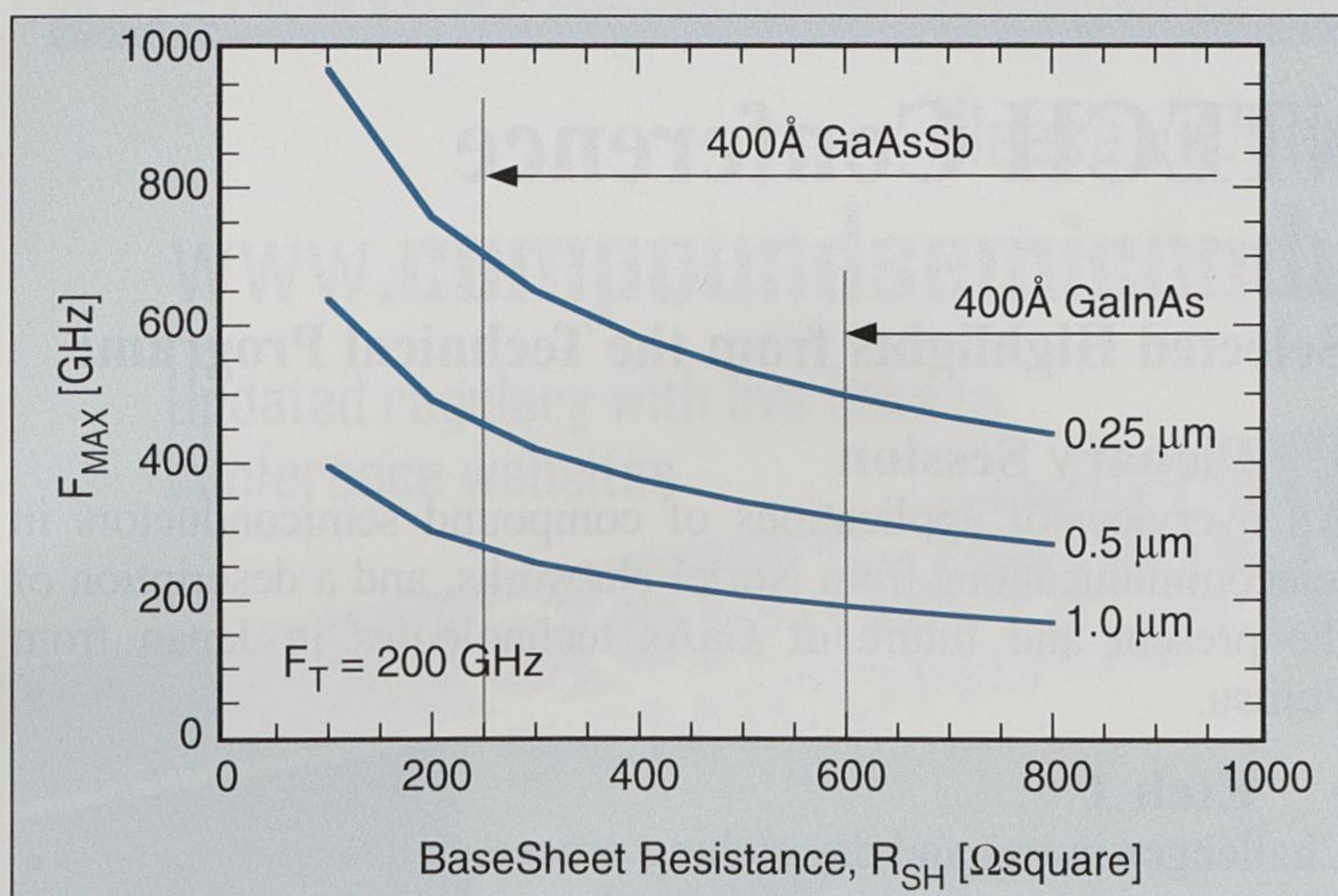


Figure 5. f_{MAX} dependence on the base sheet resistance for various design rules in conventional mesa DHBTs for $f_T = 200$ GHz. The very low R_{SH} achievable in heavily doped GaAsSb:C is expected to yield record f_{MAX} values for mesa transistors. Much lower sheet resistances are achievable with GaAsSb than with GaInAs.

halving the base thickness with respect to GaInAs. Along these lines, our group has successfully implemented narrow base DHBTs with $f_T > 150$ GHz with high current gains which can be traded off for f_{max} by increasing the base doping level (see Figure 4). It is worth emphasizing that the high current gains obtained with C-doped GaAsSb bases are significantly higher than what is generally achieved in non-graded C-doped GaInAs bases for the same Gummel number. This experimental observation is not completely accounted for, but it raises the interesting (but still unsubstantiated) possibility of lower Auger recombination rates in GaAsSb when compared to GaInAs. Low base transit times can also be achieved in thicker, lower resistance, base layers through the use of base energy gap grading techniques [11] combined with a type I $Al_{0.52}In_{0.48}As$ emitter. When all factors are considered, current gain cutoff frequencies of 200 GHz appear well within the reach of InP/GaAsSb/InP DHBTs: clearly, the most significant challenge does not lie with f_T but rather with f_{max} because of the low hole mobility in GaAsSb. One way around this problem would be the pursuit of extreme scaling for InP/GaAsSb/InP DHBTs, but can there be another solution?

Our MOCVD facility is currently tackling the base sheet resistance issue by taking advantage of the affinity of GaAsSb for C doping to achieve extremely high incorporation rates. New and still unpublished experiments to be described in detail elsewhere show that base sheet resistances as low as 250 $\Omega/sq.$ could be achieved in 400 Å thick base layers. This is in contrast to a minimum of approximately 600 $\Omega/sq.$ for a GaInAs base doped near the incorporation limit of $10^{20}/cm^3$. Such low base sheet resistance values would enable better f_{max}/f_T ratios to be achieved in InP/GaAsSb/InP DHBTs than with GaInAs-bases! The low GaAsSb sheet resistances are owed to the high efficiency of C-doping in GaAsSb and to a very weak dependence of hole mobility μ_p on the doping level over the concentration range $10^{19} - 10^{20} cm^{-3}$ for material grown in our laboratory (because of

the dominance of alloy scattering in GaAsSb). Higher doping concentrations directly contribute to a higher base conductivity. In contrast, higher acceptor concentrations are mitigated by a lower hole mobility in GaInAs in such a way that hole mobility is reduced by a factor of 2-3 in going from 10^{19} to $10^{20} cm^{-3}$. The low base sheet resistance achievable in heavily doped GaAsSb bases are expected to result in excellent device performance for conventional mesa type transistors. Figure 5 shows expected f_{max} values based on typical InP/GaAsSb/InP process parameters with an assumed $f_T = 200$ GHz for various emitter and base stripe geometries. For example, the 1 μm label stands for a 1 μm emitter stripe with self-aligned 1 μm base contacts defining a non-undercut 2000 Å InP collector layer which provides a breakdown voltage $BV_{CEO} = 6-8$ V). All structures can be implemented by optical lithography, and involve strictly conventional processing. Work is currently underway to incorporate these high conductivity GaAsSb base layers into functional high-speed DHBTs.

Conclusions

Despite a short development cycle, InP/GaAsSb/InP DHBTs are emerging as a promising technology with potential applications in both long talk-time wireless and high-speed fiber communication systems. Indeed, the very low device turn-on voltages (0.4 V) make the devices attractive alternatives to GaAs HBTs for 3G applications while the prospect for high cutoff frequencies and high breakdown voltages will likely result in applications in 40+ Gb/s fiber systems.

Acknowledgements

We would like to acknowledge the contributions of Nouredine Matine, Martin Dvorak, Selena Lam, and Oliver Pitts (whose collective contributions have enabled the writing of the present article), as well as our collaborators at Agilent Research Laboratories (Nick Moll and Denny Houg) and Nortel Networks (Tom MacElwee). This work was supported by the Natural Sciences and Engineering Research Council of Canada and through Agilent External Research Grants.

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Previewing the 2000 GaAs MANTECH Conference

This year's Gallium Arsenide Manufacturing Technology (GaAs MANTECH) conference takes place in Washington D.C. on May 1-4. As Conference Chairman Monte Drinkwine explains, the theme "Compound Semiconductor Manufacturing in the New Millenium" is especially appropriate:

"At the time of the first GaAs MANTECH conference [15 years ago], high volume manufacturing of compound semiconductor products was more a wish than a reality. Three-inch wafers were 'big' wafers; contact lithography was the mainstay; HFETS and HBTs were laboratory curiosities; 20-30 wafer starts per week were considered 'production'.

"Now, the advent of the Communication Revolution and the Information Highway has created real demands for high volumes of compound semiconductor products. Six-inch wafers are becoming the standard; stepper lithography is ubiquitous throughout the industry; ICs based on heterostructure devices are in very high volume production; and wafer-outs are above the 1000 per week mark level at some fabs.

"15 years ago, other technologies claimed that 'GaAs is the technology of the future – and always will be.' Well, maybe it took until the new millennium, but the future has arrived!"

Selected Highlights from the Technical Program:

• Plenary Session

An overview of applications of compound semiconductors in telecommunications from Nortel Networks, and a description of the present and future of GaAs technologies in Japan from Fujitsu.

• Etch 1

Challenges in wet and dry etching processes.

• Competing Technologies

TRW and NTT discuss InP, Infineon talks about SiGe BiCMOS, and Motorola discusses RF silicon LDMOS

• Higher Frequency Technologies

Lucent describes compound semiconductors in wireless communications, while Raytheon, Sanders and M/A-COM discuss mm-wave technologies and applications.

• Etch II

Papers describing enhanced manufacturability of through-wafer via process technology.

• Materials

Advancements in materials for high performance microwave devices.

• Characterization and Yield Enhancement

All aspects of test and characterization from incoming wafer qualification to reliability testing.

• HBTs

A series of papers focusing on HBT reliability issues, from Agilent, Hitachi, TRW, Kopin and Northrop Grumman.

• GaN and SiC

Booz-Allen & Hamilton gives a market perspective of transitioning new technologies, Motorola asks "Commercial wide bandgap RF power devices – fact or fiction?" and NRL and Nitres discuss GaN electronic devices.

• Metals

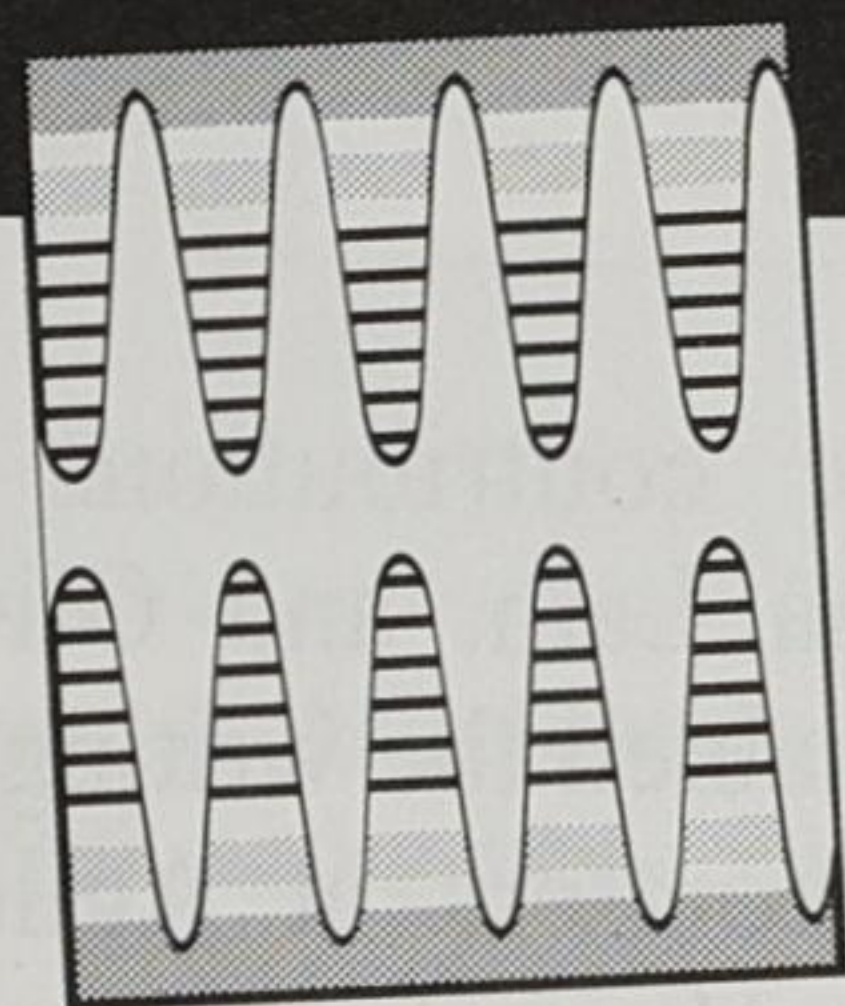
TriQuint, Oki and GaAsTEK discuss the importance of robust, high quality contacts and interconnects

• Metamorphic Devices

The status of metamorphic HEMTs is discussed by Raytheon, IMEC, the Fraunhofer Institute and TriQuint.

• Manufacturing

Anadigics and Motorola talk about production of 150 mm GaAs MESFETs, Filtronic will presents their approach to 150 mm PHEMT manufacturing, and TRW will describes high volume Ka-Band MMIC production.

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September 10-15

Other MANTECH Events:

Workshop – Monday

The Workshop has four topics, all with emphasis on practical applications:

- HBT Basics and Reliability: Phil Canfield of Conexant will focus on the fundamental aspects of HBT operation and how they relate to device reliability.
- Failure Mechanisms and Analysis Techniques: Sammy Kayali from the Jet Propulsion Laboratory will provide insight into both the fundamentals of device failure as well as methods for their detection and prevention.
- Epitaxy Basics: Tom Hierl of IQE plc will discuss both MBE and OMCVD fundamentals as well as the issues in both R&D and high volume production epitaxy.
- Applied Statistics in Manufacturing: SPC and DOE: Nick Burn of Nortel Networks will describe these essential tools for today's competitive manufacturing environment.

SEMI Standards Compound Semiconductor Committee Meeting – Wednesday Evening

A discussion of the development of internationally approved standards for wafer specifications (GaAs and InP dimensions/orientations and electrical properties), epitaxial layer specifications (which properties should be specified, how will they be verified), and non-destructive test methods.

Panel Session - Future Of Gate Lithography – Wednesday Afternoon

The successful transition of GaAs products into full high rate production (over 1,000 wafer starts per week) requires manufacturable processes that enable 0.15-0.10 μm T-gate structures. As an alternative to the traditional E-beam lithography approach, a new commercially available, high-resolution high-speed lithography system is required. Potential candidate technologies are high speed E-beam, X-ray, or Deep UV i-line phase shift systems, and these will all be represented at the panel discussion.

Interactive Forum – Wednesday p.m.

An opportunity for face-to-face discussion with the authors of all the regular-session papers, plus the Ugly Picture contest.

Rump Session – The Need for a GaAs Roadmap - Wednesday Evening

Although the total market for compound semiconductors is growing rapidly, GaAs is at a crossroads - significant advances in other compound semiconductors and in Si/SiGe has enabled these technologies to compete in applications that were previously dominated by GaAs. How should our industry respond? Representatives from the market analysis community, industry, and government share their views on market dynamics, industry needs, and GaAs roadmap planning.



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The GaAs Companies Come Roaring Back

MARIE MEYER

After taking a breather for a few months, shares in the GaAs companies in the Compound Semiconductor Portfolio have all resumed their upward march.

Boosted by record results for the December quarter, shares of **Alpha Industries** rose 131% in January and February. The company reported net income of \$6.3 million, up 86% compared with last year's quarter. Deliveries to Motorola, Alpha's largest customer, accounted for 34% of sales, driven by shipments for new digital handset platforms.

Tom Leonard, CEO and Vice Chairman of Alpha, stated, "Alpha's focus on the wireless marketplace, especially handsets, is driving our dynamic growth. Alpha's sales for wireless applications are up 75% over this time last year and up 20% over last quarter. Our Wireless Semiconductor Products division is now 66% of sales and growing." He also said that Alpha is expanding its capacity to keep up with demand.

Alpha shares also got a big boost on February 11 when the company announced its acquisition of Network Devices, Inc. (NDI) (see page 76). Analysts applauded the move as a way to kill two birds with one stone: it simultaneously opened up more production capacity and gave Alpha access to HBT technology. The latter factor is expected to allow the company to make inroads into the handset power amplifier market.

Shares in **Anadigics** rose an impressive 183% in the first two months of the year.

Commenting on the outlook for Anadigics, Hans Mosesmann of Prudential Securities said "Our research has identified a stronger than originally anticipated demand for Anadigics' products. The primary upside is being detect-

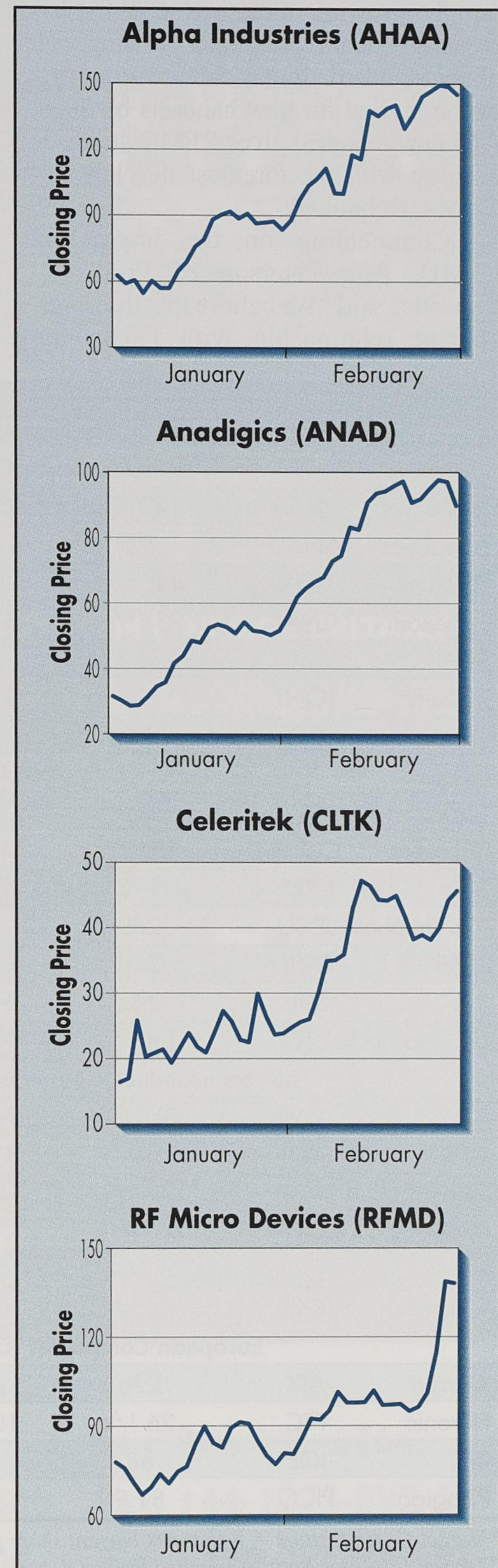
ed in the area of cellular handsets, but we also have detected some acceleration in the company's cable business." Anadigics was also boosted by their entry into the handset switch market. On February 15 the company announced it had orders for more than 10 million RF switches and had begun production shipments of a single supply 3-volt RF switch to be used in a 800 MHz Digital CDMA/AMPS dual-mode phone.

Anadigics had record sales of \$40.1 million for the December quarter, up 78% over the fourth quarter of the previous year. Net income was \$4.4 million compared with a loss in the year-ago quarter.

Celeritek shares jumped in early January when a stock-picking column on the MSN web site touted the company's high speed InP technology. Problem is, as Celeritek was quick to point out, it has an InGaP process, not an InP process. In fact, Celeritek took the unusual step of issuing a press release correcting the misstatements in the article.

Happily for them, the company got a more sustained rally a few weeks, on the basis of more substantiated news. CIBC World Markets upgraded their rating from "hold" to "buy", with a 12 month target of \$58 per share. Analyst Dale Pfau said that Celeritek's GaAs operations are continuing to improve on the basis of increasing shipments to Motorola for dual-band, dual-mode CDMA handsets. In addition, Pfau believes that the recent introduction of InGaP HBT GaAs power amplifier and fiber optic products should strengthen the company's product portfolio.

RF MicroDevice's shares were up 77%, and continue to climb. They went from looking a bit battered in late January to looking stellar in late February on the basis of their new alliance with Qualcomm. The two companies are going to cooperate on the development of



PAs for inclusion in Qualcomm's CDMA chipsets, and they have left open the possibility of future collaboration on other RFICs for CDMA.

As noted in our previous issue, CDMA is a particularly strong niche for GaAs, as the performance of the PA is critical. [See CS 6(1), p. 69.] And it is a rapidly growing niche, as CDMA has recently become the fast growing cell phone standard. It may capture up to 40% of the market for new handsets by 2004. And now this deal gives RFMD an inside position with the foremost developer of CDMA technology.

Commenting on the impact on RFMD, Pete Peterson of Prudential Securities said "We believe that the development relationship with Qualcomm

locks up the company's position in the CDMA market and we believe that this places the company at a premium position compared to its competitors." He expects that Qualcomm will represent 10% or more of RFMD's sales by early next year. RFMD's planned second fab now becomes critical. "As long as RFMD can support delivery to Qualcomm, we believe that RFMD will be the prime provider of PAs to Qualcomm," Peterson said.

Shipments are expected to begin in early summer, with sales ramping to higher level in the last quarter of the year.

TriQuint was also a stellar performer, with shares up nearly 100% since the first of the year. Their results for the

December quarter and the 1999 calendar year, released on February 10, were particularly good. Revenues for the quarter were a record \$49.4 million, a 60% increase over the comparable period of 1998. Net income was also a record at \$10.2 million, a 196% improvement over the year-ago period. Revenues for the full year were \$163.7 million, up 47% over 1998. TriQuint reported a record net income of \$25.0 million, compared to net income of \$6.2 million in 1998.

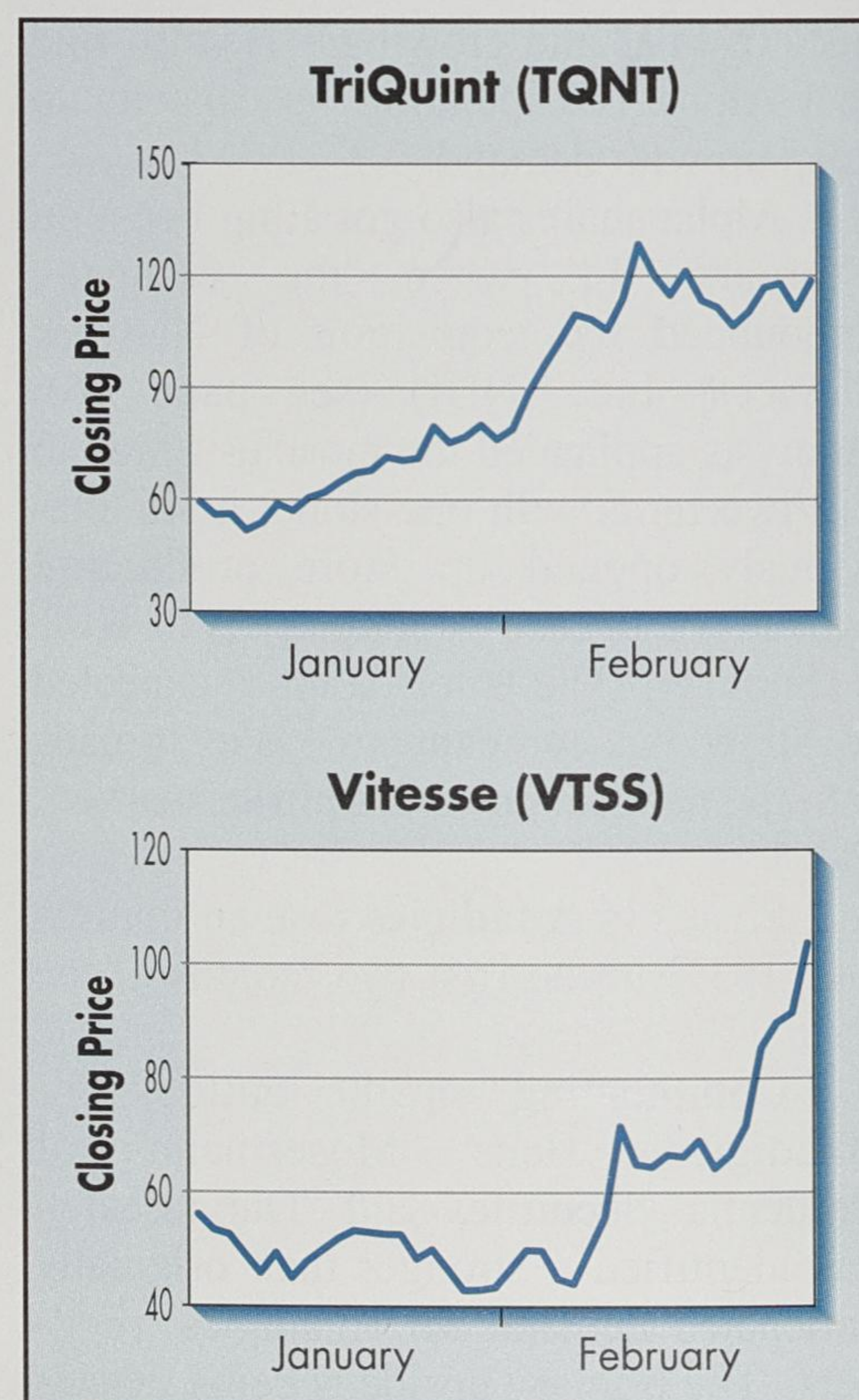
In commenting on the results, Steven J. Sharp, TriQuint's Chairman, President and CEO stated that, "1999 was our fifth consecutive year of increasing revenues and improved financial results for TriQuint. Our accomplishments were many and covered all elements of the business. These results reflect the strong demand in all of our product areas as well as the fast growth of our targeted communications market. Our manufacturing operations continue to perform extremely well resulting in further expansion of gross margins. In summary I am very proud of our employees accomplishments."

TriQuint's stock split two-for-one on February 22.

Company	Symbol	Last	52 Week Low-High	Market Cap*	P/E Ratio**
U.S. GaAs IC Companies					
Alpha Ind.	AHAA	143 ³ / ₈	13 ¹ / ₂ - 156 ¹ / ₂	2.851B	99.19
Anadigics	ANAD	94	8 ⁵ / ₈ - 104 ⁹ / ₁₆	2.562B	901.25
Celeritek	CLTK	46 ¹¹ / ₁₆	3 ⁵ / ₈ - 50	348.2M	N/A
Conexant	CNXT	93 ¹¹ / ₁₆	8 ¹ / ₂ - 132 ¹ / ₂	18.978B	313.56
RFMD	RFMD	175	19 - 164	13.967B	277.78
TriQuint	TQNT	117 ¹¹ / ₁₆	5 ¹ / ₈ - 135 ¹ / ₂	4.454B	171.83
Vitesse	VTSS	92 ⁷ / ₈	20 ³ / ₈ - 115 ¹¹ / ₁₆	14.620B	199.47
U.S. Opto Companies					
Agilent	A	108	39 ¹³ / ₁₆ - 115 ⁷ / ₁₆	48.816B	72.12
Coherent	COHR	98 ³ / ₁₆	11 ⁵ / ₈ - 107 ³ / ₈	2.437B	153.79
Cree	CREE	193	15 ¹ / ₈ - 201	6.367B	306.14
JDS Uniphase	JDSU	280	21 ³ / ₈ - 285 ¹¹ / ₁₆	99.714B	N/A
Ortel	ORTL	218	6 - 229 ¹ / ₈	2.714B	N/A
SDL	SDLI	442	26 ³ / ₁₆ - 472 ¹ / ₈	15.632B	570.95
Uniroyal Tech.	UTCI	54 ¹ / ₄	7 ¹ / ₄ - 72 ⁷ / ₈	671.2M	86.67
U.S. Semiconductor Materials & Equipment Companies					
ATMI	ATMI	51 ¹ / ₁₆	16 ⁷ / ₈ - 50 ⁷ / ₈	1.338B	135.14
AXT	AXTI	45 ³ / ₄	10 ⁷ / ₈ - 49 ⁹ / ₁₆	856.7M	92.78
Emcore	EMKR	145 ¹ / ₁₆	11 ¹ / ₄ - 173	2.242B	N/A
Kopin	KOPN	91 ⁵ / ₁₆	6 - 99 ³ / ₄	2.731B	3014.58
Tegal	TGAL	8 ⁹ / ₁₆	2 - 13 ¹ / ₂	92.3M	N/A
Trikon	TRKN	14 ¹ / ₂	1 - 17 ¹ / ₄	136.4M	N/A
European Companies (Currency Data in Euros)					
Aixtron	AIX	226	63 - 244 ¹ / ₂	3.45B	358
Filtronic	FTC	26 ¹ / ₄	10 ¹ / ₂ - 34 ⁵ / ₈	2.1B	72.56
IQE	IQE	68	12 ¹ / ₂ - 77	925M	>100
Picogiga	PICO	81.9	9.91 - 85	129M	124

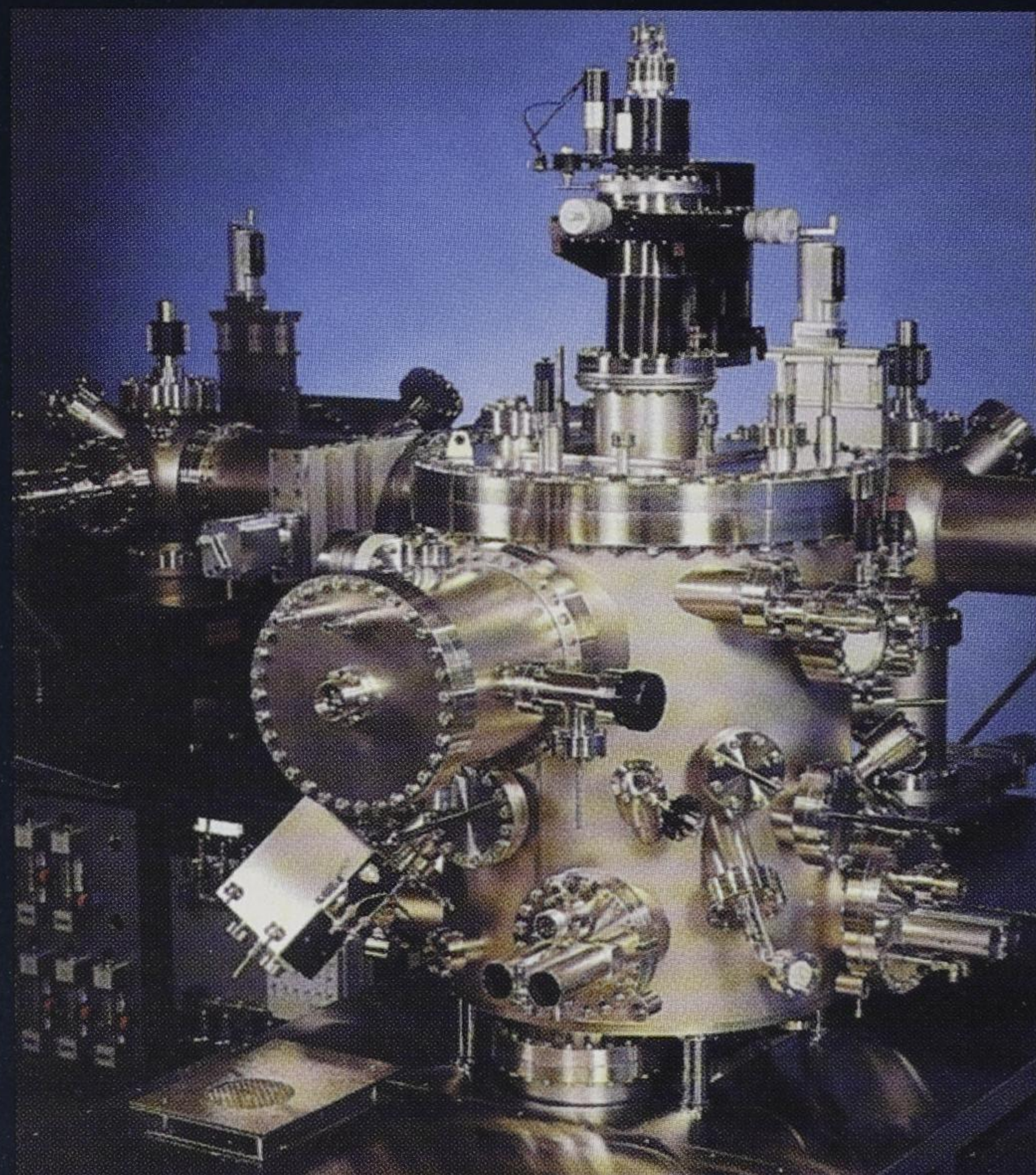
*Market Capitalization = # shares x current share price

** Price/Earnings Ratio = (income for last 4 quarters ÷ # shares) ÷ current share price

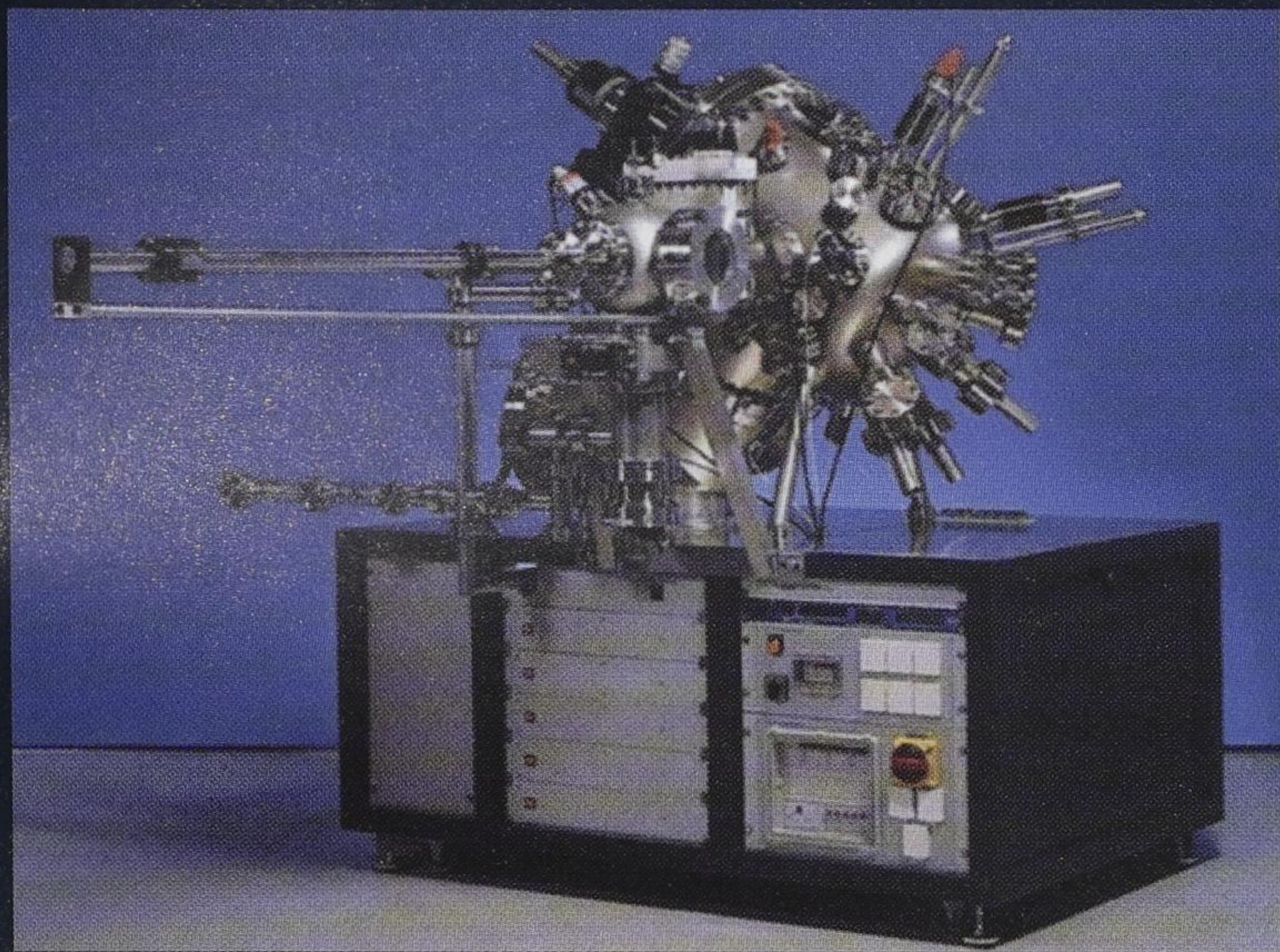


MBE TECHNOLOGY

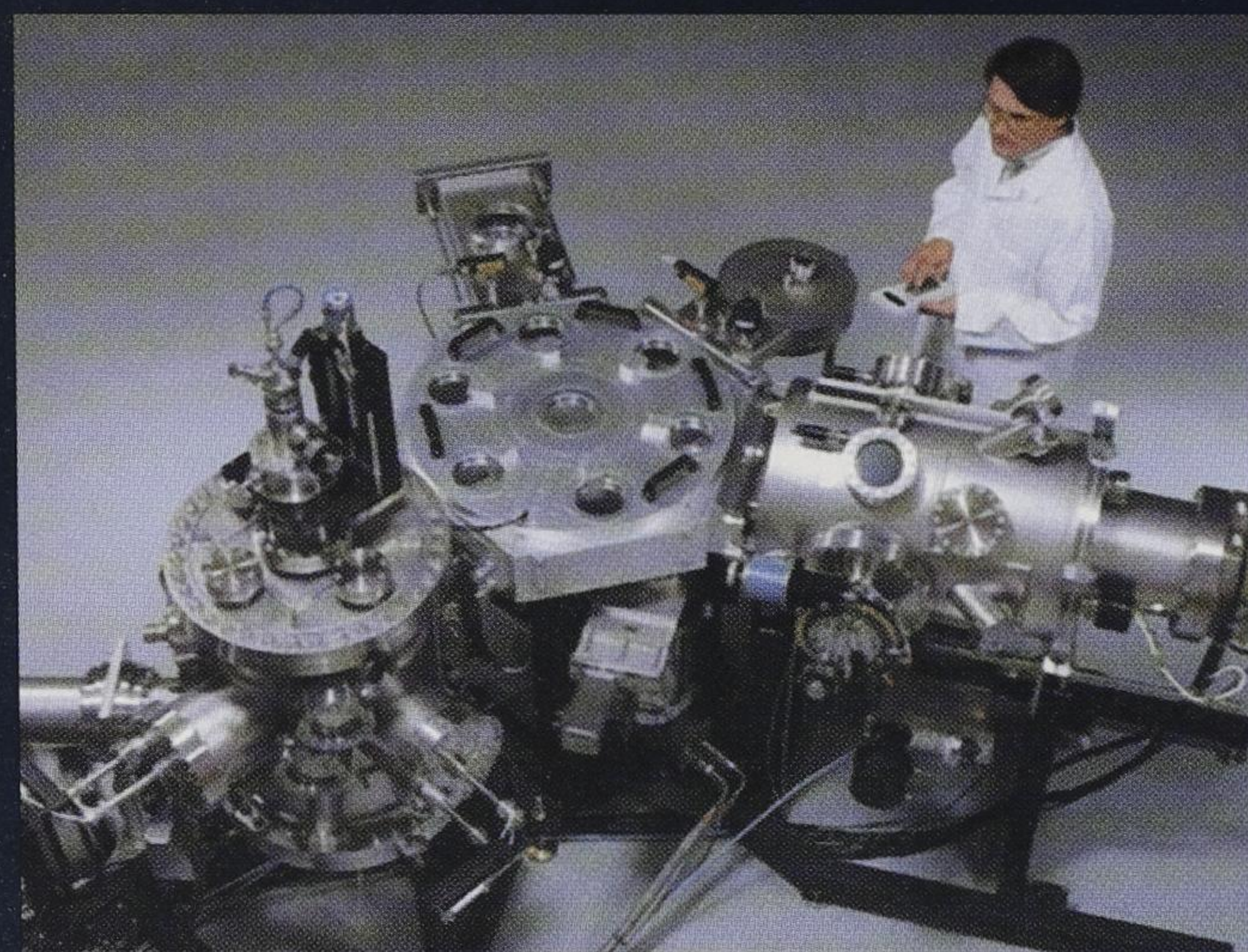
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