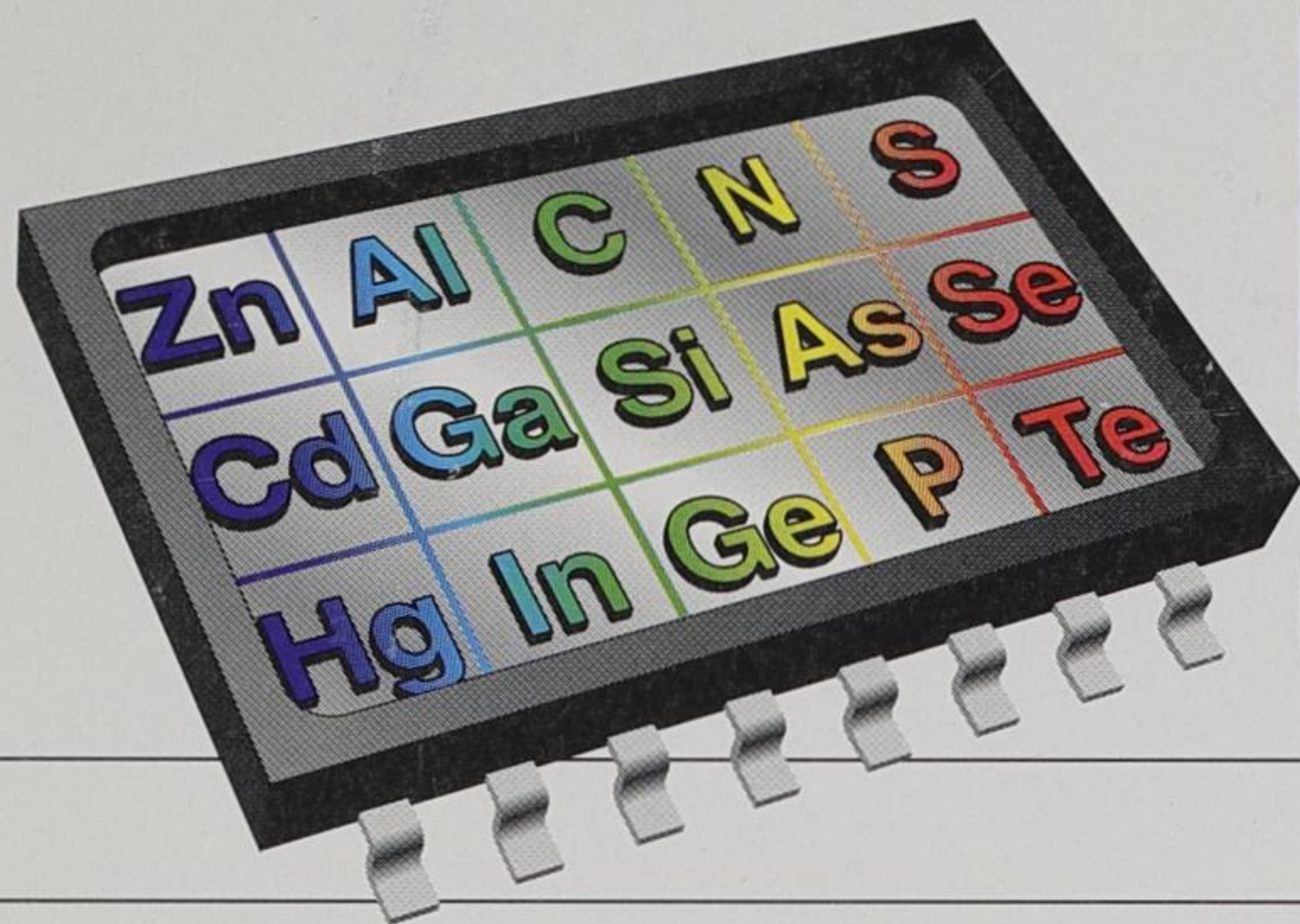




COMPOUND

SEMICONDUCTOR

July 2000

Volume 6 Number 5

New Technologies for Laser Diodes & VCSELs



5th Anniversary Issue



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<http://www.emcore.com>



Opportunities at Picogiga

Picogiga, the first commercial MBE supplier and the quality leader, is seeking a professional to staff an East Coast sales office. The successful candidate for this job should be mature with several years' experience in semiconductor materials and sales. He/she should have good computer and communication skills both written and verbal. This position will primarily handle sales and customer service with Picogiga customers in the eastern United States, but will interact with customers throughout the country.

Salary and benefits will be commensurate with the candidate's experience and training and will be competitive with industry standards. Picogiga is an equal opportunity employer.

Persons interested in this position should contact
Frank J. Bruni

Picogiga, Inc.

4773 Sonoma Hwy. #62
Santa Rosa, CA 95409
Tel. (707) 539-2508
Fax (707) 539-4808
E-mail fjbruni@aol.com

Engineering Career Opportunities

Spectrolab, Inc., A Hughes Electronics Company, the world's leading manufacturer of space and terrestrial photovoltaic systems, has career opportunities in its photonic devices division.

- **III-V Materials Growth Engineer** Epitaxial film deposition and characterization of III-V materials. BS required. Experience with MOVPE systems and materials characterization desirable.
- **III-V Solar Cell Project Engineer** Device design of III-V multijunction solar cells. PhD +1-2 yrs. or MS + 5 yrs. experience required. Must have strong understanding of physics of photovoltaic cells or detectors. Project management and proposal writing experience desirable.
- **Sensor Product Engineer** Design, fabricate and test III-V detectors, plus process documentation and proposal/report writing. BS required, MS preferred, plus 3-4 yrs. experience in III-V detectors required.
- **HBT Device Engineer** Develop III-V microelectronic devices (HBTs and HEMTs). Must be knowledgeable in electrical characterization and device processing. BS, MS, or PhD in EE, MatE, Physics, or related fields plus 1-2 yrs. experience required.
- **Thin-Film Process Engineer** for solar cell manufacturing. BS required and 1-4 yrs. experience preferred. Characterization of metals/dielectric films, SPC, DOE, and database management experience desirable.
- **Product Engineer** Project leader for manufacturing of solar cells. Good communication skills and customer interfacing is essential. BS required. MIL-SPEC and ISO-9001 experience desirable.

Please specify the **position category** to which you are responding.

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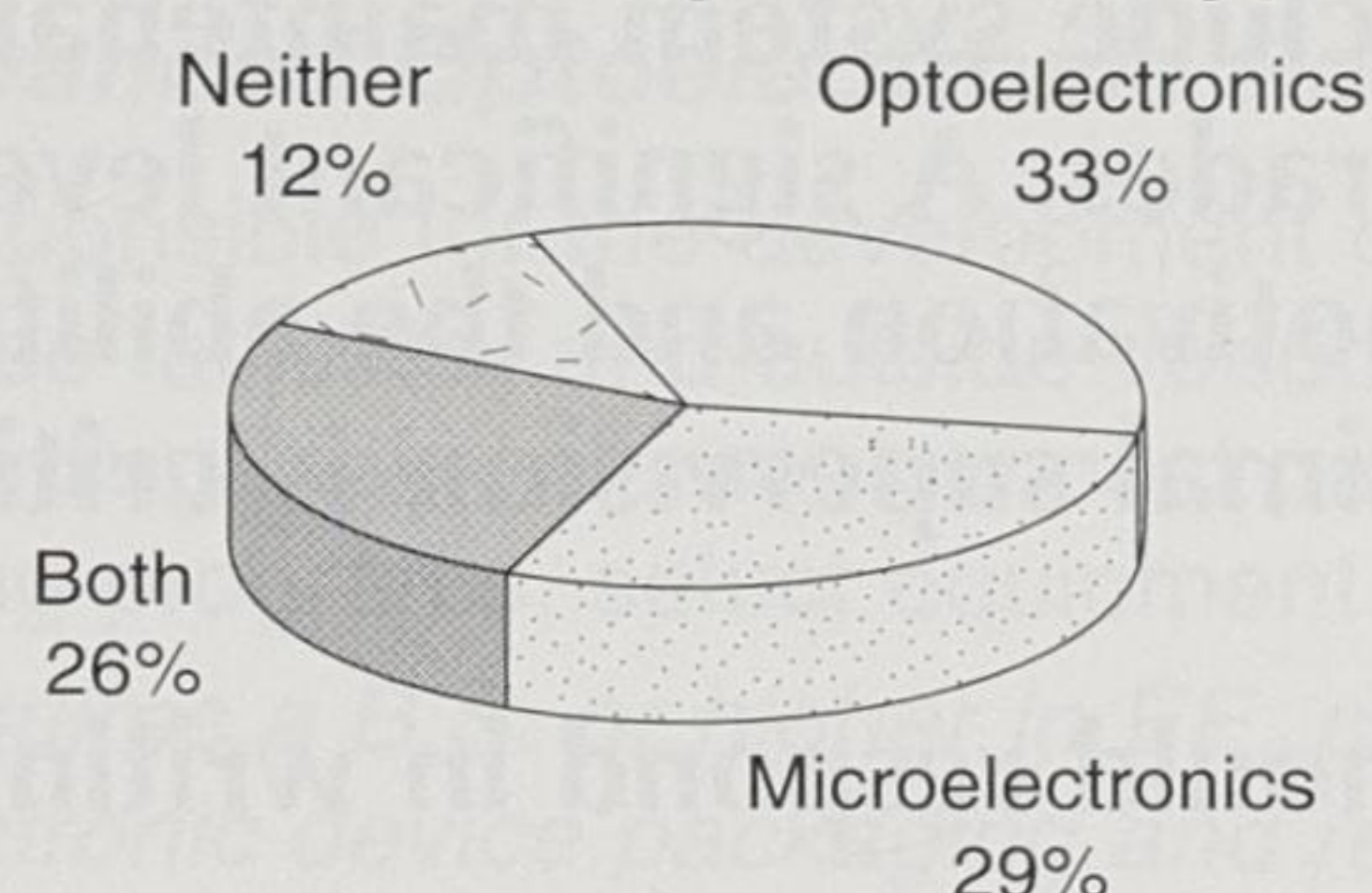
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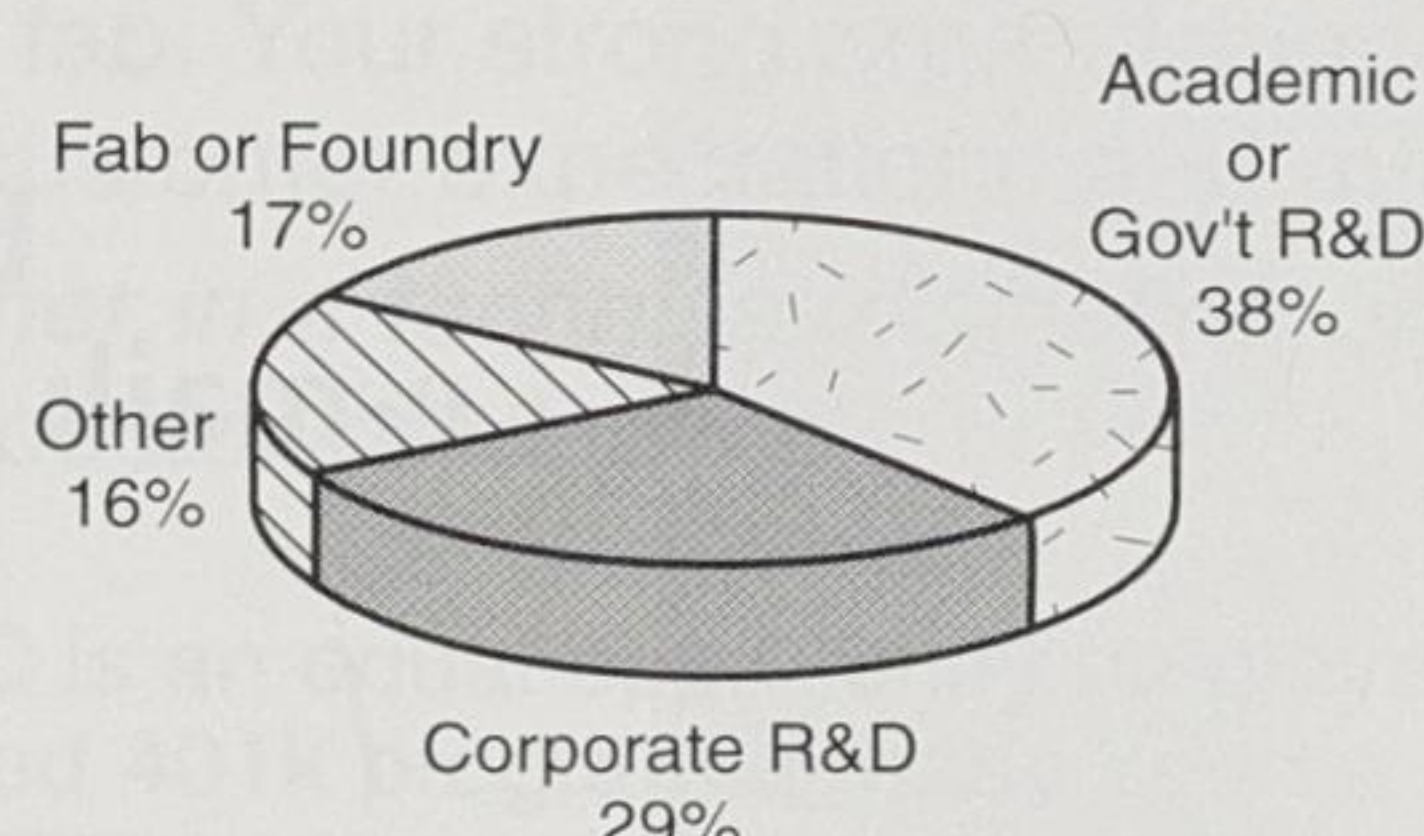
EMPLOYMENT ADS

Recruitment is one of the biggest issues in the compound semiconductor industry today. Therefore, we are reorganizing our Employment Section to make it more useful. Beginning with this issue, it now occupies a more prominent position in the magazine. And, for a limited time, we are also offering a free tie-in to the Employment section on our web site, CompoundSemiconductor.net (please note this is a dot-net, not a dot-com, address).

Compound Semiconductor Subscribers by Device Type



Compound Semiconductor Subscribers by Place of Employment



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vi for rates

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Purchase an Employment ad in Issue 6 (August) or Issue 7 (September/October) and receive a free space to run the same ad on our new web site for up to four months. The site address is www.compoundsemiconductor.net (please note this is a dot-net, not dot-com address)

We have subscribers at more than 850 compound semiconductor facilities around the world, including virtually every fab and R&D center in the compound semiconductor field. We deliver a very targeted audience that you won't be able to reach using any other publication.

If you are interested in advertising your compound semiconductor-related job openings in this space in our next issue, we need to hear from you by August 4. The deadline for the subsequent issue is September 15. Interested parties should contact:

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Managing Editor
COMPOUND SEMICONDUCTOR Magazine
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Compound Semiconductor Materials Characterization

Philips Analytical offers a wide range of analytical instruments for materials characterization in the thin films / semiconductors market. We are looking for an applications specialist to support our pre-sales and after-sales activities. Responsibilities include demonstrating our products to potential customers and providing training and support to existing customers. Candidates should have a BS, MS or PhD in a relevant scientific discipline. Previous experience of the use of X-ray diffraction or photoluminescence in a laboratory or industrial environment is an advantage. Effective written and verbal communication skills are essential. Some travel required.

If you or someone you know is interested in this vacancy, please forward a resume by email joanne.perloff@Philips.com, fax to (508) 647-1113, or mail to Philips Analytical, 12 Michigan Drive, Natick, MA 01760.

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PHILIPS

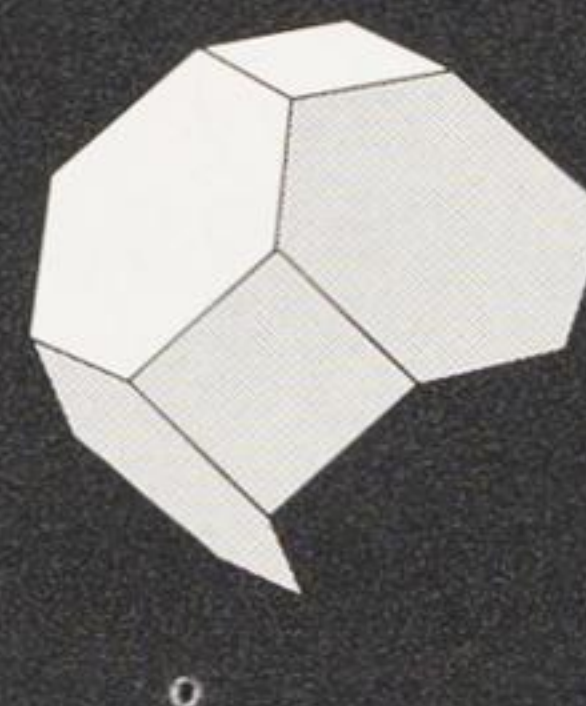
Employment Opportunities at NOVA CRYSTALS, INC.

- Principal Scientists
- Members of Technical Staff
- Process Engineers
- Manufacturing Engineers
- Foundry-Production Manager

Nova Crystals, Inc., (www.NovaCrystals.com), is a developer of high-performance opto-electronics components (VCSELs, LEDs, Receivers, etc.) for applications in fiber-optic data/telecommunications, solid-state lighting, and other applications. Nova's operations are based in San Jose CA. Founded in late-1998, Nova is backed by strategic and venture capital.

The company offers a competitive compensation package that includes a base salary, an equity signing bonus, year-end performance-based bonuses in cash and equity, a competitive 401(K) plan, and a comprehensive medical and dental plan.

Interested candidates should send cover letter and CV to:



Yolanda Deason
Nova Crystals, Inc.
174 Component Drive
San Jose, CA 95131
Email: deason@novacrystals.com
FAX: 408-434-6330

MBE Field Service Engineer (USA)

VG Semicon, the world's largest supplier of production Molecular Beam Epitaxy systems, is seeking engineers to enhance its US Field Service team and to meet the challenges of the industry's rapid expansion. Applicants will need a solid background in electronics, mechanical engineering and computing. Experience working with Ultra High Vacuum systems would be an advantage. After training in the US and UK, duties will include system maintenance, customer training and installation of upgrades. A significant level of travel is required. Self motivation and the ability to work with minimal supervision is critical.

Interested parties should respond in writing to



VG Semicon
The MBE Company

VG Semicon
100 Cummings Center
Suite 451G
Beverly MA 01915
e-mail: sales@vgmbe.com



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■ ***VCSEL Device Development***

Senior position responsible for next generation VCSEL product development from device design to manufacturing implementation. You will work with our MOCVD engineers, process engineers, and customers to meet the company's aggressive technical and business objectives in the rapidly growing ≥ 10 Gbps and 1.3 micron data communications markets.

Requires a Ph.D. or equivalent in EE, physics, or related field and two or more years hands-on experience with GaAs or InP-based VCSEL devices.

■ ***Compound Semiconductor Device Development***

Senior position responsible for developing high-speed optoelectronic and electronic devices (GaAs and InGaAs detectors, laser diodes, high-speed LEDs, GaAs and InP RF devices) for advanced optical communications applications. Working with our MOCVD and process teams, you will lead all aspects of development, from device conception and epitaxial design through process development and product implementation.

Requires an M.S. or Ph.D. in EE, physics, or related field and five or more years experience in III-V device modeling and design.

■ ***Compound Semiconductor Process Engineering***

Responsible for developing and improving all aspects of III-V device process technology and yield, including mask design, photolithography, metallization, dielectric deposition, and wet/dry processing for a range of high speed and optoelectronic devices; this is a key technical leadership position.

Requires a B.S. or higher in EE, ChE, physics, or related field and three or more years experience in III-V materials and device processing.

■ ***Semiconductor Test and Reliability Engineering***

Responsible for all aspects of implementing and running a III-V device characterization and reliability facility, including GHz range and automated on-wafer and packaged device testing equipment. You will select equipment, design test procedures and fixtures, develop reliability and burn-in protocols, work closely with customers, and manage department operations.

Requires a B.S. or higher in EE, physics, or related field and two or more years experience with high-speed III-V optoelectronic devices. Familiarity with Bellcore standards is a plus

■ ***Advanced Optoelectronic Packaging Engineering***

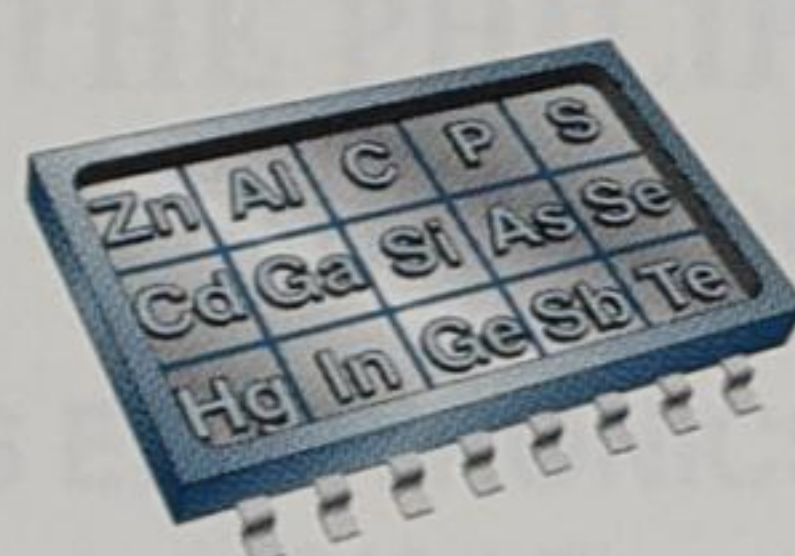
Responsible for the development of advanced ≥ 10 GHz optoelectronics device packaging. Working with customers, in-house facilities, and outside vendors, you will develop and implement packaging for current and next generation devices, including high-volume, low cost packaging, and hermetic, hybrid, flip-chip, and novel configurations. You will manage packaging programs, select equipment for internal capacity, and qualify on-and off-shore vendors to ensure product reliability.

Requires a B.S. or higher in EE, physics, or related field and three or more years experience with high-speed III-V optoelectronic device packaging and reliability. Familiarity with Bellcore standards is a plus.

■ ***Semiconductor Production Manager***

Responsible for production control, materials, and scheduling to maintain costs and throughput in a high-growth, multi-product epitaxy and device fab. Your strong organizational skills and MRP/ MES system implementation experience will enable the company to meet customer expectations and attain its aggressive growth targets.

Requires a B.S. or higher in a technical discipline or business/materials management and three or more years relevant experience in semiconductor production.



COMPOUND SEMICONDUCTOR

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If you have excellent communication skills and are knowledgeable about the compound semiconductor industry, we want to hear from you! Part-time and work from home applications will be considered.

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The Assistant Editor will be responsible for writing feature articles and editing news items for print and Internet publication. Applicants should have excellent writing skills, knowledge of compound semiconductor technology, and an interest in both scientific and commercial developments.

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Contact:

Prof. Gary W. Wicks
The Institute of Optics
University of Rochester
Rochester, NY 14627
wicks@optics.rochester.edu

KEY ACCOUNTS / PROJECT MANAGERS

VG Semicon is the world's leading manufacturer of Molecular Beam Epitaxy (MBE) equipment, which is used in the fabrication of electronic devices for the telecommunications industry. As part of our growth plans, we are looking for experienced individuals to fill the following senior positions:

KEY ACCOUNTS MANAGER

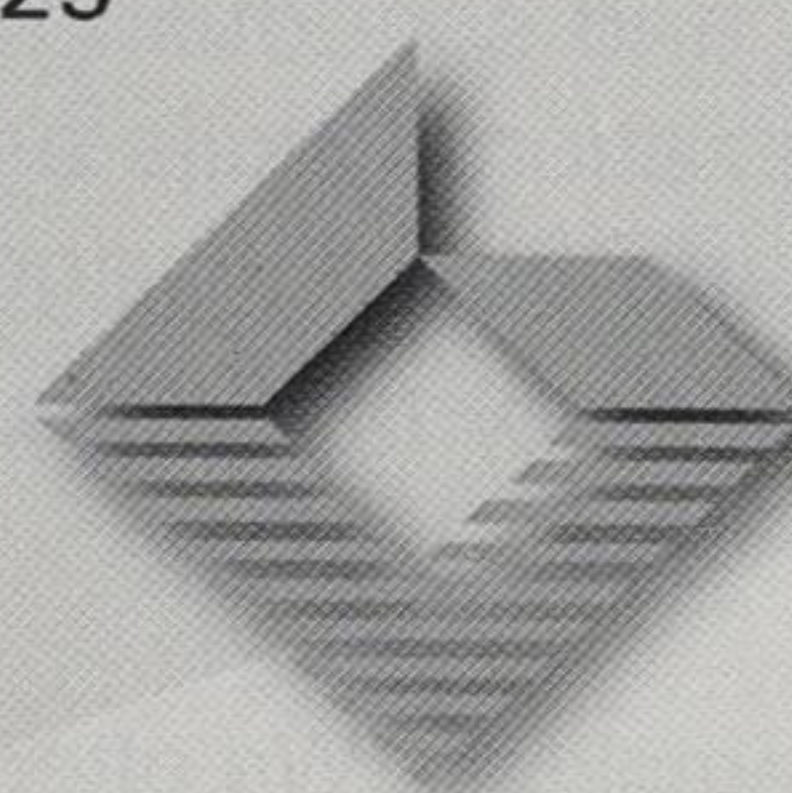
The Key Accounts Manager will be responsible for managing all aspects of our business interaction with a defined number of major international customers. The main responsibility is to fully understand customers' requirements and to effectively define and manage practical solutions. Applicants should have excellent communication skills and be able to demonstrate a successful track record in both the technical and commercial aspects of the telecommunications and/or semiconductor industry.

SENIOR PROJECT MANAGER

The Senior Project Manager will define and manage major electro-mechanical and/or software development projects using a combination of internal and external resources. Applicants should be able to demonstrate excellent communication skills combined with a strong background in mechanical, electronic and software engineering.

These positions will be at a senior management level within the company. In addition to the skills noted above successful applicants will also require general skills and knowledge in the science and technology, commercial management, sales and marketing, and customer support aspects of the semiconductor equipment business. Successful candidates will probably have a PhD in a relevant scientific discipline. Direct knowledge of the MBE process will be a significant advantage. These positions will be based in the United Kingdom. We offer a highly competitive compensation package, including 25 vacation days per year.

Please send your resume to:
VG Semicon
100 Cummings Center, Suite 451G
Beverly MA 01915
e-mail: sales@vgmbe.com



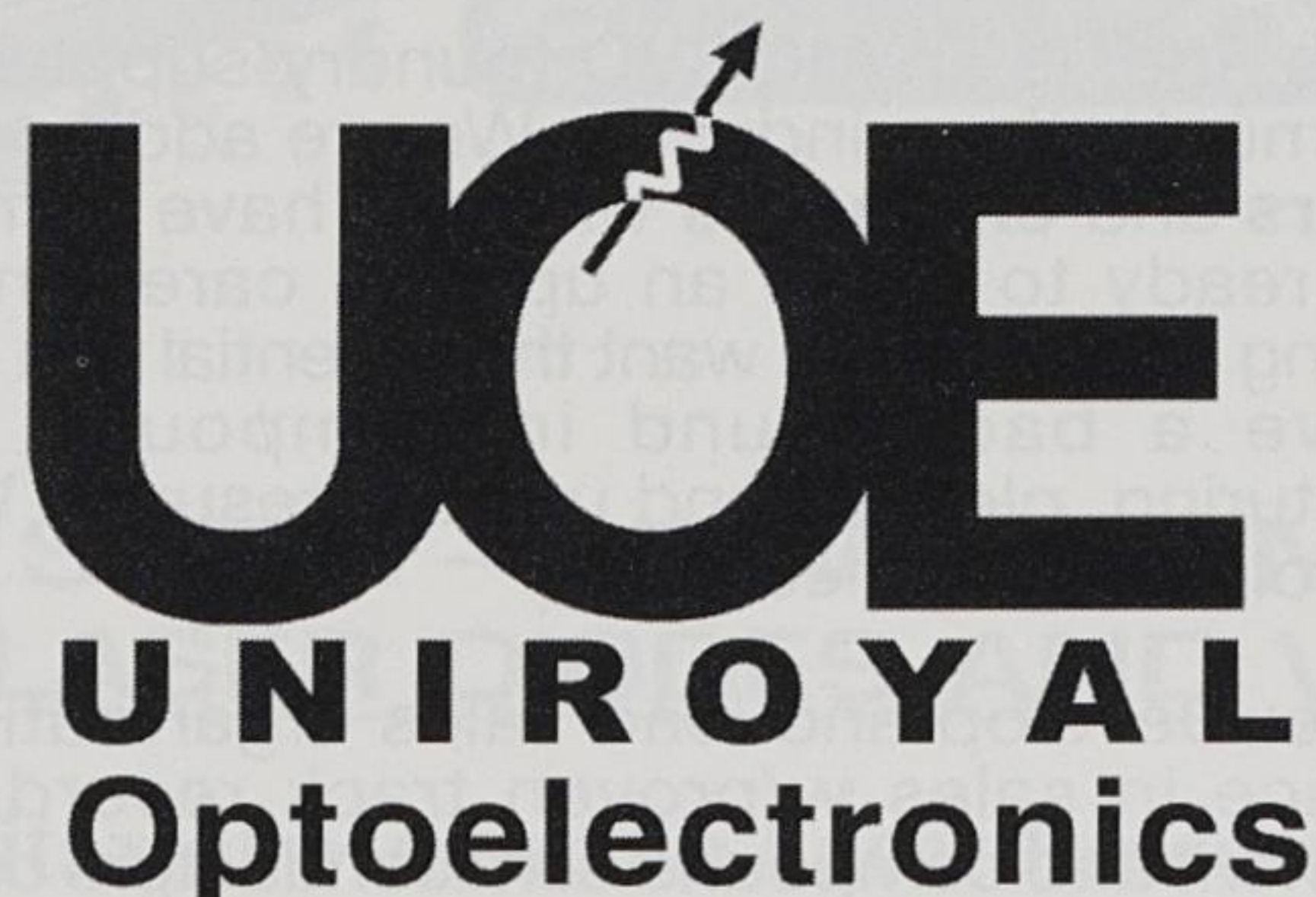
VG Semicon

The MBE Company

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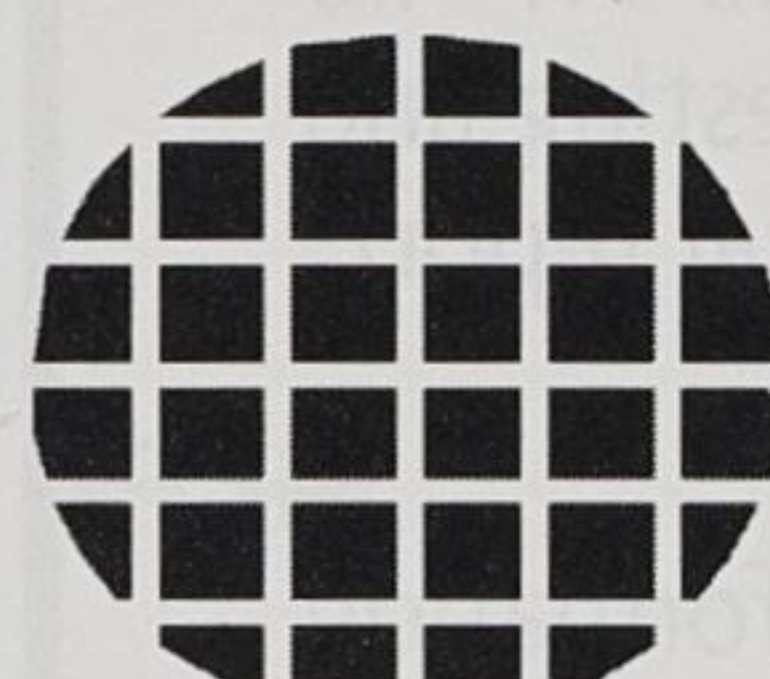
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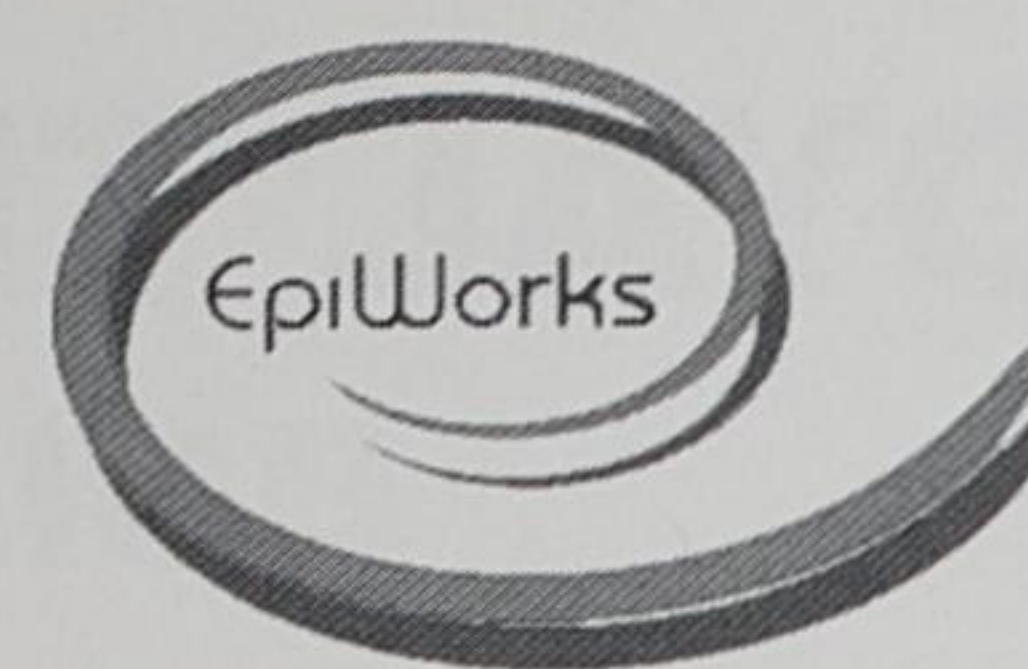
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MS in Computer Science, Computer Information Systems, or related field required. Minimum of three years' software development using C++ in a networked environment required. Experience must include development of object-oriented client/server software using C++ on a Windows NT platform; design of FT/IR spectroscopic applications; and the design of real-time control software for robotics.

Send two copies of your resume/letter of qualification to: **Case#19983846, P.O. Box 8968, Boston, MA 02114.**

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EpiWorks offers its employees **significant** stock option compensation and a competitive salary/benefits including relocation. Fax resumes to EpiWorks, Inc. 217-244-7757

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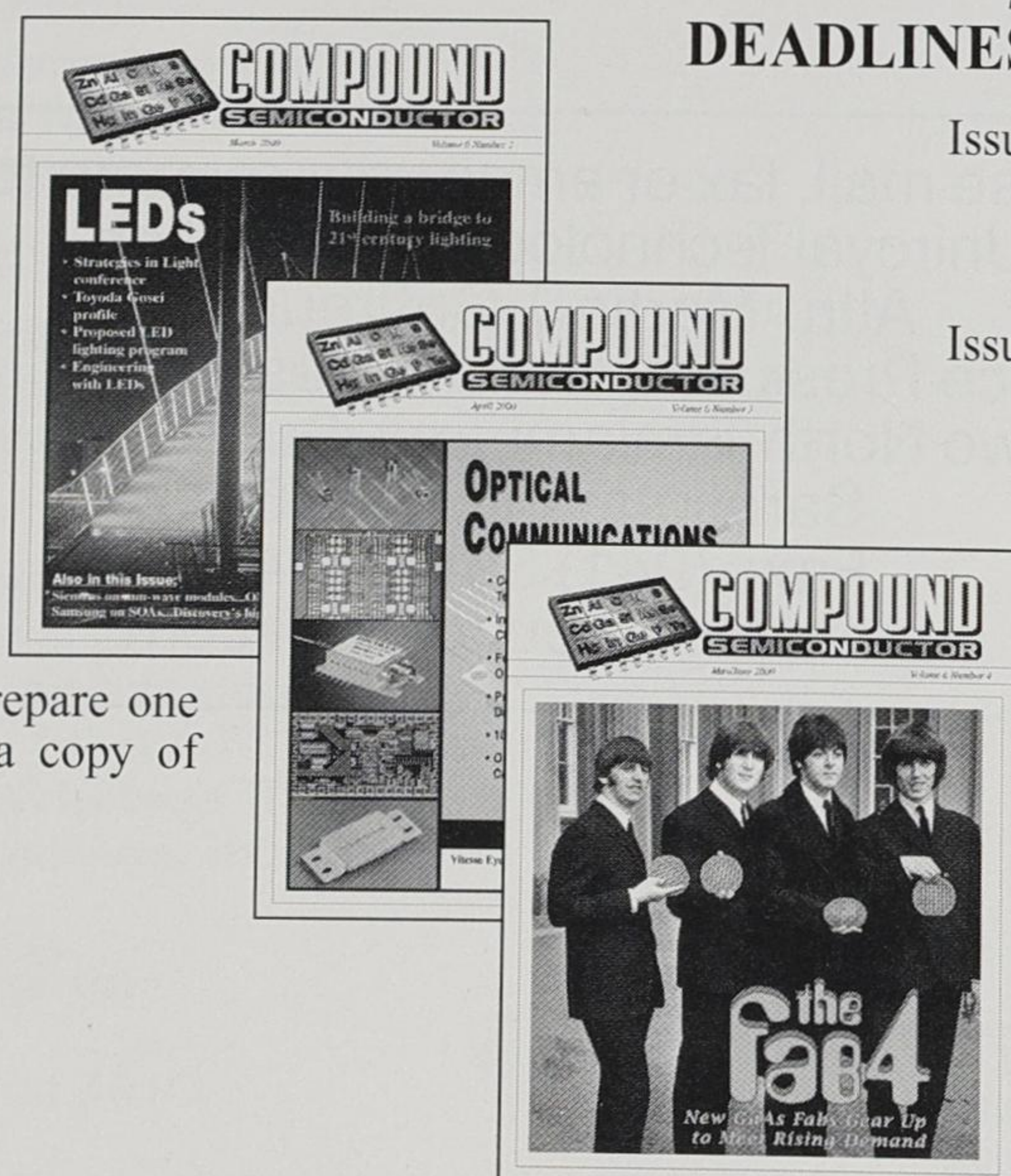
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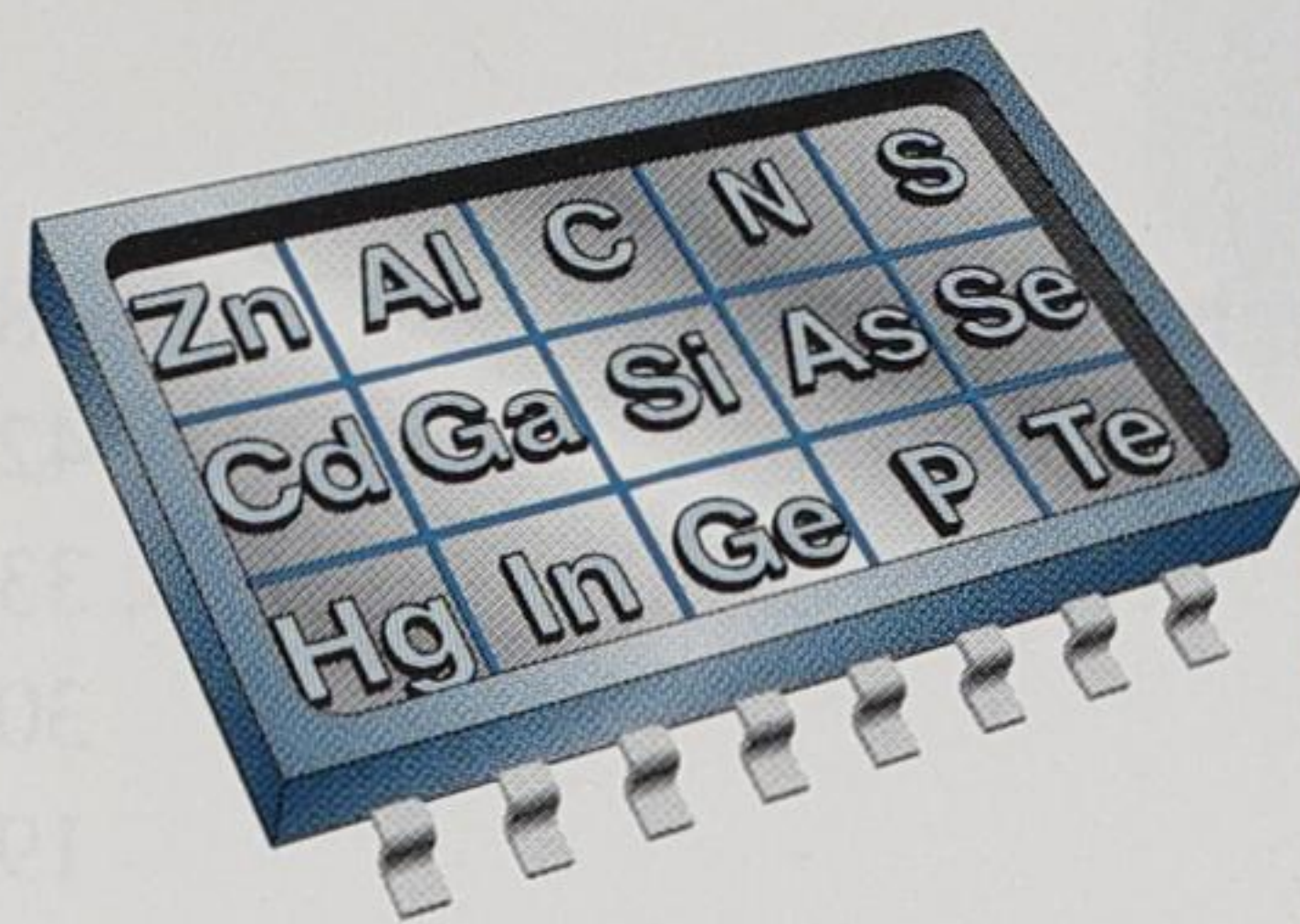
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DEADLINES

Issue 6 (August)	Orders due August 4 Materials due August 11 Publication Date: August 25
Issue 7 (Sept./Oct.)	Orders due September 15 Materials due September 22 Publication Date: October 6

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71 InGaAsN: Extending GaAs-based Lasers to Fiber Optic Wavelengths

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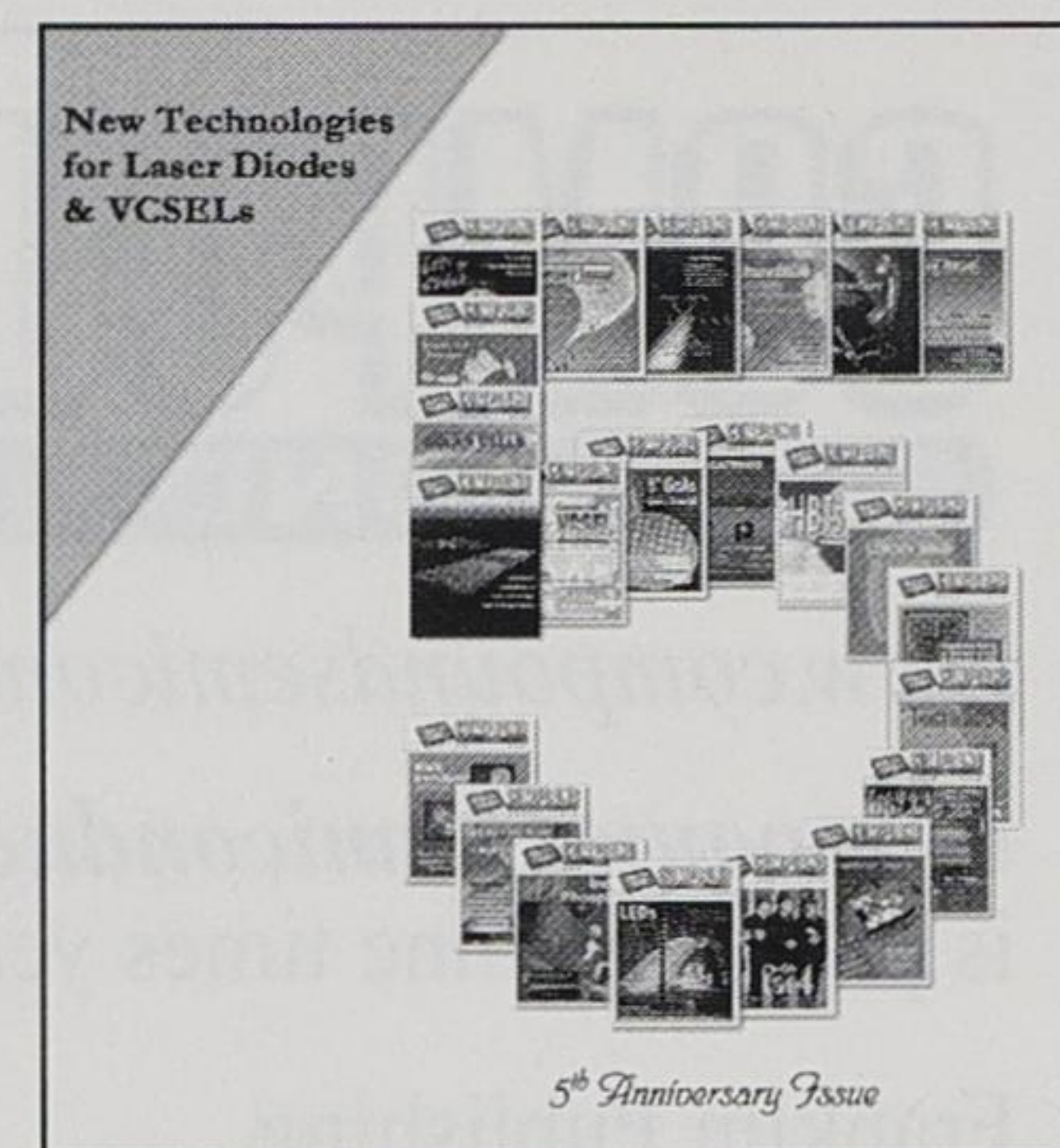
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While we doubt that this issue's cover will be nearly as popular as our last one, it illustrates the fact that we have reached the 5th anniversary of our publishing debut. A brief historical retrospective begins on page 32.

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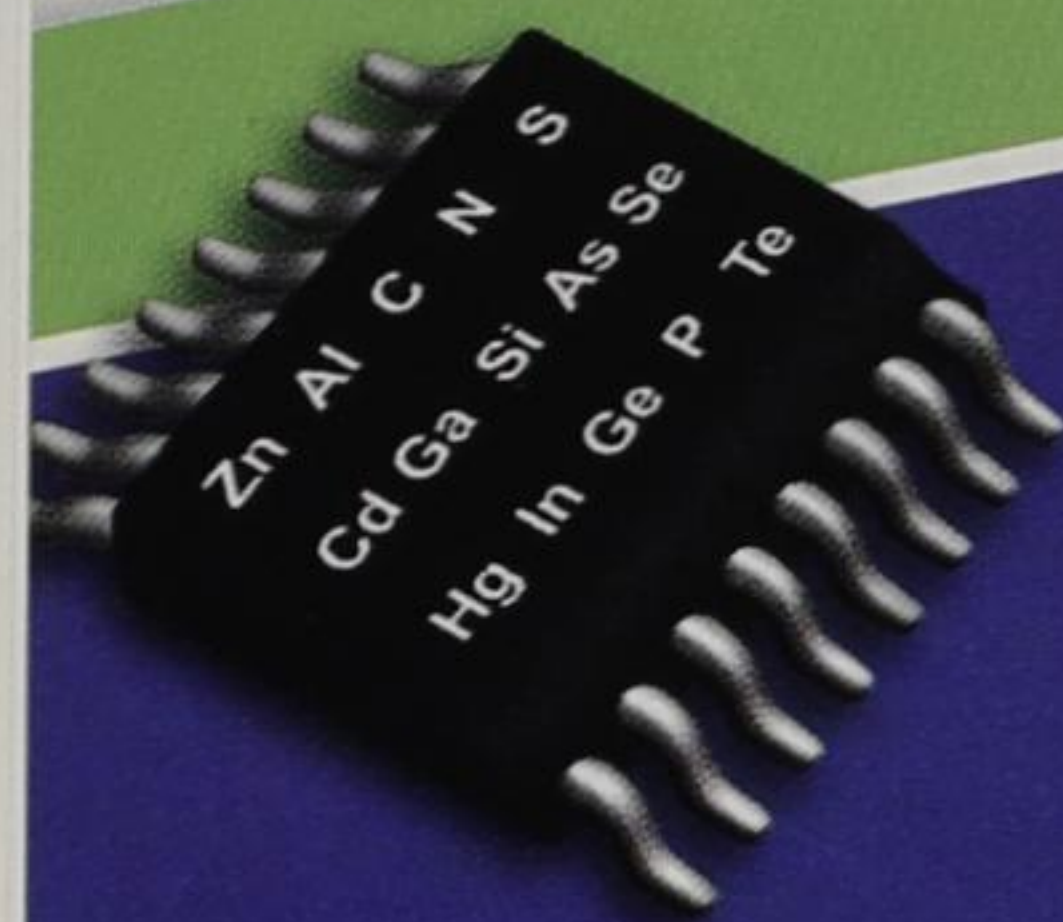
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Capacity Expansion in the GaAs Industry Continues

The cover story in our last issue described how a number of companies were increasing their capacity for making GaAs ICs. One new GaAs fab was just recently completed (Filtronic's new 6" fab in England), and four new GaAs fabs are under construction (WIN Semiconductors and Advanced Wireless Semiconductor Company are both building new GaAs fabs in Taiwan; Nortel and RF Micro Devices are each adding to their existing GaAs capacity by building new fabs in North America). There are also several companies that are converting to 6" or adding new processing lines at their existing facilities. The list includes Alpha, Anadigics, and Conexant. Now comes more news in a similar vein from TriQuint, Motorola, M/A-COM and Marconi.

TriQuint Purchases New Facility, Introduces HBTs

TriQuint Semiconductor will purchase Micron Technology's former DRAM fabrication facility in Richardson, Texas. The move will provide a home for TriQuint's Texas operation, which currently shares leased space with Raytheon at the Dallas campus of Texas Instruments.

"The new facility has plenty of room to house all of our present TriQuint Texas Operations, as well as space for a very high volume six-inch wafer manufacturing operation," says Steve Sharp, TriQuint's CEO. "By making this move now, TriQuint can provide six-inch manufacturing of all high volume processes in both Oregon and Texas in 2001." TriQuint recently completed an expansion of its Hillsboro, Oregon GaAs fab and is poised to convert that facility to 6-inch operation.

Sharp feels that customers need a supplier with high capacity in more than one location and interchangeability of plants to ensure a continuous source of supply. "The purchase increases TriQuint's total revenue capacity to well over \$1,000 million upon full equipment installation," he adds.

In related news, TriQuint recently released its first InGaP-based HBT products. TriQuint intends to move its HBT process to the Richardson site, and also to its Hillsboro facility, where it has recently bought a further 17 acres ready for future expansions.

M/A-COM to Share Sanders' 6-Inch GaAs Facility

Sanders, a Lockheed Martin Company, and M/A-COM, Inc., a unit of Tyco International, have struck a deal that will allow M/A-COM to use Sanders' GaAs fab in Nashua, NH to manufacture MMICs on 6-inch GaAs wafers for wireless telecommunications applications. Sanders is currently in the process of converting its Microelectronics Center (MEC) to 6-inch operation,

and will continue to use the facility to manufacture MMICs for aerospace and defense markets.

"This significant fab expansion enables M/A-COM to introduce our next generation wafer processes faster and more cost effectively," says M/A-COM's president Rick Hess. "It also provides greatly needed additional capacity to meet the accelerating market demand for our GaAs wafers and products for communications applications." Hess added that the move will assure M/A-COM's customers that the capacity they need for 2001 is available.

M/A-COM expects to be in full operation by the first half of calendar year 2001. The Nashua plant is just ten miles from M/A-COM's GaAs fab in Lowell, MA; the company also operates GaAs fabs in Colorado Springs, CO and Roanoke, VA.

Motorola's 6-Inch Conversion Triples Capacity

Motorola has completed the conversion of its CS-1 facility in Phoenix, AZ from 4-inch to 6-inch wafers, resulting in a three-fold increase in capacity. The conversion was completed three months ahead of schedule, and the company claims that CS-1 is now the world's largest RF GaAs facility. It is also one of the first to run all the GaAs processes—implanted MESFETs, PHEMTs, and HBTs—on a 6-inch line. The facility was recently re-certified to QS-9000.



Marconi Plans Switch to 6-Inch Wafers

Yet another company has announced plans to convert to 6-inch operation: this time the fab in question is owned by Marconi Caswell Technology (Caswell, UK)—formerly known as GEC Marconi Materials Technology, or GMMT. The move is apparently related to Marconi's new GaAs-based optical modulator technology, which was previewed at the Optical Fiber Conference earlier this year. While these devices may not be produced in the same volumes as RFICs, they consume a much more space on the wafer, making a move to 6" an economic necessity.

From unity comes strength.



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Celeritek Receives Orders from Gilat Satellite Networks

Celeritek has received development and pre-production orders from Gilat Satellite Networks for antenna-mounted outdoor units (ODUs) designed to transmit and receive RF signals for broadband access and cellular applications. In addition, Celeritek will supply Gilat with satellite transmit units. Employing GaAs-based subsystems, these are intended for use in Gilat's high-volume data, rural telephony and broadband two-way satellite systems. Commercial volume production is expected to begin in the third calendar quarter of 2000 and to reach full production by the second calendar quarter of 2001.

While Celeritek primarily supplies GaAs devices to wireless and military markets, the Gilat orders reflect a growing market for the company's integrated ODUs and radio transceiver subsystems operating at satellite frequencies (C-, Ku- and Ka-bands) for VSATs (very-small aperture terminals), says the company. VSATs are used to transmit voice, fax, data and video using fixed-site terminals and offer a cost-effective alternative to regions lacking adequate telecommunications infrastructure, or for remote locations and inaccessible terrain. Celeritek supplies system providers such as Gilat and STM Wireless with VSAT sub-

systems and PAs that typically provide up to 5 W in the extended C-band, up to 2 W at the Ku-band and 0.25 W at Ka-band. The company also manufactures RFICs for Ericsson and Hughes Network Systems.

Another major market for Celeritek exists in cellular, PCS and fixed wireless applications. The company ships production quantities of its "TrueTriange" InGaP HBT chipsets to several handset manufacturers, and wireless communications made up 50% of its business last year. Celeritek also supplies filtered LNAs, PAs up to 20 W and integrated transceiver radio front-ends for base-station applications.

In addition to HBTs, Celeritek also runs MESFET and PHEMT processes at its 57,000 sq. ft facility in Santa Clara, California. This houses an 11,000 sq. ft fab for processing 4-inch GaAs wafers and includes 28,000 sq. ft of manufacturing area.

Celeritek's modules provide a third major market for the company. The modules are assembled for operation at a range of frequencies, notably for point-to-point radio applications at ISM, 7, 15, 18, 23 and 38 GHz.

Teledyne Supplies PAs to Hughes Network Systems, Adaptive Broadband

Teledyne Technologies will supply Hughes Network Systems (HNS) with MMIC PAs for use in Hughes' broadband VSAT (very small aperture terminal) and DirecPC systems. HNS of Germantown, Maryland is a unit of Hughes Electronics Corporation that supplies broadband satellite and wireless products, services and networks. The company has installed over 300,000 VSATs worldwide and is also one of the largest manufacturers of direct-to-home satellite television systems.

Teledyne (Mountain View, CA) buys GaAs MMICs and fabricates PA modules and assemblies for broadband wireless microwave and millimeter wave applications, RF filter solutions for fixed access applications, and electromechanical switches for communications, space and defense applications.

In more news, Teledyne will also supply 500,000 GaAs MMIC PAs to Adaptive Broadband for its AB-Access U-NII (Unlicensed National Information Infrastructure) band radio. AB-Access technology spans the frequency range from 2 to 42 GHz. The first releases for AB-Access are for applications using the 5 GHz U-NII and 2.5 GHz MMDS (Multi-channel, Multi-point Distribution Service) frequency bands.

Alpha Ships PHEMT Switches to Groupe Sagem

Alpha Industries is shipping production volumes of 3 V GaAs PHEMT RFIC switches to Groupe Sagem, a French manufacturer of GSM wireless phones. Alpha says the value of these shipments—which are the first volume shipments of its most advanced GaAs IC switches—is expected to reach the multi-million dollar level this year.



Intelligent Epitaxy Technology, Inc.

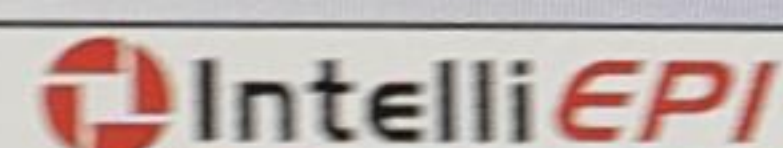
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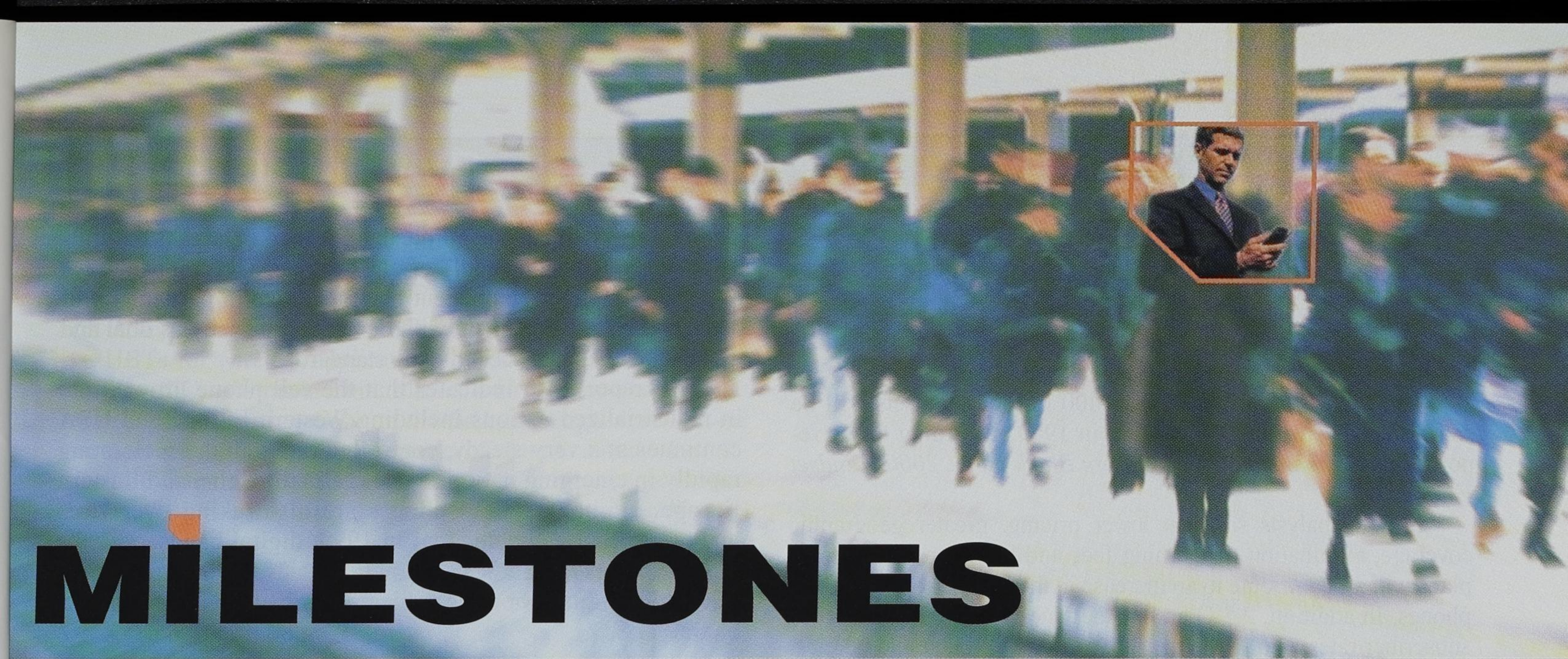
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Wireless Phones Offer Manufacturers Endless Opportunities

Cahner's In-Stat Group (Scottsdale, AZ) predicts that more than one billion wireless handsets will be sold worldwide in 2003. In the US alone, more than 400 million handsets will be sold in 2002, up from 277 million in 1999, according to the report: *The Component Manufacturers Black Hole: 2000 Handset Forecast*.

In-Stat analysts say that lower pricing, greater geographic coverage, elimination of roaming fees and lower priced payment plans will all contribute to an increase in the popularity of wireless phones. In addition, 2.5 G and 3G services will continue to drive subscriber rates, and in the next four years will make the wireless handset "the most pervasive method of accessing the Internet".

"Soon, all digital phones will be Web-enabled," said principal analyst Ray Jodoin. "Applications such as instant messaging and mobile e-commerce will transform the handset from being a "nice to have" wireless phone to a "must have" information appliance."

Advances in handset technology such as bigger screens, color, holographic displays, voice recognition and global positioning satellite (GPS) services will also propel the market.

In-Stat warns that the one hurdle that the market faces is the ability to obtain a steady supply of components. The company says that semiconductor component manufacturers in particular will be hard-pressed to keep up with demand, especially as dual and triple-mode handsets become the standard.

The report also indicates that the cell phone growth rate in industrialized nations including Western Europe and USA continues at a very steady, controlled rate, but is accelerating rapidly in emerging nations such as Brazil, China and Eastern Europe. Digital wireless phones are also taking over from analog. In-Stat estimates that in 1999, digital handsets in the United States comprised more than half of total sales. In 2000, the digital phone is projected to have a 78.5% market share.

Encoder Reduces RFIC Design Time

Agilent Technologies and Anadigics have teamed to develop a design tool that changes the way sample prototyping is performed for RFICs. Using Agilent's new Advanced Design System (ADS) encoder, Anadigics can provide wireless and broadband customers with design flow information while preserving RFIC intellectual property. The encoder enables designers to verify their systems early in the design process using an exact electronic model of Anadigics RFIC solutions, which can reduce the overall design cycle time. Anadigics eventually aims to offer virtual samples of all of its products starting with PAs and switches.

39 GHz Auction

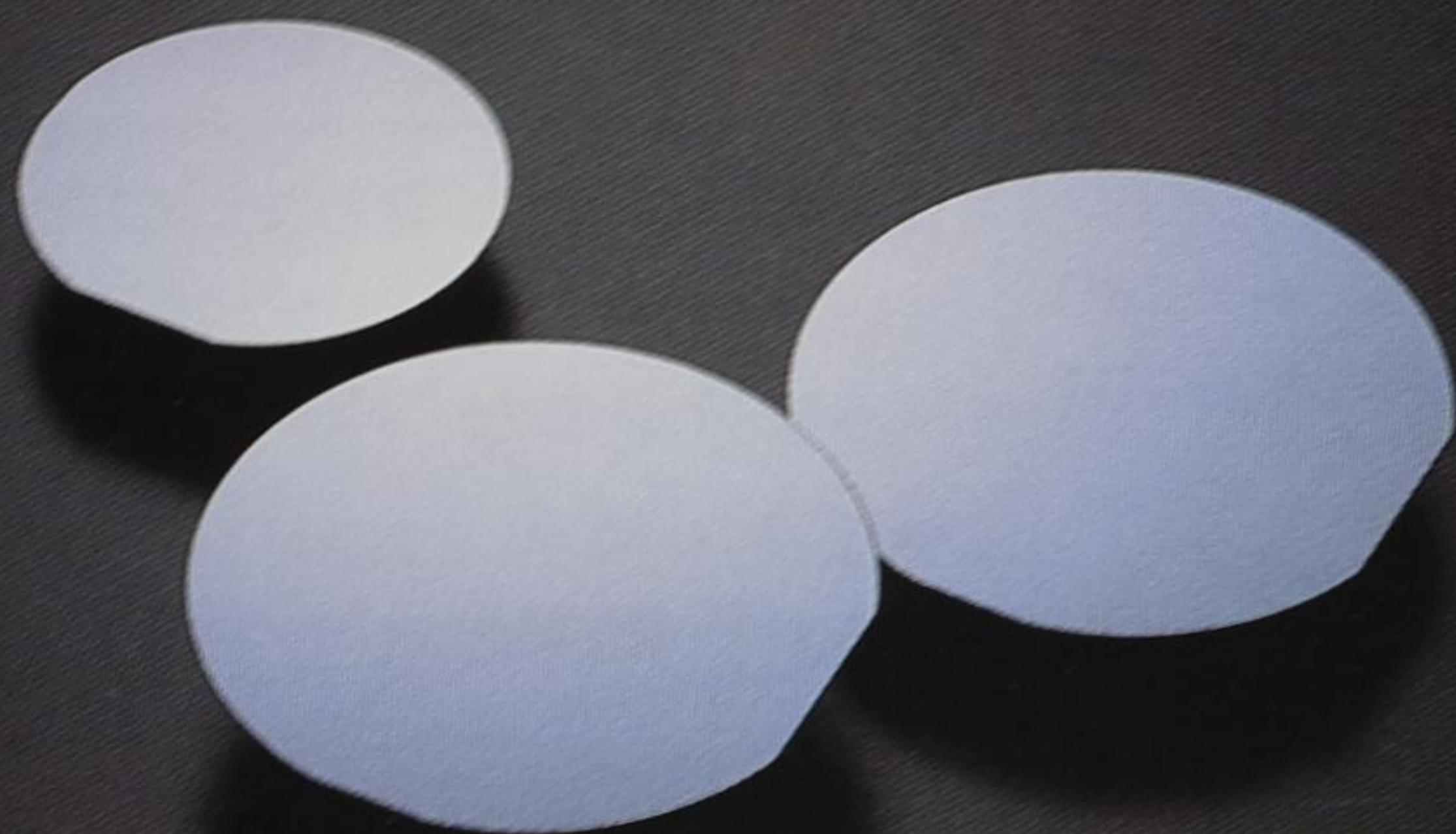
The Federal Communications Commission raised more than \$410 million at its auction of licenses for the 39 GHz frequency band held in Washington, DC recently. A total of 2,173 new fixed wireless licenses will allow companies to provide a variety of fixed wireless services, including point-to-multipoint links.

RFMD W-CDMA Chipset

RF Micro Devices (RFMD) recently announced a single-mode W-CDMA chipset solution using its "optimum technology matching" approach. The new chipset contains a PA, LNA, mixer, IF amplifier/demodulator, modulator/IF amplifier, upconverter, and PA driver. "The current chipset offers a complete RF to IF solution for W-CDMA using [GaAs] HBT, SiGe and BiCMOS process technologies. It is an example of the advantages of Optimum Technology Matching methodology," said Alastair Upton, RFMD's director of digital cellular products. The first W-CDMA phones are expected to launch commercially in 2001, with prototype units this summer.

In more news, RFMD has established an R&D group to focus on RFIC design, packaging and semiconductor processes. It has also established its first sales and support center, located at Reading, UK.

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Sterling to Develop GaN/SiC HBTs, 4-inch SiC Substrates

Sterling Semiconductor has been awarded \$688,000 to develop HBTs for wireless applications based on GaN and SiC epitaxy on SiC substrates. This follows a first phase that demonstrated an HBT using GaN on 4H-SiC. Sterling's development partners are Astralux, Inc. of Boulder, Colorado and the University of Colorado at Boulder. Recently acquired by Uniroyal [CS 6(4), p. 10], Sterling manufactures SiC substrates, epitaxy and devices.

"The GaN/SiC HBT offers the potential for greater power densities than are currently available in similar GaAs HBT devices," said Robert Soran, Uniroyal's president and COO. "In addition to defense radar applications, high power HBTs are being considered for a variety of future fixed and mobile wireless applications such as wireless internet, broadband data transmission and satellite-based communications systems."

Sterling has also been awarded \$987,000 to develop 4-inch SiC wafers. The 15-month contract is funded by the Ballistic

Missile Defense Organization (BMDO) and will be monitored by the Army Research Laboratory in Adelphi, Maryland. A 4-inch SiC wafer would provide around four times more real estate compared to the currently-available 2-inch wafers.

In the last three years Sterling has increased its wafer sizes from less than 1/2-inch to 2-inches on a commercial basis, and began producing 3-inch wafers on an R & D basis this year. The company intends to make 4-inch wafers for research purposes through 2001 with commercial production anticipated in 2003.

"A transition from the current industry standard 2-inch SiC substrate to a 4-inch substrate is particularly important for making cost-competitive semiconductor devices," said Robert Soran. "While we do not underestimate the technical challenges associated with creating larger SiC wafers we are encouraged that Sterling's rate of progress exceeds others in the industry."

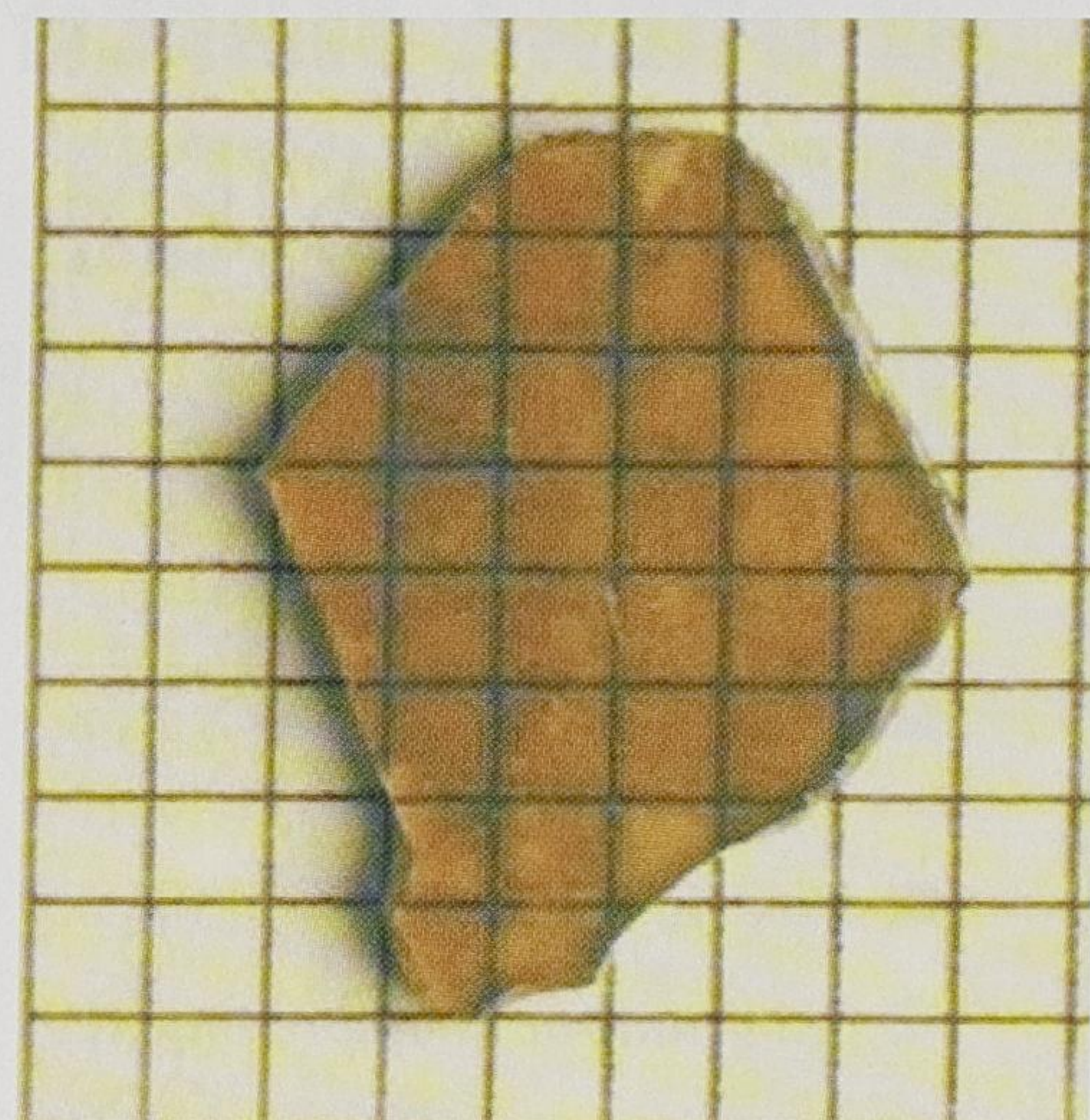
Epitaxial III-nitrides Demonstrated on AlN Substrates

Scientists at Rensselaer Polytechnic Institute (Troy, NY), in collaboration with Crystal IS, Inc. (Latham, NY), have recently demonstrated high quality, epitaxial growth of AlN and $\text{Al}_x\text{Ga}_{1-x}\text{N}$ on AlN substrates.* Crystal IS supplied the substrates, which were prepared from bulk AlN crystals grown by the sublimation-recondensation process. The paper reported epitaxial growth by OMVPE on substrates approximately 5 mm in diameter, which were cut in the (11 $\bar{2}$ 0) orientation (the so-called "a-face" orientation). This orientation is special because it is non-polar: strain along the [11 $\bar{2}$ 0] direction will not introduce an electric field. The Crystal IS - Rensselaer team reported better surface preparation on this orientation using a proprietary chemical-mechanical polishing (CMP) technique. The epitaxial layers grown were about 1 micron thick and were grown at 1100°C at a growth rate of 0.5 $\mu\text{m/h}$ after a thermal cleaning at the same temperature under a hydrogen and ammonia flow. Trimethylaluminum (TMA), trimethylgallium (TMG) and ammonia (NH_3) were used as the source materials, and the carrier gas

was hydrogen. No buffer layer was used. While very high quality Rutherford back-scattering/ion channeling results were presented (χ_{min} of 1.5% for the homoepitaxial layer and 2.2% for the $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ layer), X-ray rocking curves revealed the presence of low-angle grain boundaries. The $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ layer was doped with Si to achieve n-type doping with a resistivity of 20 $\Omega\cdot\text{cm}$ and a Hall mobility (at room temperature) of 20 cm^2/Vs . The group believes that the high mobility at such high aluminum concentration is because of the improved crystal quality of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer grown on AlN.

Crystal IS has made further progress in increasing the size of AlN bulk crystals. Carlos Rojo, VP of Manufacturing, has reported the growth of 14 mm diameter boules from which were prepared single crystal substrates that are larger than 1 cm^2 and 350 microns thick. An earlier typical c-face substrate grown at Crystal IS is shown in the figure. The company was recently awarded an SBIR Phase II contract from BMDO (administered by AFRL) to develop 50 mm diameter AlN substrates. Dr. Rojo believes that the 50 mm diameter substrates will be marketed in 2002. Crystal IS also has a Phase I SBIR from the AFRL to develop an innovative approach to increase the

growth rate of AlN and a Phase I STTR, from ONR, to fabricate improved nitride HFETs on AlN substrates in collaboration with Rensselaer Polytechnic and Sensor Electronic Technologies (Latham, NY).



An aluminum nitride c-face substrate is shown on top of a 1×1 cm^2 grid. The substrate is 0.6 mm thick and has both sides polished. Excellent planarity has been achieved. X-ray diffraction indicates that most of the area of these typical crystal grains is low-angle-grain-boundary-free. The orange color results from broad absorption lines centered around 3.5 eV and 2.85 eV, which are due to oxygen impurities and nitrogen vacancies.

* L. J. Schowalter, Y. Shusterman, R. Wang, I. Bhat, G. Arunmozhi, and G. A. Slack, *Appl. Phys. Lett.* **76**, 2000, p. 985.

Cree Demonstrates World Record SiC Power Rectifier

Cree and Kansai Electric Power Company (Osaki, Japan) have successfully demonstrated a SiC rectifier with a power blocking voltage of 12.3 kV for use in electric power switching. This record blocking voltage exceeds the highest value commercially available for silicon or other known semiconductor materials, and could lead to a significant reduction in the power loss associated with Si-based devices. Cree is under a three-year contract with the Osaka based company—the fourth largest electric power company in the world—for the development of SiC power devices for use in power transmission systems.

In existing systems, a large number of Si diodes are stacked in order to achieve the hundreds of kilo-volts required for power transmission. SiC has

the potential to half the number of devices needed and result in a 50% reduction in power loss compared to Si devices. The new rectifier exhibited a very low on-resistance, allowing for a forward voltage of only 4.9 V, and a current density of 100 A/cm², which is more than five times that of conventional Si devices.

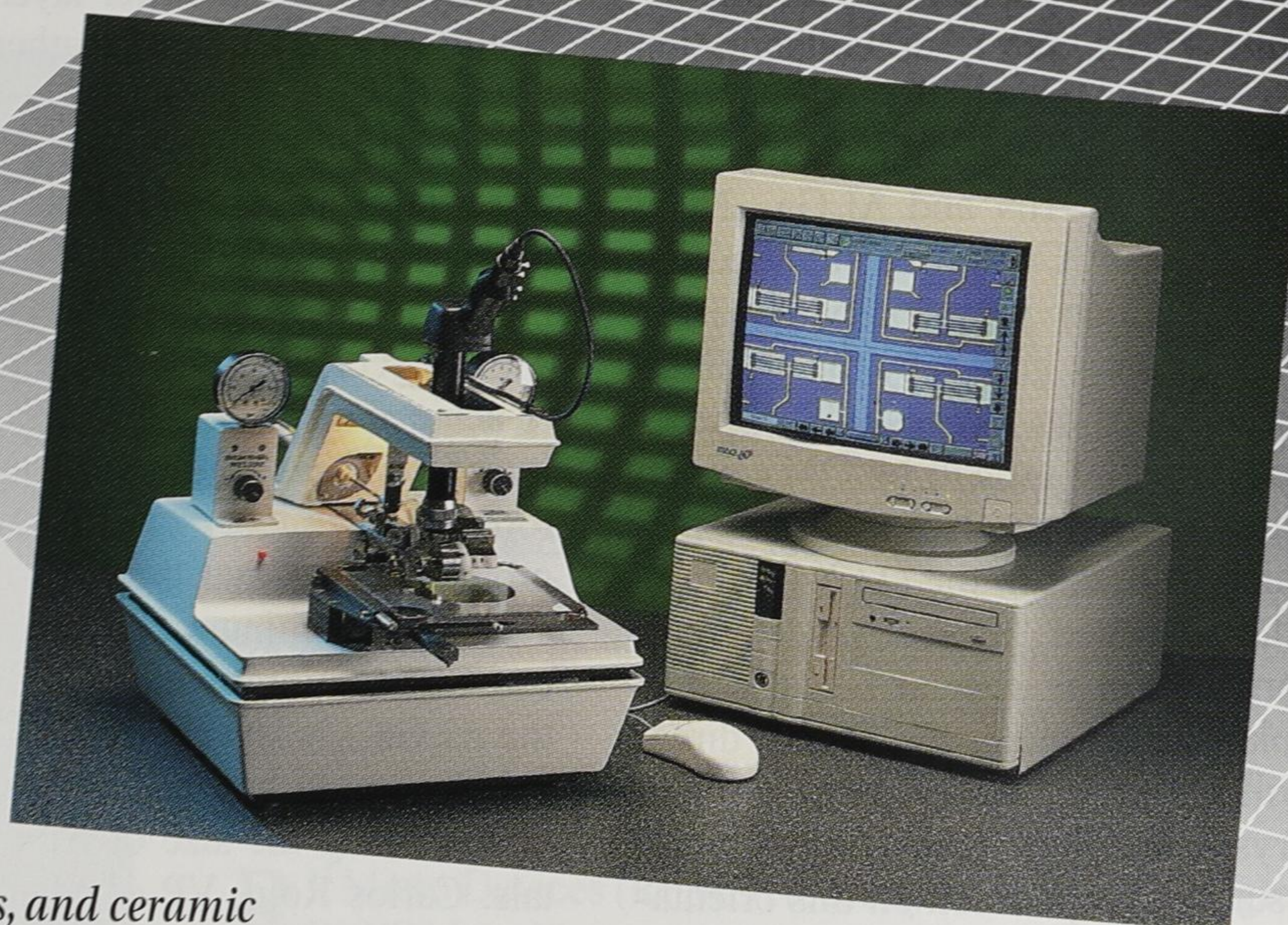
"This is a milestone in power and efficiency and demonstrates the range of capabilities and robust properties of SiC-based devices compared to Si devices," says John Palmour, Cree's director of Advanced Devices. "We have overcome some major technical barriers, doubling the rectifier's blocking voltage and simultaneously reducing their on-resistance in less than a year, and are now demonstrating extremely efficient power devices."

eV Products Wins CdZnTe Radiation Detector Contract

The eV Products group of II-VI Inc. (Saxonburg, PA) has received a \$700k contract from NASA to supply 22,000 CdZnTe radiation detectors for installation in the new SWIFT research satellite. CdZnTe is used to detect X-rays and gamma rays in a variety of applications including medical diagnostic equipment, industrial gauges and environmental monitoring devices [see CS 5(5), p. 39]. A further 23,000 detectors may be ordered by NASA following completion of the initial contract.

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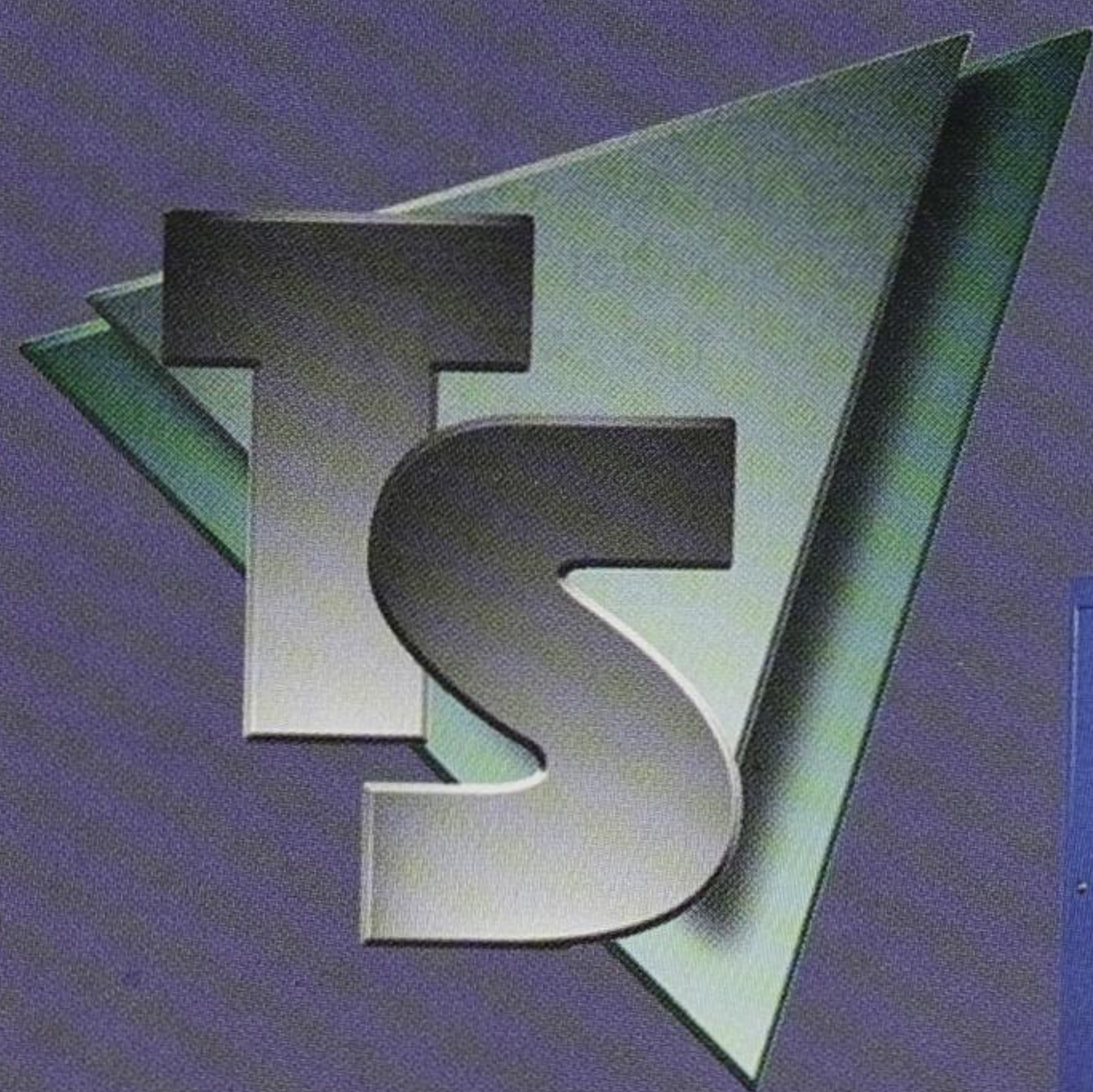
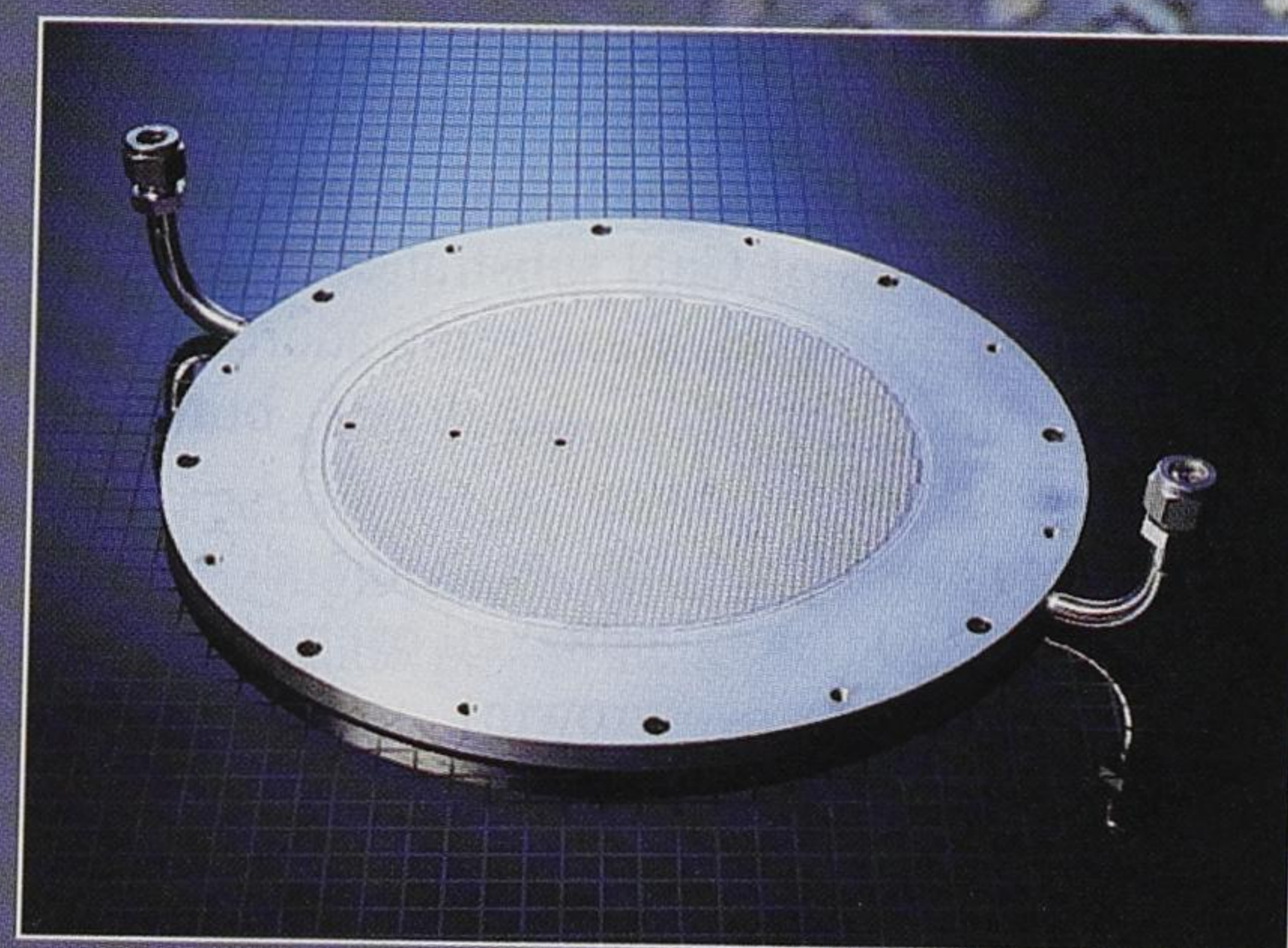
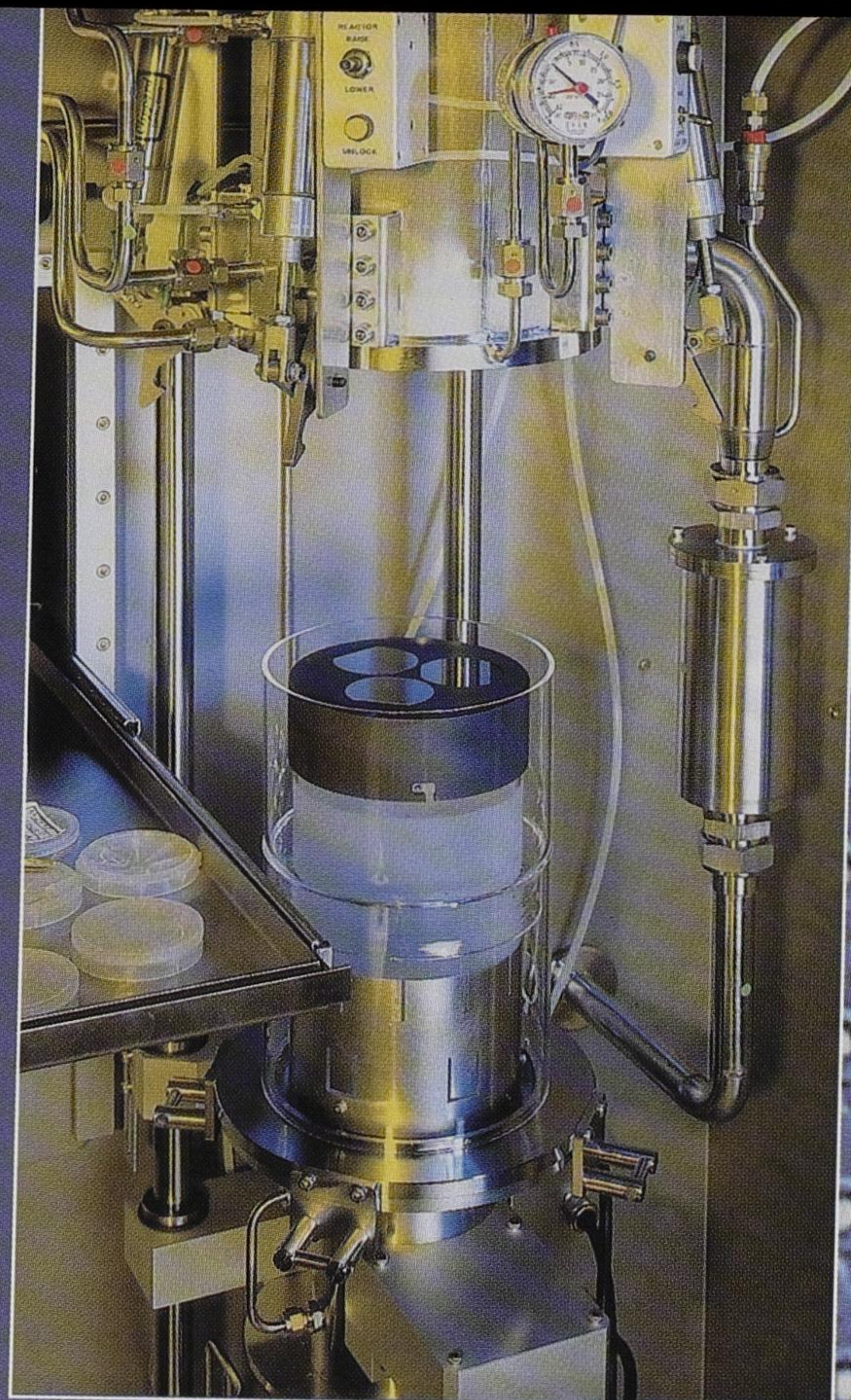
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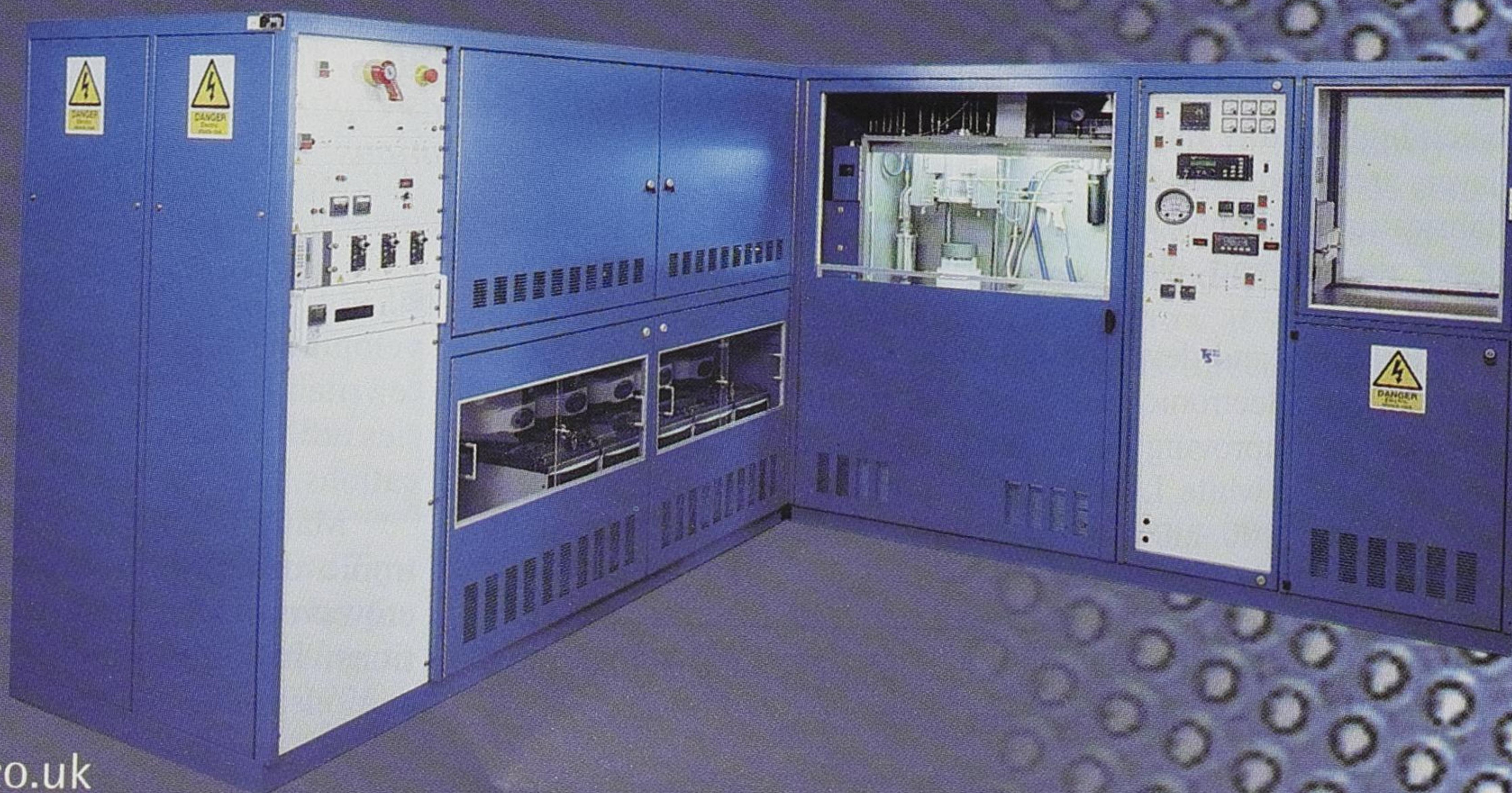
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Update on GaN Technology and Markets

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Since the announcement of the first commercial GaN-based blue LEDs in late 1993, worldwide activity in GaN research, development and manufacturing has undergone tremendous growth. Today there are nearly 100 companies and more than 200 universities and research centers worldwide engaged in GaN materials, process and device development. In addition, nearly 30 companies supply supporting infrastructure (materials, equipment, analysis, etc.). The regional distribution of this activity is shown in Figure 1.

Broken down by primary activity, a total of 95 companies are working on materials processes and devices, while 26 companies provide supporting technologies such as equipment, analysis and services. Meanwhile, more than 235 universities and research institutes are concentrating on materials, processes, devices and analysis.

Although GaN LEDs have been a commercial success and the market is maturing, a great deal of research activity is continuing on all aspects of GaN substrates, devices and processes. At the basic research level, areas being addressed include crystal growth, thin-film deposition, substrates, buffer layers, p-type doping, contacts, and etching.

Of particular interest has been the development of techniques such as LEO (lateral epitaxial overgrowth), also known as ELOG (epitaxial layer overgrowth), and pendeo-epitaxy, which permit the growth of high-quality (i.e. low defect density) GaN buffer layers on non-lattice-matched substrates such as sapphire and SiC. Such high quality buffer layers are essential to the fabrication of long-lived laser diodes and electronic devices.

Research and development also continues on a wide range of both optoelectronic and electronic devices. LED research is focused on improving device efficiencies. For example, a long term goal for white LEDs is to improve performance to levels greater than 100 lm/W, compared to the 20 lm/W typical of

"High-brightness LEDs will continue to penetrate the outdoor sign, automotive, traffic signal and display backlighting markets, as well as capturing an increasing variety of illumination applications."

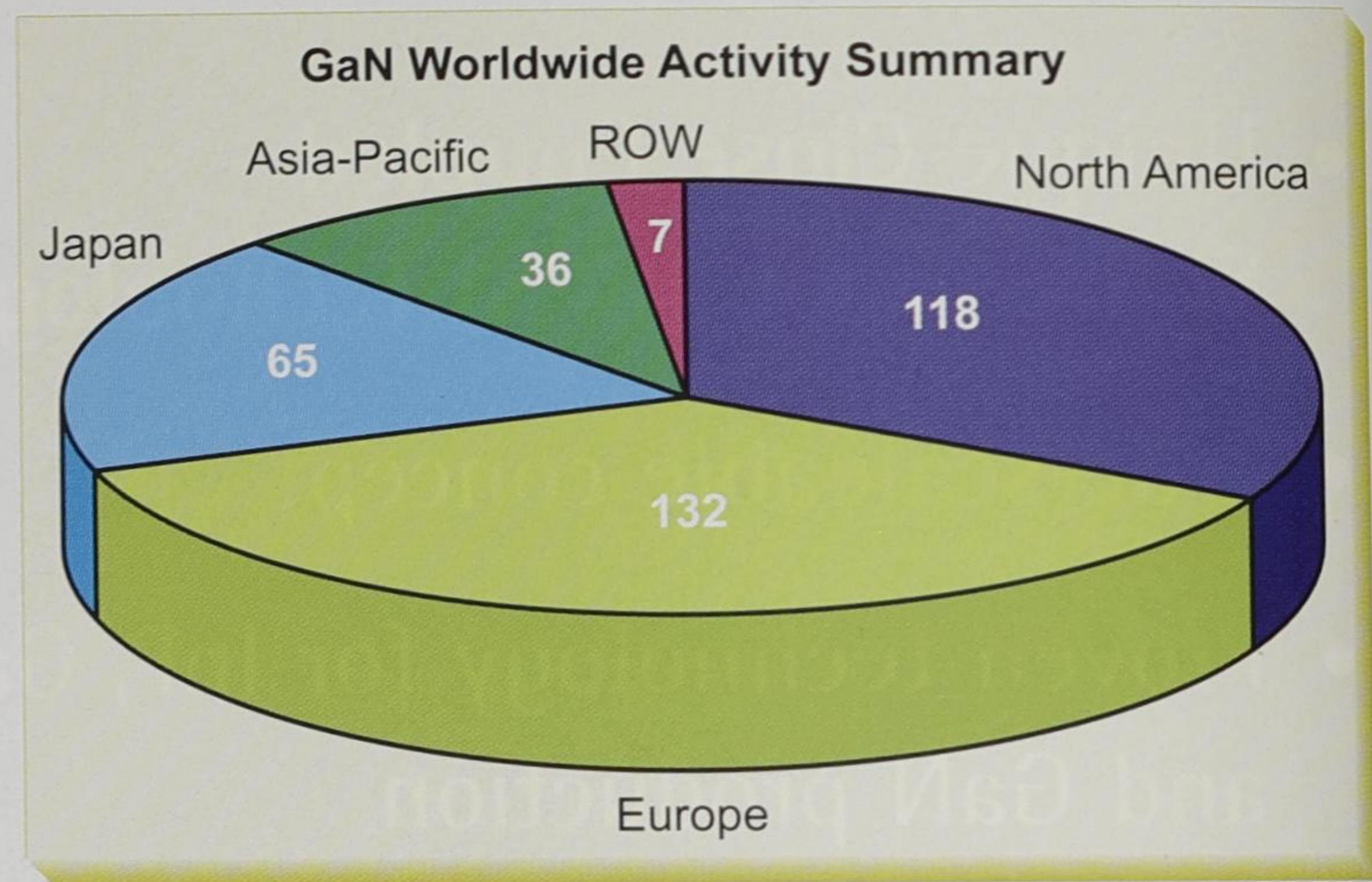


Figure 1. Regional distribution of the nearly 100 companies and 200 universities and research centers worldwide engaged in GaN materials, process and device development.

today's devices, in order to compete in the general illumination market with incandescent bulbs and fluorescent tubes.

For laser diodes, Nichia has already demonstrated 10,000-hour lifetimes and begun shipping devices commercially, and

other facilities around the world are working to match this achievement—at least 20 laboratories have demonstrated functioning blue laser diodes. In addition to improving device lifetimes for low-power (5 mW) devices, several laboratories are also de-

veloping higher power devices (>30 mW) that can be used in rewritable optical storage applications. A number of laboratories are working on UV photodetectors for visible blind applications, and limited commercial sales have already begun.

Many laboratories are also conducting research on electronic devices for a variety of applications, including microwave power, high-temperature and high power applications, including mobile telephone and fixed wireless base stations, satellite earth stations and power conversion control

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and protection for industrial, military, aerospace and automotive environments. Some of the device types being researched include microwave power HEMTs, low-noise HEMTs, MES-FETs, Schottky barrier diodes, Heterojunction diodes, and HBTs.

Unlike optoelectronic devices, these electronic devices are still in the research stage, and commercial production is not expected for two more years.

GaN Market History and Outlook

Although the activity summarized above encompasses a wide range of materials, processes and devices, the only significant market for GaN devices to date has been for high-brightness blue, green and white LEDs. Since the announcement of high-brightness GaN-based blue LEDs by Nichia and Toyoda Gosei in late 1993, a robust worldwide market for these devices has developed. In a little over six years, the market has grown from virtually nothing to \$420 million in 1999. Since 1995, the compound annual growth rate (CAGR) has been 79% per year. GaN-based blue, green and white LEDs are used in a variety of applications, including full-color outdoor signs, automotive interior lighting, traffic signals, back-lights for cell phone displays, niche illumination applications, and general purpose indicator and display applications. The market history for GaN-based LEDs is shown in Figure 2.

GaN-based blue-violet laser diodes operating at 405 nm have been developed by Nichia Corporation, and were introduced to the market on a sample basis in early 1999. These devices are used in a variety of applications, including sensing, spectroscopy,

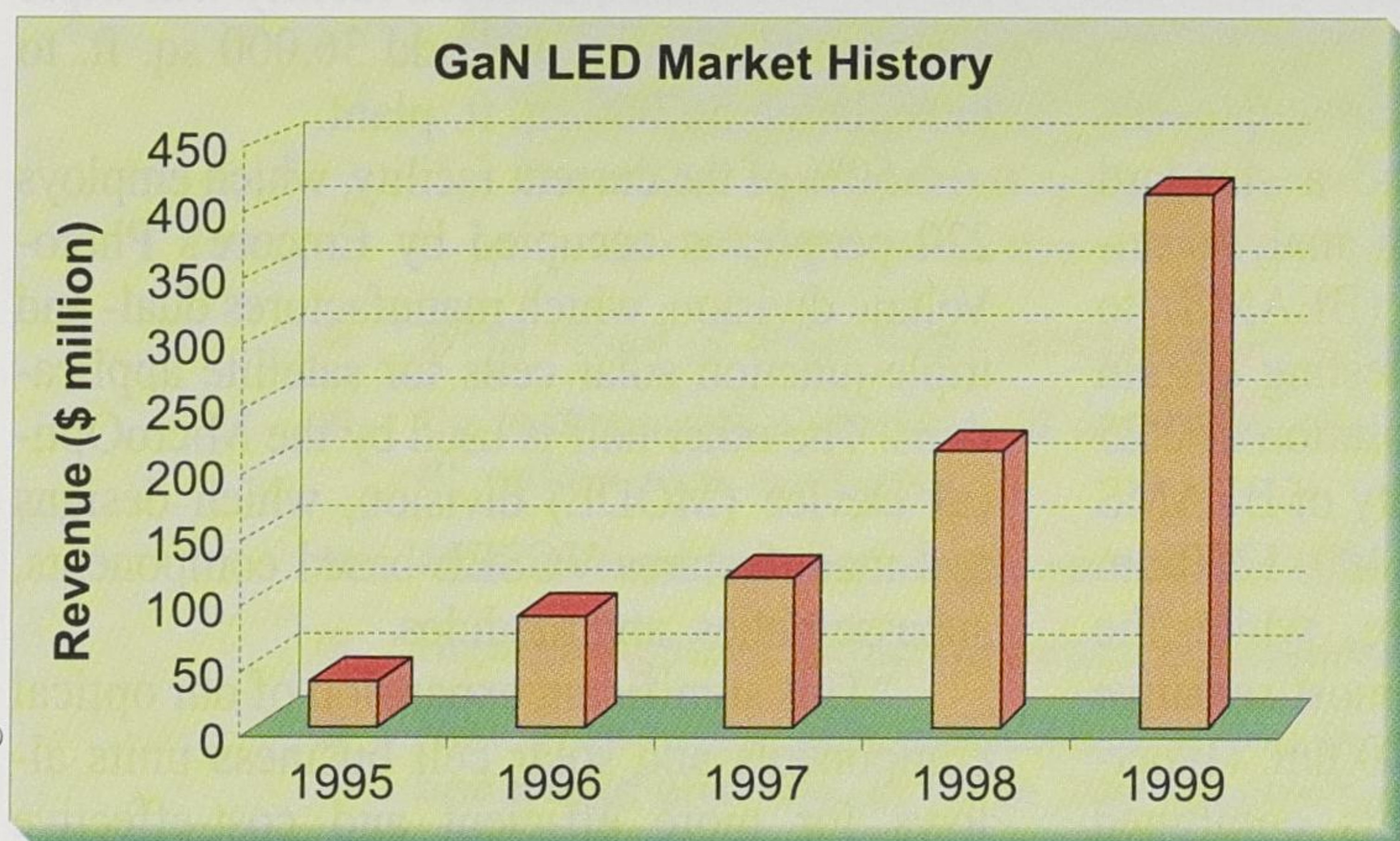


Figure 2. Since high-brightness blue LEDs by Nichia and Toyoda Gosei were introduced in the mid-1990s, the market for devices made from GaN has grown from almost nothing to \$420 million in 1999—a CAGR of 79% per year since 1995.

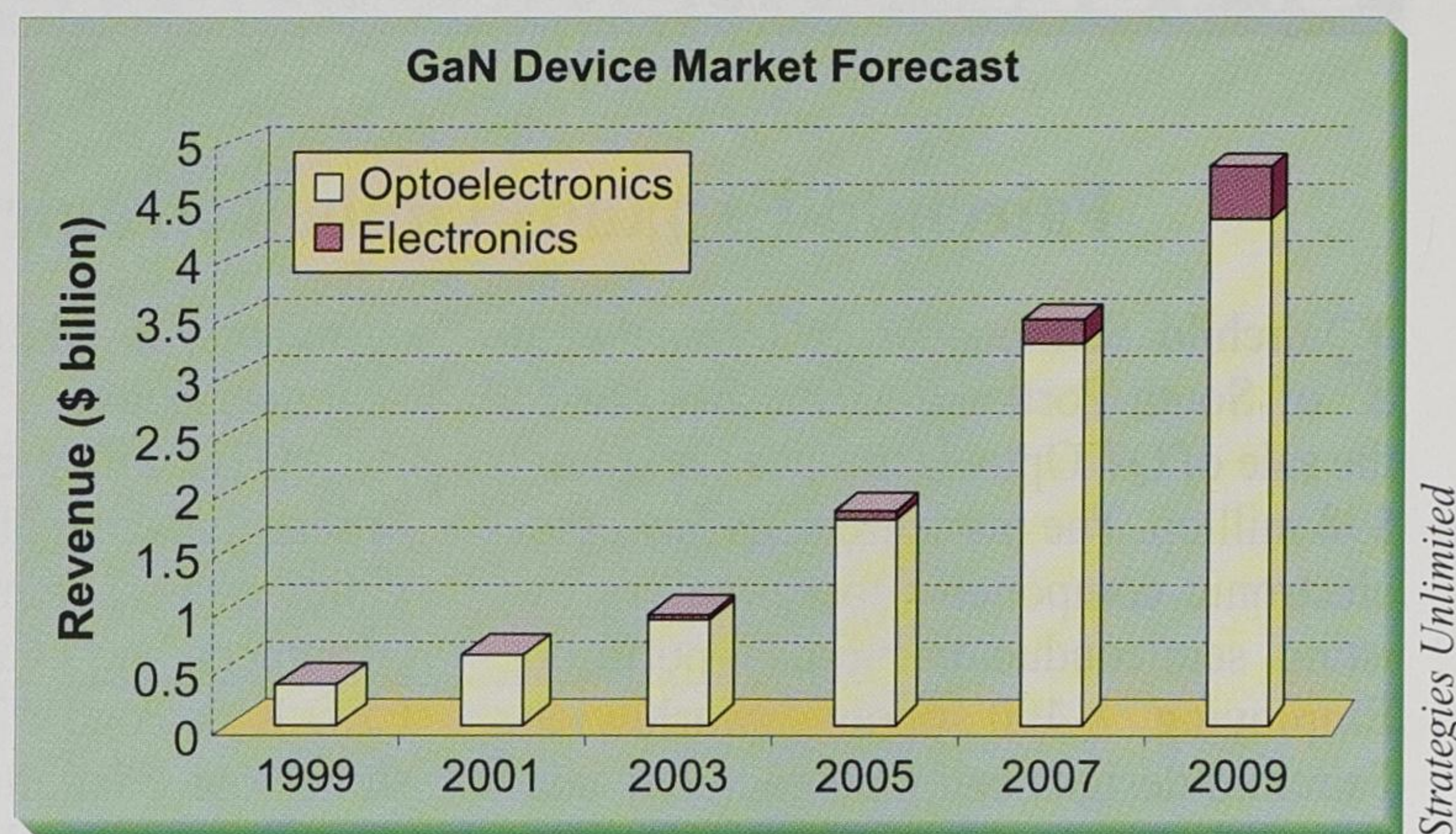


Figure 3. Market forecast for GaN-based optoelectronic and electronic devices. The total GaN device market is projected to grow to over \$4.8 billion in 2009 compared with \$420 million in 1999, representing a CAGR of 28%.

laboratory research and next-generation optical storage system development. However, no commercial blue laser-based optical storage systems have yet been introduced to the market.

With optoelectronics leading the way, the GaN device market will experience strong growth over the next 10 years. Blue laser diodes will begin to be used in high-density DVD drives in 2002 and will capture a large share of the optical storage market in subsequent years. The electronic

device market is forecast to begin in 2002, with modest shipments of RF/microwave and high-temperature devices, and to expand in subsequent years to include power switches, power rectifiers and high-voltage rectifiers.

The market forecast for both GaN-based optoelectronic and electronic devices is shown in Figure 3. The total GaN device market is projected to grow to over \$4.8 billion in 2009 compared with \$420 million in 1999, representing a CAGR of 28%.

In 2009, electronic devices are forecast to account for just 9% of the total GaN device market. This is due primarily to the fact that this market is expected to begin in 2002, compared to the optoelectronic device market, which began in 1994. However, during the forecast period after 2002, the electronic device market is forecast to grow at 94% per year, while the optoelectronic device market is forecast to grow at 27% per year.

The above is an abstract of the recently released report: *Gallium Nitride—2000: Technology Status, Applications and Market Forecasts*. For more information, contact Strategies Unlimited at (650) 941-3438, e-mail at info@strategies-u.com, or visit the company's web site at www.strategies-u.com.

Fairchild Expands Optoelectronics Portfolio with QT Optoelectronics

Fairchild Semiconductor International of South Portland, Maine has closed the sale of QT Optoelectronics for around \$98 million. The purchase adds key optoelectronic components to Fairchild's existing semiconductor product portfolio. Employing 8,400 people worldwide, Fairchild designs and manufactures analog and power devices, optocouplers, logic and mixed signal chips, and non-volatile memory devices for computer, telecommunications, automotive, consumer and industrial markets.

QT Optoelectronic (QTO) designs and manufactures LED lamps and displays, infrared components, custom optoelectronics, and optocouplers, making it one of the world's largest companies focusing solely on optoelectronics. The Sunnyvale, California-based company counts Rockwell, Nortel, Lucent, Philips, Motorola, Honeywell, and IBM among its

customers, in addition to major component distributors.

"QTO will strengthen our communications and computer markets, while providing new automotive and consumer customers," says Fairchild's president and CEO Kirk Pond. "This purchase demonstrates our commitment to grow through acquisition, as well as new product development."

"QTO will now have access to and benefit from a number of Fairchild's strengths, including its design and process technology, manufacturing and packaging capability and financial resources," commented Steve Sherman, QTO's president and CEO. "Fairchild will provide QTO the additional muscle it needs to quickly expand our business."

In 1998, QTO bought Motorola's optocoupler manufacturing business, doubling the size of its own optocoupler busi-

ness in the process. Prior to this QTO bought business units from Harris and Philips Semiconductor. The company maintains a 35,000 sq. ft. facility in the suburbs of Wuxi, China, where it employs over 500 people producing LED displays using externally purchased chips, and infrared switches.

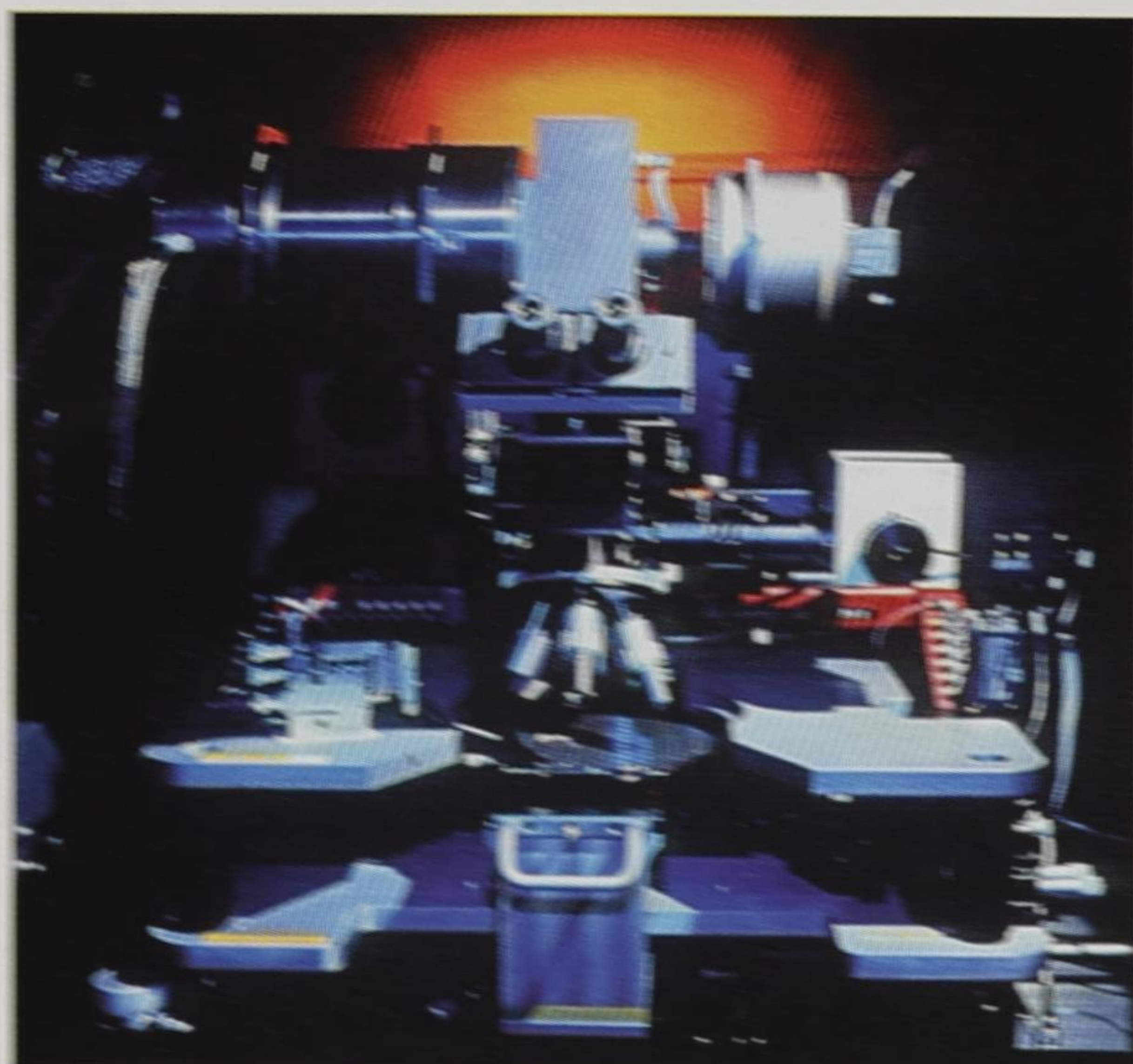
QTO recently transferred LED display and IR switch production from its 70,000 sq. ft. manufacturing site in Kuala Lumpur (Malaysia) to Wuxi. This move provided extra capacity in the Malaysian facility, which already employs 1,000 people, to handle the increased optocoupler production demands brought on by the Motorola acquisition. The company also maintains a die preparation facility in Singapore, where purchased epitaxial wafers are diced and metallized prior to die attach and packaging at the Kuala Lumpur facility.

HgCdTe Array Allows Analysis of Wafer Defects

Hypervision (Fremont, CA) has incorporated a mercury cadmium telluride (HgCdTe) array into its line of emission microscopes and backside wafer inspection systems. Used in the Hubble Space Telescope to detect the gas content of interstellar ob-

jects, these HgCdTe arrays are sensitive to IR emission from hot spots caused by current leakage. Hypervision says that this can lead to a 10-fold increase in sensitivity to defects, particularly when inspecting the backside of silicon wafers and packages.

A beam splitter couples the HgCdTe array and a standard backside emission analysis microscope system (BEAMS) to produce a wafer testing system with a spatial resolution of 0.25 μm . The sensitivity of BEAMS is optimal in the 400–1200 nm wavelength range, while the HgCdTe array is most sensitive from 1000 to 1500 nm. Hypervision claims this combined system yields the highest spectral response available in commercial emission microscopes, and allows these arrays to be used in wafer-level work for the first time.



Hypervision's new emission microscope uses an HgCdTe array to detect wafer-level defects.

Emcore Increases Capacity at New Mexico Facility

Emcore plans to significantly expand its Sandia Technology Park site in Albuquerque, New Mexico to house the company's solar cell, optical components and networking products. Scheduled for completion by December 2000, the expanded facility will triple cleanroom capacity and add 36,000 sq. ft. to the existing 50,000 sq. ft. plant.

50% of the current facility, which employs 220 people, is occupied by Emcore's Photo-Voltaic division, which manufactures dual- and triple-junction solar cells for satellite applications. The other half is used by the MicroOptical Device (MODE) division, which designs and manufactures VCSEL-based components, subassemblies, and modules.

"This significant expansion of our optical components and solar cell business units allows for more efficient and cost-effective manufacturing operations," says president and CEO Reuben Richards. "By expanding our resources in one centralized facility, we will have the increased manufacturing capacity to meet growing customer demands for all product lines."

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Osram Demonstrates LED Room Lighting

While LEDs are now regularly found in applications from dashboard backlighting to large-format video panels, Osram Opto Semiconductors (Regensburg, Germany) is the first company to demonstrate general LED room lighting.

To achieve the desired color, Osram integrated 14,000 white, blue, blue-green, green, orange and red LEDs into a ceiling fixture (see photo). Computer controlled color mixing was used to achieve a color temperature of 2500–3000 K, similar to that of an incandescent light bulb. The color temperature describes a temperature at which a black body radiates to achieve a particular wavelength. A warm white has a higher temperature and a cooler white, such as typically supplied by fluorescent sources, has a lower temperature. In total, the installation achieves 600–700 lm/m²—adequate for normal office lighting, says the company. Mini reflectors are employed to distribute the light without causing glare.

Osram employed white LEDs with a luminous flux of around 1 lumen and colored devices outputting 2 lumen, for a total power consumption of just 0.1 W per device. By comparison, a single 15 W light bulb produces 90 lumen (or 1400 W in total). Despite this poor performance, the promise of low power consumption, robust



construction and longevity is driving the intensive research into improving the performance of LEDs [see CS 6(3), p. 82].

Osram Opto Semiconductors

Cree Expands Blue and Green LED Product Line

Cree has unveiled blue and green LEDs featuring a smaller chip area that enables a 50% reduction in power consumption compared to its standard and high brightness blue and green emitters. Available in production quantities, these devices are currently shipping into high volume consumer applications including cellular phones, high-resolution video boards and segmented LED displays.

Mike Dunn, general manager for optoelectronics said; "We are responding to our customers' requirements for lower power LEDs for use in applications where power consumption and cost are primary considerations. We believe demand for these new devices will be driven by continued miniaturization, particularly in the cell phone and high resolution video screen display market as well as in traditional cost sensitive, high volume LED applications."

North Carolina-based Cree's new blue LED features a 200 × 200 μm InGaN-on-SiC chip and offers 0.65 mW power output at 465 nm, with a FWHM of 65 nm. With a wavelength centered on 525 nm, the company's green LED offers 0.85 mW output (at 10 mA) from an InGaN-on-SiC chip of the same dimensions. This compares to up to 3.5 mW for its deep blue "super bright" devices and 1.5 mW for a 525 nm green product, which employ a larger 260 × 260 μm chip.

LumiLeds and Dialight Market Traffic LEDs

LumiLeds Lighting and Dialight Corporation have entered into an agreement to jointly market their complete LED traffic signal product lines in North America. Dialight, the largest US supplier of red, green and amber traffic lamps using LEDs, first introduced an LED-based traffic signal in 1994, and also manufactures arrows and pedestrian signage lit by LEDs.

"By effectively expanding our individual product lines and sales channels, we expect to accelerate the adoption of LED traffic signal technology," said Gary Durgin, Dialight's VP of marketing. "LED signals have already gained widespread acceptance, but we feel we can make even greater strides working with a technology leader like LumiLeds."

Menko de Roos, Business Unit Manager at LumiLeds, added; "Dialight brings to this venture not only its market leadership, but also a complete offering of signals in all three colors and a range of voltages. We are seeking similar partnerships in Europe and Asia to more aggressively promote LED technology on a global basis." LumiLeds recently developed a revolutionary package of traffic signal components containing high-flux LEDs, which provide up to 10× the flux of conventional high brightness LEDs [CS 6(1), p. 71].

Microvision Demonstrates Miniature Display Based on Cree LEDs

Microvision (Bothell, Washington) has demonstrated a miniature display that uses Cree's LEDs to create a full-color high-resolution video image. Cree already owns 4% of Microvision stock and was among the investors who put \$25 million into Microvision earlier this year to accelerate development of the company's Retinal-Scanning Display technology, which uses red, green and blue emitters to project information directly on the retina [see CS (5) 6, p. 11]. The initial focus of the demonstration was to ensure that blue and green devices developed by Cree during the first phase of a multiyear development agreement were sufficiently bright to create a quality image on the eye.

The Microvision system affixes Cree's LEDs to three sides of a miniature optical cube. This light is subsequently

modulated at very high speeds and scanned by tiny vibrating mirrors through a compact lens into the viewer's eye—the impression produced is of seeing a full-size computer or television screen at arm's length. Microvision believes a large market exists for such miniature displays in small portable devices such as handheld or wearable wireless Internet devices and computer games, viewfinders for digital cameras and camcorders, and computers. This will also go some way towards solving concerns cited by industry analysts regarding the small size of display screens required for portable devices, says the company.

"We've been viewing DVD full motion video, and a variety of static images through the display," said Steve Willey, Microvision's executive VP.

"We are really pleased, because the imagery of our display exhibits none of the field-sequential 'color break-up' or defective pixel effects that haunt miniature display panels made from liquid crystals and liquid crystals. We think our customers and ultimately consumers will react very well to the improved image quality and reliability."

"This first demonstration has exceeded our best expectations. With the LEDs, alignment tolerances were very forgiving which should give us an [advantage] in high volume manufacturing," added Microvision's president and CEO Rick Rutkowski. "We have a well-funded program going forward, that will provide us with exclusive access (for scanning displays) to ongoing improvements made by Cree in the brightness and efficiency of these LEDs."

FIBER OPTICS NEWS

Agilent Targets Four-Fold Component Capacity Increase

Agilent Technologies is undertaking an aggressive expansion of its manufacturing capacity for fiber-optic components. By expanding each of its manufacturing sites, Agilent plans to quadruple its capacity within two years, in order to stay ahead of the explosive market demand. The expansions will take place at Agilent's epitaxial wafer and device manufacturing plants in San Jose, CA and Ipswich, UK, in addition to its back-end packaging facilities in Singapore and Malaysia.

"One of the major initiatives that propelled us into a leadership position in fiber optics was our commitment to win in high-volume applications," says Bill Sullivan, senior VP and general manager of Agilent's Semiconductor Products Group. "Our fiber-optic manufacturing capabilities are second to none, and customers that need to ensure availability and affordability of critical components for fast-growing markets realize that."

In support of the capacity expansion, Agilent expects to invest more than \$175 million in capital equipment and plant expansions. The company has recently placed a multi-million dollar order for additional multi-wafer reactors for laser device epitaxy, which are slated for installation by the end of July.

SDL And JDS Uniphase Extend Pump Laser Supply Contract

SDL and JDS Uniphase have extended the contract under which SDL supplies grating-stabilized 980 nm pump lasers to JDS Uniphase for incorporation into the latter company's erbium doped fiber amplifiers (EDFAs). The contract extension extends through 2001 and more than doubles the base quantities covered in the previous contract.

The SDL grating-stabilized pump laser product line features high power and excellent reliability required for high-performance EDFA designs. "This agreement demonstrates the significant value that SDL pumps deliver to leading manufacturers of EDFAs," says Donald Scifres, SDL's chairman and CEO. "Our production capability of both the laser diode chips and the modules that house them is among the largest in the industry. The move to higher channel count systems requires more pump laser power, without sacrificing reliability. SDL's pump laser technology is field-proven with more than 500 million device hours of operation."

JDS Uniphase is a leading supplier of high performance EDFAs, the optical amplifiers essential to the operation of high capacity, high-speed DWDM telecommunications networks. JDS Uniphase also manufactures 980 nm pump lasers at its facility in Zurich, Switzerland.

Novalux Has High Hopes for Mystery Laser Technology

Novalux, a 2-year old company based in Sunnyvale, California, has unveiled what it claims to be a "breakthrough in laser technology." Details of the so-called Novalux extended cavity surface emitting laser (NECSEL) are sketchy to say the least. The device is reportedly capable of achieving much higher output powers than standard VCSELs, while sharing many of their advantages such as a circular output beam for improved fiber coupling. The novelty of the device appears to be in the design of the cavity, which is much larger than in a standard VCSEL in order to scale the output power. NECSELs use conventional semiconductor materials, and are electrically pumped.

"A key feature is that the technology is highly manufacturable," says Aram Moohradian, Novalux's founder. "As surface emitters, the devices can be fabricated and tested at the wafer scale, unlike edge-emitting lasers. We are combining standard semiconductor materials with features of conventional [non-semiconductor] laser technology to achieve high output power at low cost. This is a platform technology that can be applied to many applications; pump lasers for EDFAs or Raman amplifiers, fixed and tunable wavelength sources for telecommunications, high power visible devices and more."

Novalux recently opened a new class 10 clean room that the company believes to be the only such facility for processing

4-inch GaAs wafers for photonic applications. The company has attracted a large amount of capital investment, which is being used to expand its facilities and install epitaxial capability.

The combination of high output power and low manufacturing cost is certainly very attractive, although it remains to be seen whether the technology will attain the required cost, performance and reliability levels to penetrate mainstream applications.

Infineon and Vitesse Launch VSR Solution

Vitesse Semiconductor and Infineon's Fiber Optic Division have jointly introduced a complete OC-192 fiber optic link for Very Short Reach (VSR) applications over distances of up to 300 m [see CS 6(3), p. 52]. The solution employs Vitesse's VSC7166 16x12 OC-192 converter IC together with Infineon's VCSEL-based PAROLI parallel optic modules. The link meets the specifications for a VSR data transmission scheme proposed by Cisco Systems in the Optical Internetworking Forum (OIF), a proposal which is gaining acceptance with other networking industry leaders such as CIENA Corporation and Juniper Networks. "The VSR standard and its immediate adoption by Vitesse and Infineon is a significant step forward in providing cost effective, inter-operable OC-192 interconnects to service providers," said Peter Wexler of Juniper Networks.

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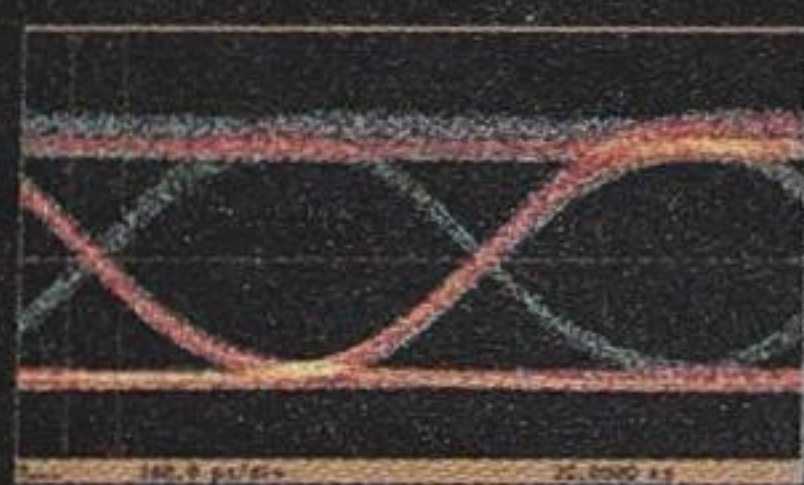


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SILICON UPDATE

Silicon Quantum Dot Memories

ROBERT A. METZGER



As any material grower can tell you from personal and painful experience, losing lattice matching during film growth results in a film which is typically useless for device applications. The goal of most material growers is to either grow material with lattice spacing identical to that of the substrate, or when mismatched material is required, to make certain that the strain in the thin film does not become so great as to be relieved by the generation of defects. The goal is to maintain two-dimensional crystal growth and its associated periodic atomic placements, which in turn generates the desired band-structures needed for successful device performance. If lattice match growth conditions are lost and the strain becomes too great, two-dimensional growth can quickly give way to three-dimensional growth, and the subsequent formation of three-dimensional hillocks.

When given lemons, make lemonade.
When having lost lattice match growth conditions, make quantum dots.

While many of you may consider quantum dots the domain of III-V growers (quite possibly due to the fact that there seem to be so many ways during the growth of ternary and quaternary alloys to lose lattice match growth conditions and generate dots), in fact, many in the Si community are beginning to embrace the quantum dot. While III-V researchers are attempting to harness the unique quantum states of dots to enhance the optical properties of materials (as in the case of quantum dot lasers), Si researchers are starting to look to dots for their ability to store small amounts of charge, making them potentially useful in the fabrication of ultra-small memory elements. If such dots are placed in the vicinity of the channel of a transistor, this stored charge (or absence of charge) can alter the threshold behavior of the transistor,

thereby making it potentially useful as a memory element.

This effect was first demonstrated by Sandip Tiwari and coworkers at IBM in 1995 [1]. Based on a standard n-MOS silicon FET structure, a thin tunneling oxide (1–2 nm) separates the inversion surface of the *n*-channel FET from a distributed film of silicon quantum dots that cover the entire surface channel region. A thicker oxide (5 nm or greater) then separates the dots from the control gate of the FET. An injection of an electron occurs from the inversion layer by way of tunneling when the control gate is forward biased with respect to source and drain. The resulting stored charge in the dot screens the gate charge and reduces the conduction in the inversion layer, which in turn shifts the threshold voltage of the device to be more positive.

The Si dots can be readily formed on the non-crystalline SiO₂ layer by any Si thin film growth technique, though typically this is done in a conventional LPCVD reactor configured for poly-silicon deposition. In the case of Tiwari's work, the dots were typically spherical in shape with a 5 nm dimension, separated by 5 nm, and with a density of 1×10^{12} cm⁻². When the control oxide thickness is 7 nm (between the dots and the control gate), a threshold shift of nearly 0.36 V occurs when each dot has been injected with a single electron. By controlling the gate bias, the charge could be injected and removed from the dots, this behavior allowing the FET to operate as a true bistable memory element at temperatures below 77 K.

Subsequent to this initial work, operation of these devices has now been extended to room temperature, the uniformity and integrity of the tunneling oxide and dots enhanced by the incorporation of oxy-nitride layers, and p-MOSFETs relying on hole tunneling have also been

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reported. Unlike E²PROMs, which also rely on charge injection through a tunneling oxide region, these devices can be operated at smaller voltages (as small as 1 V for charge injection), and at much faster speeds. In addition, these devices have been operated in excess of 10⁹ write/erase cycles without showing any degradation, and the characteristics of the charge storage within the dot is sufficiently stable such that refresh times are in excess of weeks [2, 3].

As pertinent as these developments may be to next-generation memory devices, this is not an area typically addressed by III-V devices. However, the use of quantum dots to store charge, which in turn alters the localized band structure of the material in which it is embedded, should be of great interest to those in the III-V community. The abundance of III-V materials, in which

band structure can be varied with alloy content, has opened up many device opportunities not accessible to standard silicon-based devices. In the same manner, the ability of quantum dots to store as well as release charge under the correct proper biasing conditions, and in turn alter the electrical characteristics of a device, represents one more degree of design latitude, which, if incorporated in such structures as MESFETs, HEMTs or HBTs, should offer even greater design flexibility and device performance. Perhaps a valuable lesson can be learned from the Si quantum dot researchers.

[1] Sandip Tiwari et al, *Appl. Phys. Lett.* 1996, 68(10), p. 1377

[2] K. Han et al, 2000, *IEEE Elec. Device Lett.*, Vol. 21(6), p. 313

[3] I. Kim et al, 1999, *IEEE Elec. Device Lett.*, Vol. 20(12), p. 630

Silicon Moves in on GaAs Applications

Several new silicon and SiGe product announcements could increase the pressure on GaAs

Conexant Announces CDMA RFIC Subsystems Using SiGe

Conexant has introduced its first wireless products manufactured using its internal SiGe process—a family of transceiver subsystems for 2G and 3G CDMA. “Our new generation of CDMA RFIC subsystems provides the highest level of integration and a superior level of performance for the CDMA market,” says Mohy Abdegany, VP of Conexant’s Wireless Communications division. “In addition, our advanced SiGe process provides the lowest power consumption in their class.”

The company claims that its dual-band transmit subsystem reduces current consumption by up to 20% compared to competitive devices. This part is designed to operate with Conexant’s existing power amplifier modules, which are implemented in a GaAs HBT process. Several receiver subsystems were also introduced: a SiGe version and a BiCMOS version that offers “the highest level of integration for a dual-band, tri-mode receive RFIC subsystem used in CDMA applications”.

Infineon Unveils SiGe 10 Gb/s Chipset

Infineon Technologies has launched one of the industry’s lowest power 10 Gb/s chipsets designed and processed using its B7HF SiGe process, which features a transit frequency of more than 75 GHz. The chipset uses around half of the power of competitive devices, claims Infineon.

“By replacing today’s GaAs ICs and first generation bipolar Si technology with our SiGe chipset solution, telecom and datacom OEMs can build high-performance fiber optic systems at a highly competitive cost structure,” says Marc Gebert of Infineon’s high-speed communication ICs business unit.

The chipset includes a laser/modulator driver that consumes 1.7 W, as well as a 16:1 multiplexer with clock multiplication unit (CMU) and a 1:16 demultiplexer with clock and data recovery (CDR). The latter parts run on a single 3.3 or 5 V power supply and consume about 1 W of power. Finally, a transimpedance amplifier (TIA) for use with either APD or PIN photodiodes is also available: due to the high transimpedance of this device, which requires only 170 mW, a post amplifier can be eliminated in most receiver applications.

World’s First 10 Gb/s CMOS Transceiver from Newport

Newport Communications (Irvine, CA) has produced the world’s first serial 10 Gb/s transceiver chipset based on a CMOS process. The integrated chipset consumes significantly less power than other 10 Gb/s devices fabricated with specialty SiGe, GaAs or bipolar processes, says Newport.

“Conventional serial 10 Gb/s solutions in today’s market consume extraordinarily high power and require very expensive specialty processes,” says Joseph Vithayathil, VP of sales and

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SILICON UPDATE

marketing. "At Newport, we use a mainstream CMOS production process, allowing us to integrate more functions on-chip and resulting in a very low power and cost-effective solution that can readily be manufactured in high volume."

The chipset comprises a 16:1 multiplexer with CMU, and a 1:16 demultiplexer with CDR. Based on the company's proprietary C3MOS (or current controlled CMOS) technology, the two-chip solution uses a single 1.8 V power supply and consumes a total power of 1.5 W.

In comparison, the latest 10 Gb/s ICs from Vitesse include a 16:1 mux and clock generator that consumes 1.5 W, and a 1:16 demux with clock recovery that consumes 2.25 W, both from a +3.3 V supply [see CS 6(4), p. 82].

SiGe Used in Oscilloscopes, Test Equipment

Two high-speed test applications are now starting to make use of SiGe ICs. Tektronix, Inc. (Beaverton, OR) has introduced a series of digital phosphor oscilloscopes (DPOs) that are the first test and measurement instruments to employ IBM's SiGe chips. The oscilloscopes deliver 4 GHz real-time signal acquisition and provide accurate performance at significantly increased speeds compared to standard silicon. SiGe devices are also reputed to consume less power. Over the last four years, Tektronix has invested more than \$14 million in the use of SiGe in test instrumentation.

Teradyne (Boston, MA), a supplier of automatic test equipment, has introduced a new system for testing system-on-a-chip (SOC) devices, offering 1024 digital pins and data rates of 1.6 Gb/s. The timing system architecture combines CMOS with SiGe for final timing generation. "The system uses a parallel processing architecture to achieve higher test speeds, which reduces test time and lowers test costs," said Teradyne's Brad Robbins. "This allows more parts per hour to be tested, and fewer testers are required." Currently, GaAs ICs are widely used in automated test equipment, with Vitesse being a major supplier [see CS 5(8), p. 56.]

ATMI Expands HBT Epiwafer Capacity

ATMI's Services Business (previously known as Epitronics) is expanding its growth capacity for HBT epiwafers and other device structures. The company's epitaxial foundry III-V division in Phoenix, AZ anticipates delivery of additional Aixtron 2600 G3 production reactors during the second half of 2000.

ATMI's President Phil Yin said; "With our multi-step expansion plan underway, ATMI Services' Silicon and III-V Divisions can already handle more than 100,000 wafers each month. We can already foresee the need to further expand capacity to handle the needs of the marketplace."

TRW Orders GaAs Plasma Etch Systems

TRW has ordered additional Tegal 901G diode plasma etchers, designed to etch 100 mm GaAs wafers for the manufacture of HBTs. Valued at around \$1 million, the etchers will be installed this year at TRW's Redondo Beach (CA) facility.

Cermet Receives Contracts to Develop ZnO and AlN

Cermet, a development-stage company based in Atlanta, GA focusing on III-nitride and II-VI semiconductor products, has recently received several contracts to develop emerging compound semiconductor materials such as ZnO and AlN. Both these materials are potential substrates for the growth of nitride-based devices. In addition, ZnO is a direct band gap semiconductor, with a band gap of approximately 3.37 eV, making the material a candidate for light emission in the blue and UV portion of the spectrum. Also, there exists a technology base for the deposition of high quality ZnO films using MOCVD.

Cermet was recently awarded a \$1 million contract by the Ballistic Missile Defense Organization (BMDO) to develop ZnO junction technology and demonstrate the fabrication of ZnO diodes. One advantage of ZnO is that high quality bulk material is available up to 2 inches in diameter, eliminating one of the major obstacles currently facing the nitride semiconductors. Earlier in the year, Cermet received a \$700,000 contract from the BMDO to develop high-quality, high-purity bulk ZnO material. The aim is to provide a ZnO wafer source at a projected volume price that is comparable to sapphire.

In related news, Cermet is also under contract with the BMDO to develop high-quality, high-purity bulk aluminum nitride (AlN) material. The aim is to provide a source of AlN substrates, which will enable the fabrication of nitride-based blue light emitters, high frequency transistors, UV photodetectors, and acoustic devices.

Fraunhofer Institute Founds Epiwafer Supply Company

Employees of the Fraunhofer Institute for Applied Solid State Physics in Freiburg and the venture group of the Fraunhofer Society in Munich have founded EpiNova GmbH, a commercial start-up company, to supply advanced III-V epitaxial layer structures. EpiNova is focused on MBE growth of III-V heterostructures and offers epitaxial wafers for PHEMTs and MESFETs on substrates up to 6-inch diameter, as well as MBE foundry services for lasers, infrared detectors and customized optoelectronic devices.

"EpiNova allows its customers to ramp up production quickly after the development of new products and bridges the gap between R&D and high volume production," says Dr. Martin Walther, CEO of EpiNova. The spin-off has rented lab and office space at the Fraunhofer Institute of Applied Solid State Physics in Freiburg. E-mail: info@epinova.de.

EPI Completes Facility Expansion

EPI MBE Products Group has finished adding manufacturing space for the production of its GEN2000 multiwafer production MBE system at its 75,000 sq. ft. facility in St. Paul (MN). In addition, EPI has purchased more than 871,000 sq. ft. of surrounding property for future expansion. The company has also opened a new sales and service office in Santa Clara, California.

Kopin Orders Six HBT Systems

Kopin has ordered six MOCVD reactors for the production of GaAs HBTs from Aixtron. Scheduled for delivery in 2001, this brings Kopin's total to 22 Aixtron machines—8 capable of supporting multiple 4-inch GaAs wafers and 14 for multiple 6-inch GaAs HBT production. "The HBT production systems we have ordered from Aixtron will enable Kopin to focus on capacity expansion at both our Taunton headquarters and at our recently announced second manufacturing site [in Taunton]," said president and CEO John Fan.

The new systems will enable Kopin to increase its 4-inch epiwafer capacity by more than 30%, and its 6-inch capacity by more than 60%. Kopin now expects its 4-inch capacity to be more than 400,000 wafers per year and its 6-inch capacity will expand to 200,000 wafers per year.

VG MBE Rector Sales Top 60 Units

VG Semicon has sold more than 60 production MBE systems, including the company's V100 (4-inch) and V150 (six-inch) systems, primarily used to manufacture GaAs-based RFICs.

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Solkatronic Expands Specialty Gas Capacities Again

Solkatronic Chemicals, a business unit of Air Products and Chemicals is again expanding capacity at its Morrisville, PA manufacturing facility to meet demand for specialty gases used in the compound semiconductor industry. Solkatronic is increasing output of its Blue Ammonia, which is used in the production GaN-based blue lasers and LEDs. Expected to be on-stream by July, this follows the company's recent doubling in capacity for ammonia and arsine [CS 6(3), p. 20].

Filtronic Buys Electroglas Wafer Probers

Filtronic Solid State has bought several Electroglas 4090f and 4090μ probers for its operations in Newton Aycliffe in the UK and Santa Clara, California. Wafer probers align each die on a wafer with pins on a probe card that measure electrical performance. The 4090f is specifically designed to test thin wafers, which are often reduced to less than 150 μm to dissipate heat and reduce the package height in wireless handsets. The 4090f uses film-based frames to hold fragile wafers in cassettes and electromagnetic grippers for transfer to a chuck for testing. Meanwhile, back-lapped wafers that remain strong enough to be held at their edges inside a cassette but sag, warp and flex can be safely handled and tested by 4090μ probers, says Electroglas.

Aixtron Ships First Reactor from New Plant

Aixtron's first reactor to come from its new MOCVD manufacturing facility, an AIX 2600G3, is being shipped to IQE/EPI for the growth of 5 × 6-inch PHEMT and HBT wafers. The new site in Aachen increases Aixtron's manufacturing capacity to 300 systems per year.

In more news, Aixtron recently sold its 150th AIX2600G3 system, and claims that in the first 5 months of the year it had sold 2/3 of all MOCVD machines to Taiwan, a total of 30 AIX2400 and 2600G3 reactors. UEC, Arima, Epistar, Procomp and others have placed orders totaling \$45.0 million, primarily for the production of HBTs, and AlInGaP and nitride LEDs.

Brush Wellman Expands Packaging Line

Brush Wellman (Newburyport, MA) has added several new integrated RF and microwave device packages based on its copper "CuPack" line, designed for use with power devices. The RF501 is small pill package that benefits from the electrical and thermal benefits of copper.

"With this package, and others in the developmental stage, we're focusing on the high power dissipation requirements of designers using LDMOS, Si, SiC, GaAs, and other semiconductor materials," said Bob Pomerleau of the company's Electronic

Packaging Group. Meanwhile, the RF705 is a single-ended out-line package suitable for among other materials SiC, GaAs and GaN. Manufactured with copper/tungsten, this package permits power dissipation up to 150 W.

FEI Receives Mask Repair Order

FEI (Hillsboro, OR) has received a \$3.0 million multiple unit order from a leading supplier of semiconductor communications electronics for equipment designed to repair photomasks, in addition to the provision of precise 3-dimensional topography profiles of mask surfaces. FEI will supply photomask repair based on its focused ion beam technology, which is integrated into a non-destructive nano-scale profiling metrology tool supplied by Surface/Interface (Sunnyvale, CA) Delivery is scheduled for delivery in the third quarter of this year.

In Brief...

Sumitomo Electric Industries (Yokohama, Japan) has recently purchased an **Aixtron AIX 2400** multiwafer MOCVD system for the growth of epiwafers for communications ICs.

KDF has relocated its manufacturing facility to Rockleigh, New Jersey. At 34,000 sq. ft., the new site offers KDF the chance to expand its manufacturing capacity for PVD systems.

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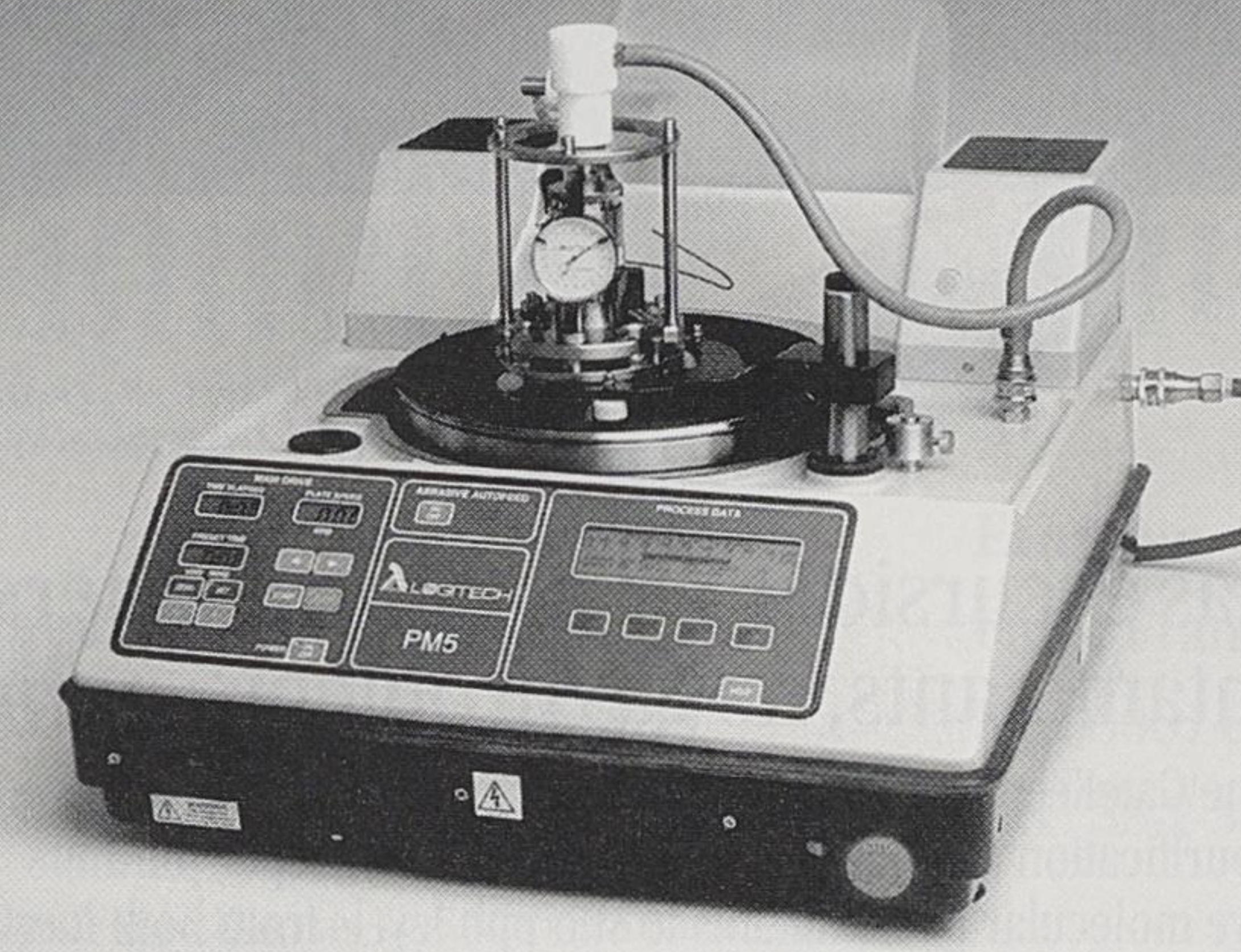
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Spectrolab Looks Beyond the Stars

Dieter Zemmrich, President of Spectrolab, Inc., describes the company's plans to develop a diverse portfolio of GaAs-based products, including HBT epiwafers.

As the market for satellites softened in 1997, Spectrolab, Inc., the world's leading supplier of solar cells, solar panels, searchlights, and solar simulators, faced a business challenge: how to leverage its core competency in gallium arsenide solar cell production into more diversified markets in order to maintain the economies of scale associated with 1-megawatt of annual production.

The company, in 1998, began a rigorous search into other fields, and selected three major market areas. Simultaneously, it ventured into the development of a business portfolio aimed at increasing the company's annual sales revenues by a factor of five.

Spectrolab is leveraging its core competency in MOVPE and its advanced wafer fabrication to serve the optoelectronic and microelectronic industries. The company currently offers GaAs HBT epitaxial wafers by MOVPE to support the fast-growing

wireless communications market for handheld mobile telephones. Spectrolab also offers a variety of sensors, including p-i-n detectors and avalanche photodiode wafers in the 1.3–1.7 μm range, using GaAs-based materials for high-speed communications. Spectrolab also continues to design and manufacture high-energy laser arrays for use in military applications.

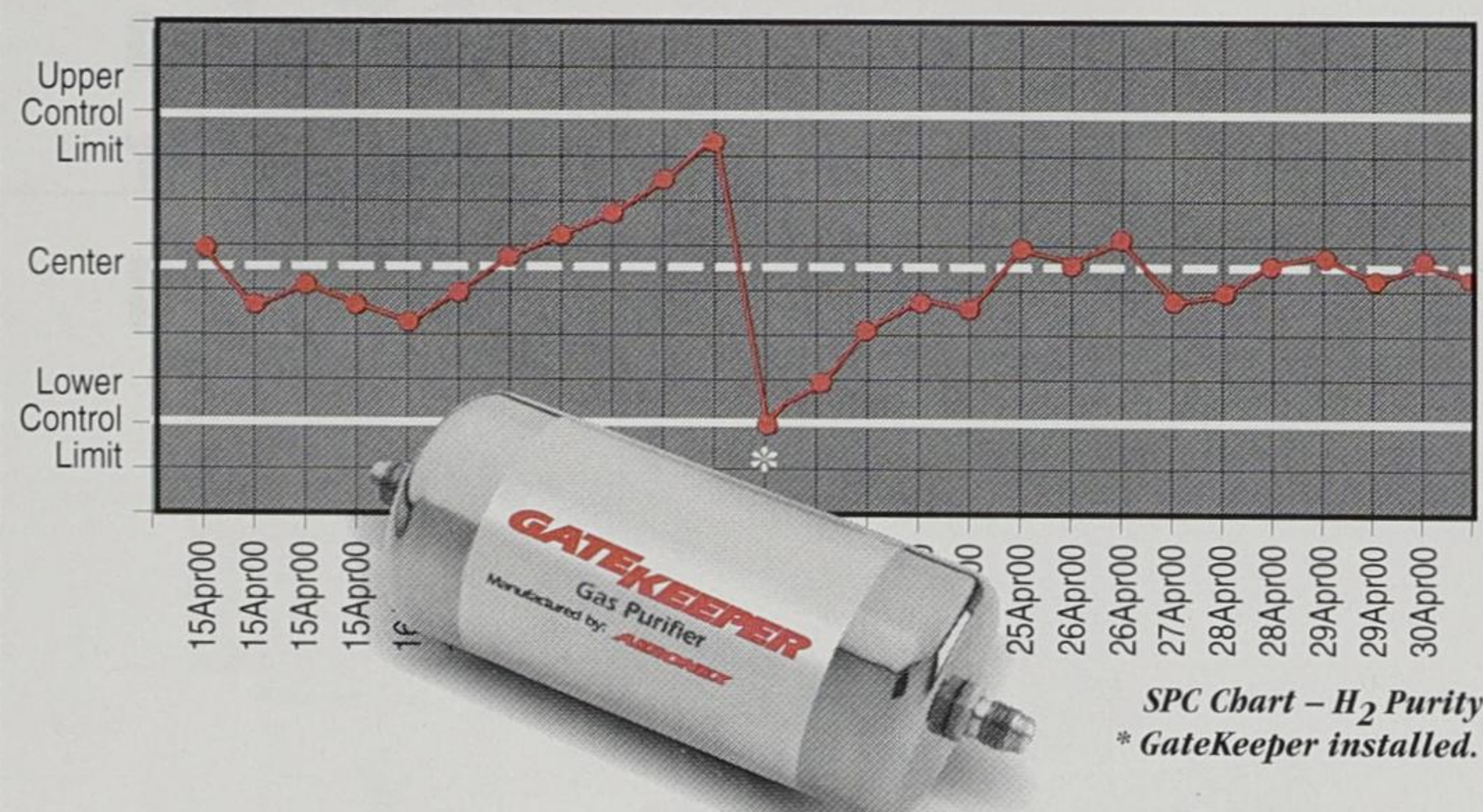
Terrestrial power generation is another major market area suited for gallium arsenide products. Global terrestrial photovoltaic (PV) product shipments reached 200 megawatts in 1999, and industry projections indicate an annual growth rate of 25% in the area of distributed energy generation. Spectrolab's recent demonstration of GaAs-based terrestrial solar cells with efficiencies greater than 30% makes these cells a more cost-effective alternative than conventional solar cell modules, thus opening a host of new applications and market segments.

Spectrolab is currently pursuing opportunities in terrestrial energy generation in a number of applications, including General Motors' electric vehicles and a new concept, "Power in a Box," wherein solar technology is harnessed in a mobile container, thus providing electrical infrastructure to remote areas.

The third major area continues to be space. As Spectrolab continues to increase conversion efficiencies of its solar cells, with latest efficiencies reaching higher than 27%, it hopes to capture an even larger portion of the market for space solar cell technology. Spectrolab already leads the world in production, however, its entry into diversified markets would enable the company to achieve even higher rates of return on investment that would fuel continuing research and development and enable Spectrolab to maintain its leadership position in the industry.

In January 2000, Boeing started the process to acquire Spectrolab, along with Hughes Space and Communications Company and Hughes Electron Dynamics, from parent Hughes Electronics Corporation. The sale is expected to complete in the third quarter of 2000.

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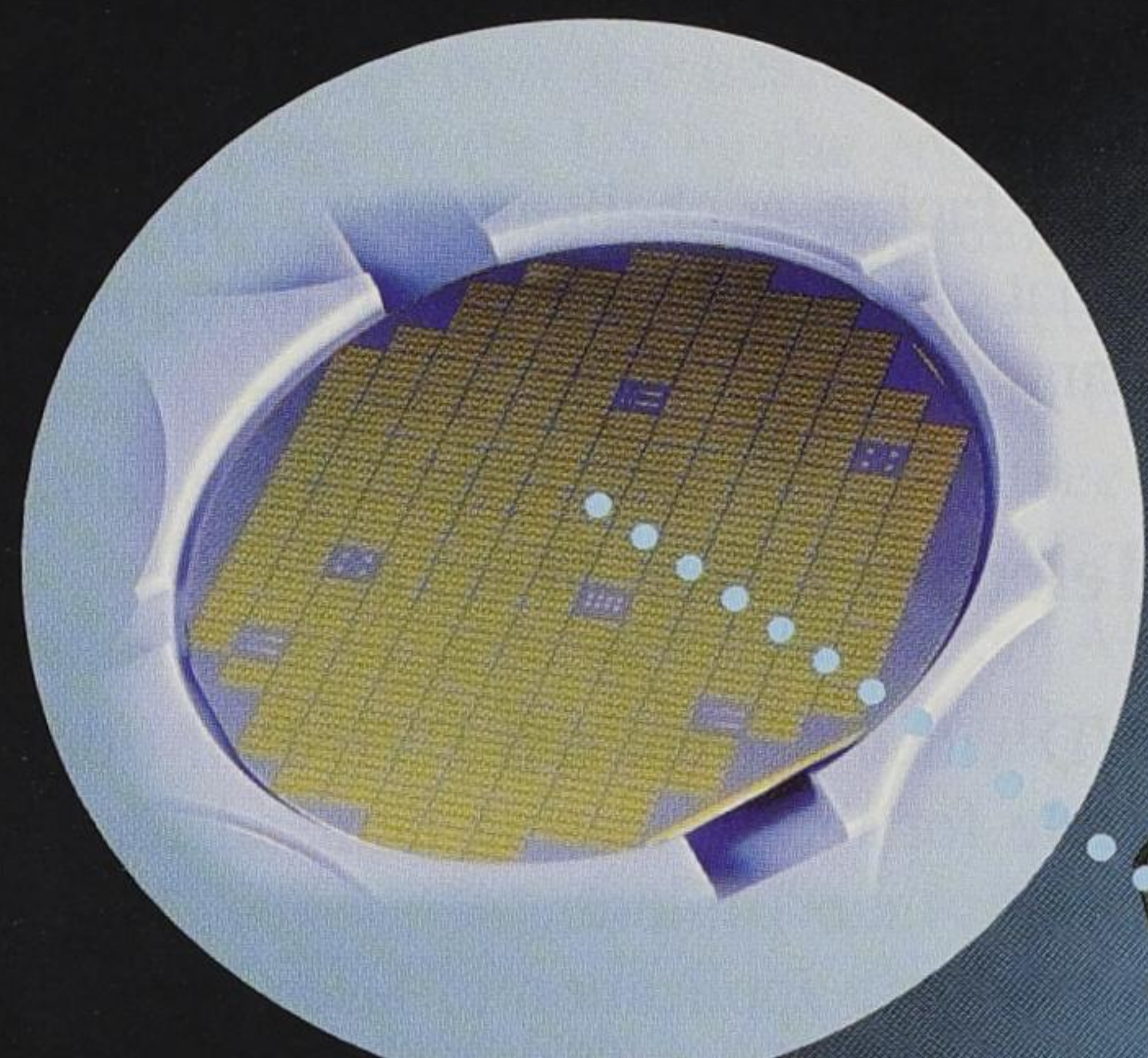
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80-Satellite SkyBridge System Gains Approval

The SkyBridge consortium, led by Alcatel, has received regulatory approval from the International Telecommunication Union to use the Ku-band (10–18 GHz) for its broadband satellite system, which will include 80 low-earth orbit (LEO) spacecraft. Previously there had been concerns that the system would interfere with existing users—both geo-stationary satellites and terrestrial systems—operating in the same frequency band.

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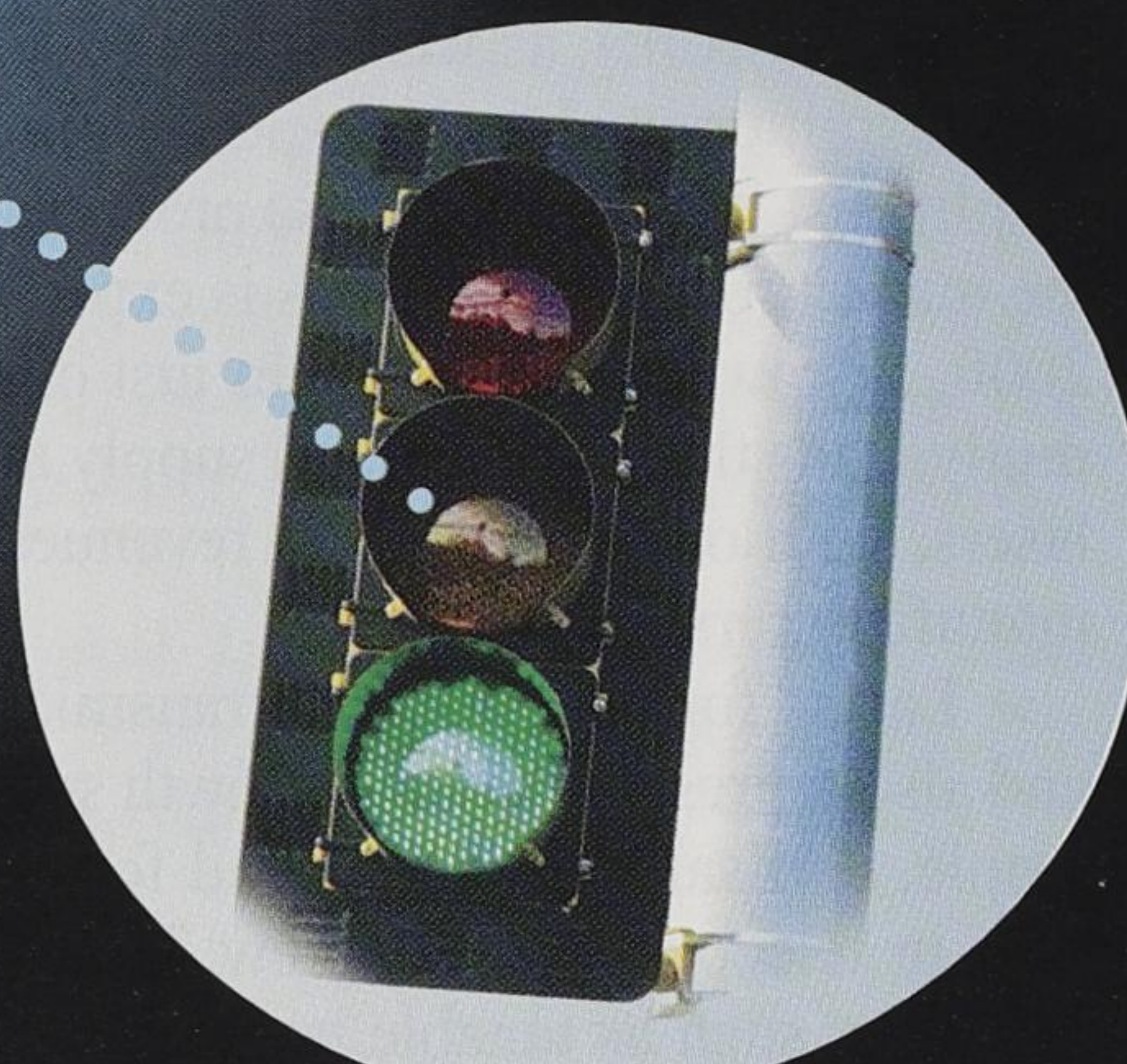
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Strong Growth Forecast for Major Laser Markets

According to reports recently published by Strategies Unlimited (Mountain View, California), the two largest segments of the semiconductor laser market will both experience strong growth in the next several years. The worldwide market for laser diodes for telecommunications applications is forecast to grow from \$1.95 billion in 1999 to \$5.35 billion in 2004, for a compounded growth rate of over 22% per year [1]. Likewise, as shown in the figure, the market for laser diodes with wavelengths less than 1 micron for use in non-communications applications is forecast to exceed \$2.2 billion by 2004, growing from \$966 million in 1999.

Telecom Laser Market to Grow 50% in 2000

Laser diodes are a key component in local and long-distance telecom networks, as well as in CATV distribution systems, both as transmitters and as high-power pump sources to drive optical amplifiers. Demand for these products is so strong at present that the market for telecom lasers is expected to reach \$2.92 billion in 2000, a growth rate of 50% in just one year. North America currently leads the world in both supply and consumption of telecom lasers, with over 50% of the revenues going to North American manufacturers.

Lasers for long distance transmission have the highest prices and also represent the high growth segment of the market. For example, unit sales of lasers used for transmission of 10 Gb/s signals in telecom systems grew 250% in 1999 alone. Some new products, such as tunable lasers, promise to seize a sizable share of specific market segments by 2004.

The report states that strong growth in revenue will continue to occur simultaneously with steeply falling prices and even stronger growth in unit sales. Laser manufacturers are able to meet expectations for continued price reductions because the sharp growth in unit sales is bringing new economies of scale and experience in an industry unaccustomed to such large volumes. Major manufacturers such as Lucent and Nortel are investing heavily in automation while at the same time rapidly increasing their capacity.

Another important point is that lasers in telecom systems are not necessarily competing against electronics and copper systems

anymore, but are instead facing a challenge from all-optical switching technologies that could make some (but by no means all) of the lasers redundant.

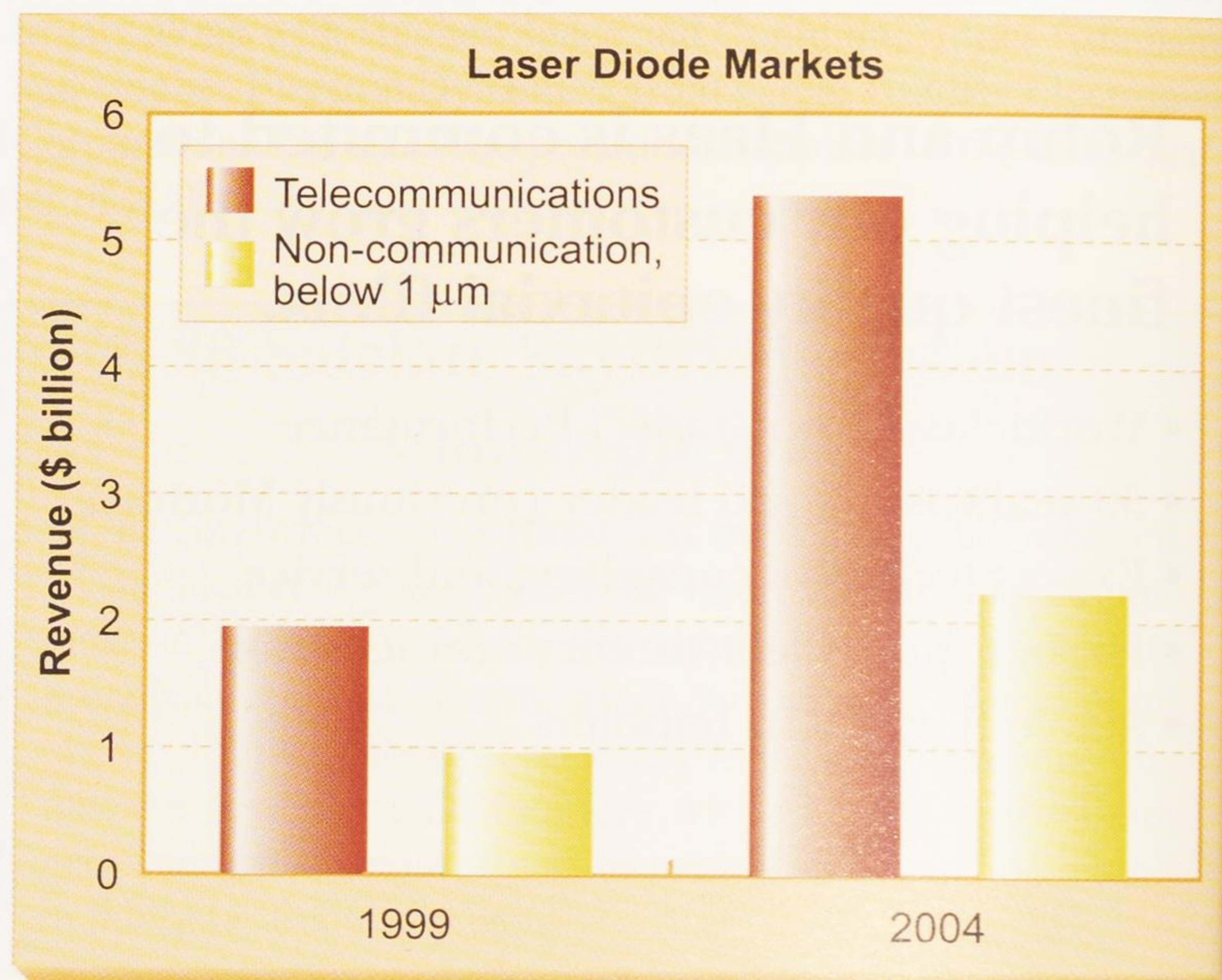
DVD Drives Non-Telecom Laser Market

The market for DVD video players and DVD-ROM drives will be largely responsible for the increasing demand for laser diodes with wavelengths less than 1 micron.

The first significant volume application of laser diodes, beginning in 1981, was in audio CD players—these systems use 780 nm lasers. Visible red (630–680 nm) laser diodes became available in 1988, and these were initially used primarily for barcode scanner and laser pointer applications. More recently, these diodes have been used in higher density optical storage systems, such as DVD-ROM drives. Other applications for lasers with wavelengths below 1 micron include laser printers, industrial material processing systems and “computer-to-plate” digital printing presses.

According to the report, a significant market for shorter-wavelength blue (400–470 nm) devices will begin to emerge in 2002. Nichia Corporation has demonstrated a long-lived (10,000-hour) blue laser diode, and Sony, Fujitsu, Toshiba and many other companies have aggressive research programs to develop these devices for high-density optical storage applications. The report forecasts blue laser diodes in optical storage applications beginning in 2002.

The majority of low-power laser diodes (<100 mW) are supplied by Japanese companies such as Sony, Rohm, Sharp, and Matsushita, while North American companies, such as SDL and Opto Power, have taken a leading role in the high-power (>10 W) market.



[1] “Telecom Laser Diode Market Review and Forecast—2000.”

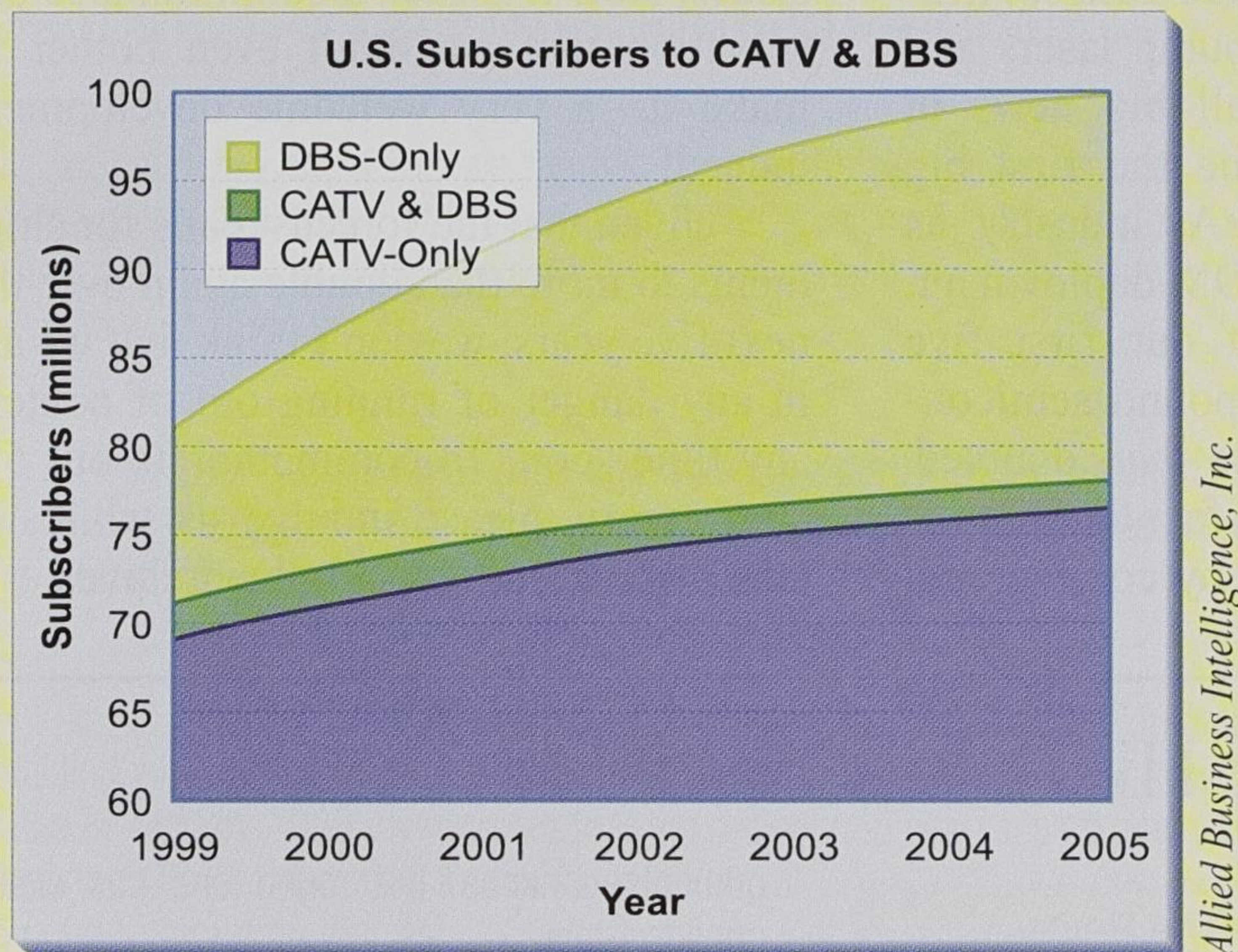
[2] “Laser Diode Market Review and Forecast—2000 (Short-Wavelength, Non-Communications).”

Both reports are available from Strategies Unlimited. TEL: +1 650 941-3438, FAX: +1 650 941-5120, EMAIL: info@strategies-u.com, WEB: <http://www.strategies-u.com>.

CATV and DBS Forecast

According to Allied Business Intelligence, the US market for direct broadcast satellite (DBS) services will grow rapidly over the next 5 years. DBS had 11 million subscribers in the US by the end of 1999, far short of the 71 million watching cable TV, mainly due to the inability of DBS to offer local channels. Recent legislative changes will remove this disadvantage, and there will be over 22 million DBS subscribers by 2005 (see figure).

"CATV Infrastructure 2000: US Equipment Markets and System Trends" is available from Allied Business Intelligence. TEL: +1 516 624-3113, WEB: www.aliedworld.com.



Semiconductor Industry to Grow to \$222 billion in 2000

According to the latest forecast by Dataquest, a unit of Gartner Group, the total worldwide revenue from the semiconductor industry is set to reach \$222 billion in 2000. This represents an increase of 31% over the 1999 figure of \$169 billion. In comparison, the total revenue from compound semiconductor markets is predicted to reach \$13.6 billion in 2000, or slightly more than 6% of the total for the industry as a whole [see CS 5(3), p. 23.]

The volatile dynamic random-access memory (DRAM) market will provide much of the industry's short-term growth, and the overall market is expected to reach \$320 billion by 2002. However, Dataquest analysts believe that an oversupply situation in the DRAM market will initiate a cyclical decline in revenue by the end of 2002. WEB: www.dataquest.com.

55% Growth Rate for Broadband Services

The North American market for broadband services will experience a CAGR of 55% over the next five years, with revenues of \$30 billion in 2005, says a report from Forward Concepts. The installed base of broadband-enabled customers will reach 35 million by 2005, and cable modems will capture about 60% of the consumer subscriber market. Digital subscriber line (DSL) will dominate in the small office, home office (SOHO) and enterprise segments.

"Broadband in the Local Loop '00" is available from Forward Concepts. TEL: Will Strauss, +1 480 968-3759, WEB: www.forwardconcepts.com.

Fiber-to-the-Building Heads FTTX Markets

Although bringing fiber to the home, desk or building (collectively termed "fiber-to-the-x") has been the dream of service providers for years if not decades, the main obstacle has been prohibitively high costs. However, as fiber-optic components decline in price and demand for bandwidth continues to increase, fiber-to-the-x services are starting to make in-roads into the broadband market, according to a new report from Communications Industry Researchers (CIR). As shown in the Table, the early leader will be fiber-to-the-building (FTTB). CIR predicts that 65% of the largest commercial and industrial buildings in the US will be connected to fiber by the end of 2000. Major corporations now view bandwidth as a key difference between success and failure. Fiber within the building, taking optics to the desktop or workstation rather than using copper cable, will also emerge rapidly within the next few years.

As far as consumers are concerned, the fastest growing segment will be fiber-to-the-curb (FTTC), as cable TV providers and independent carriers seek to offer more bandwidth as a competitive edge. For example, BellSouth, a leading US carrier, has

a policy to use FTTC in all its new residential developments. Fiber-to-the-home (FTTH) is not expected to take off to the same extent, although the potential is huge: there are over 100 million households in the US alone.

"Fiber-to-the-X: The New Market for Fiber to the Desk, Cabinet and Home" is available from Communications Industry Researchers (CIR). Contact: Rob Nolan, TEL: +1 617 923-7611, FAX: +1 804 984-0247, EMAIL: rob@cir-inc.com, WEB: www.cir-inc.com.

Fiber-to-the-X	Market (\$ million)		
	2000	2002	2004
Fiber-to-the-building (FTTB)	601	752	900
Fiber-in-the-building	108	284	612
Fiber-to-the-curb (FTTC)	247	423	937
Fiber-to-the-home (FTTH)	5	49	107

CIR

Our 5th Anniversary Issue

From the archives—a collection of big hits, near misses, and things which seemed like a good idea at the time.

MARIE MEYER

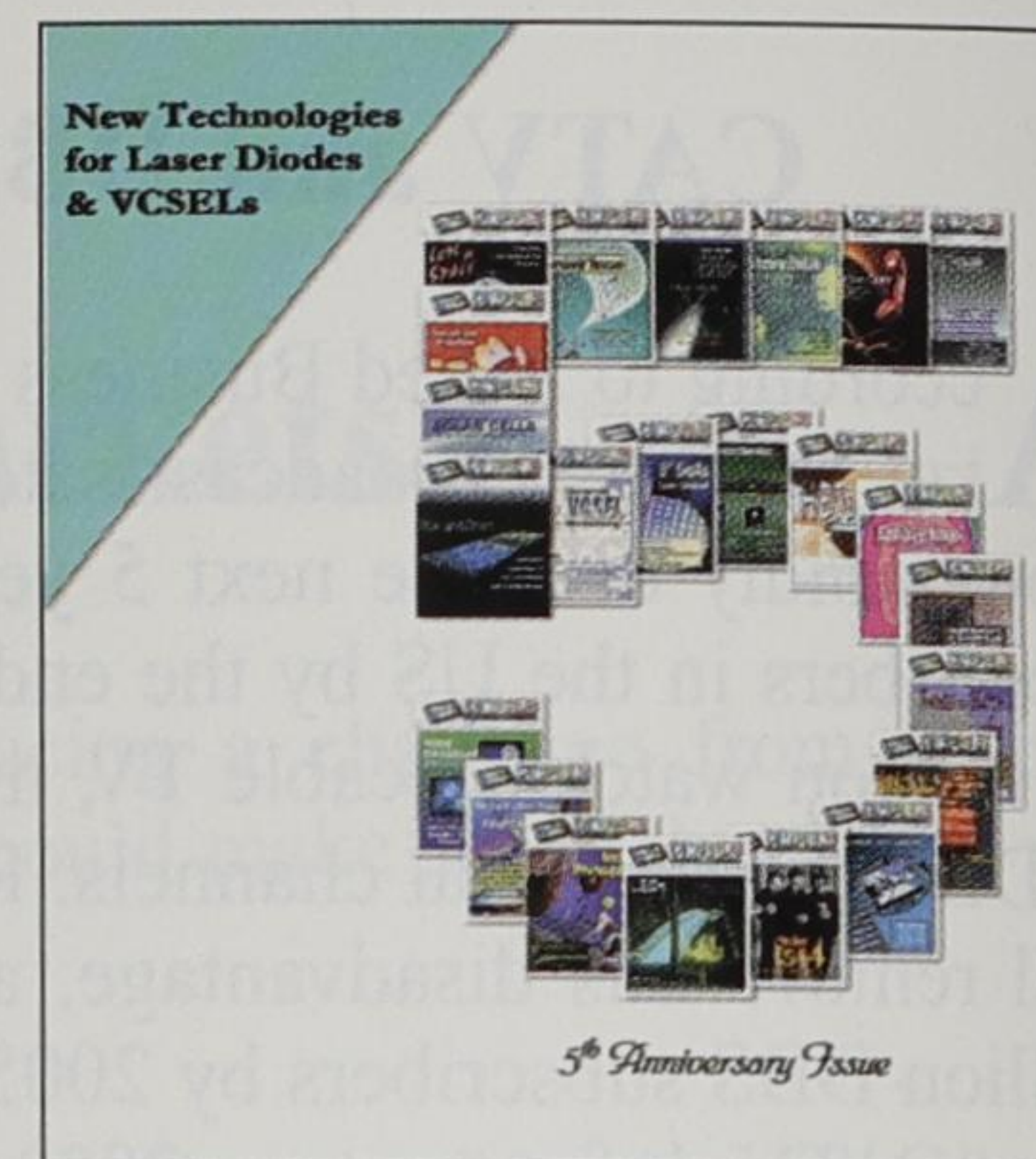
This magazine was launched on July 20, 1995. We mailed out several thousand copies, waited nervously for two weeks, and then started calling people and asking “what did you think?” The large majority of responses went something like this: “Very nice, really interesting and useful. But how on earth are you going to keep it up—won’t you run out of things to talk about after two or three issues?”

Here we are, five years later, and we still haven’t run out of topics! We were

very fortunate in that we came on the scene just as many interesting developments were emerging. Blue LEDs, AlIn-GaP red LEDs, 980nm pump lasers and III-V solar cells were all big news in 1995; then in 1996 came the first big building boom in the GaAs industry, as well as the ramp up of WDM deployment. And over the course of our first five years, shipments of compound semiconductor devices have more than doubled, reaching \$10 billion. The fact that our industry is now dominated by commercial,

rather than military/R&D concerns, was a re-occurring theme in many of our early issues. Now it is such a commonplace observation that we don’t even bother to make it—a very welcome development indeed!

Given that the forecast calls for shipments to more than double again over the next five years, we don’t think that we are in any danger of running out of content any time soon. To commemorate our 5th anniversary, please indulge us while we take a little tour through the archives.



5 Greatest Hits

1) Prophetic, Part I

“The lighting industry has been put under long range threat. It will take some time for the LED to be fully developed in all its possible display uses, and at equal performance across the entire visible spectrum . . . Nevertheless, it will happen, as, indeed, it is beginning to occur already.” Nick Holonyak, Jr., accepting the 1995 Japan Prize, as reported in our Inaugural Issue. Holonyak and a small handful of others have seen since the early 1990’s what is just now becoming generally understood—that the long term prospects for solid-state lighting using LEDs is phenomenal.

2) GaAs v. SiGe— And the Winner is . . .

One of our early claims to fame was that we were the first to point out that despite all the noise that was being made about SiGe, no companies were actually producing any SiGe devices. They did not appear on the market until early 1999, about 5 years later than expected. Shipments remain low. GaAs sales will top \$3 billion this year; SiGe sales will be around \$100 million. The forecast shows that GaAs will likely top \$10 billion in 2004, while SiGe is expected to be around \$1.5 billion. The ar-

COMPANY	SHARE PRICE	
	Jan '96*	June '00
Alpha	4.54	57
Anadigics	9.44	38
ATMI	10.375	47
Cree	7.375	173
SDL	4.25	306
TriQuint	4.75	125
Vitesse	2.1875	86.5

*Adjusted for splits

The purchase of a hundred shares of each in January, 1996 would have cost \$11,275. As of June 20, 2000, that investment would be worth nearly \$83,250.

If only we had taken our own advice . . .

March 1996 when we were the first to report that Vitesse had committed to building the industry’s first 6” GaAs fab. After that, we tried to faithfully chronicle every other company that was scaling up. (In addition to Vitesse, Anadigics, Infineon, Motorola and Filtronic are already processing 6” wafers; several other

guments continue, but round one has clearly gone to GaAs.

3) Prophetic, Part II

In March 1996, commenting on the strategic alliance between TRW and RF Micro Devices for GaAs HBTs, we said “the new alliance looks like a ‘win/win’ situation for both parties. And how. TRW got access to high volume markets it probably never could have reached on its own, as well as a major stake in one of America’s fastest growing companies. As for RFMD, they went from being a fabless design house in 1996 to being the top merchant manufacturer of analog GaAs ICs in 1999. With apologies to Nichia, JDS Uniphase, and Vitesse, one would be hard-pressed to find a more impressive story in the past 5 years than this one.

4) Big, Bigger, Biggest (Wafers)

Possibly our biggest “scoop” came in

5 Greatest Misses

1) In our inaugural issue we were absolutely floored by the fact that slightly more than 3 million LEDs were used in a billboard sized display in China. Today, pop stars take more than that out on tour. The current record is 19 million LEDs on the NADSAQ building in New York City. Now that is impressive.

2) Also from our Inaugural issue in 1995: "One of the most tantalizing possibilities is that of making white light by combining red, green and blue LEDs." We repeated this refrain a few times in 1996. It wasn't until late that year, when Nichia Chemical released their first white light LEDs, that we realized that there was a rather more straightforward way of doing it . . .

3) In 1995 and 1996 we ran two different articles about a rather expensive program aimed at growing compound semiconductor epiwafers on the space shuttle without ever asking the fundamental question: why would anyone want to do this?

4) In 1995 we said that ZnSe and GaN were pretty evenly matched as candidate materials for making blue lasers, and that it would take decades for all the issues to resolved. Wrong on both counts.

5) In May 1997 we reported that CTI Semiconductor Corporation was building what would have been the world's largest GaAs fab in South Korea. Then in January 1998 we reported that the project had been scaled down by around 50%, in response to the Asian Financial Crisis. Alas, we never got around to reporting that the whole deal subsequently went sour and is completely dead—except for the lawsuits, which may go on forever.

companies, including Win Semiconductor, Advanced Wireless Semiconductor, Marconi, GCS, TriQuint, Sanders, M/A-COM and Agilent are either building 6" fabs or have committed to putting in new 6" lines.) Now we get to watch the InP field. The credibility of the whole concept of InP ICs as a commercially viable technology recently got a huge boost, and again Vitesse was the catalyst. As we reported in our April issue, they are planning on using InP for 40 Gb/s products to be introduced within the next few years. This time, though, they'll be using a foundry partner, not building a fab. The partner is, as of now, unnamed, but TRW seems like a very good bet.

5) Buy Low, Sell High

In January 1996 we launched our "Portfolio Section", with the idea that we would track a "mythical" investment in seven stocks: Alpha, Anadigics, ATMI, Cree, SDL, TriQuint and Vitesse. Subsequent IPOs have expanded the list to more than 20, but look how well the original members of the club have done (see chart). The purchase of a hundred shares of each in January, 1996 would have cost \$11,275. As of June 20, 2000, that investment be worth nearly \$83,250. If only we have taken our own advice . . .

5 Biggest Surprises

1) The strength of the American GaAs industry. In the early 1980's and late 1990's, it was generally assumed that the American semiconductor industry as a whole was completely hopeless, and that the GaAs industry would probably turn out to be even worse, as it was populated with a lot of very small operations. But what looked like a liability then has turned out to be an asset. These small companies have a demonstrated ability to respond quickly to shifting market conditions. In 1996 the North American GaAs fabs surpassed their Japanese counterparts for the first time, and they haven't looked back. Market share for U.S. fabs in comparison to Japanese fabs has risen from 47% vs. 44% in 1996 to roughly 50% vs. 35% today. And given that American fabs have been more aggressive in expanding their capacity, this trend is likely to continue.

2) The emergence of high brightness red-yellow-orange LEDs as really interesting subject area, plus the fact that the center of gravity in LED manufacturing is rapidly shifting to Taiwan.

3) IBM's decision to sell their Laser Enterprise Unit to Uniphase in 1997 for less than \$75 million. The 980nm pump laser that was developed at IBM is probably the single most important WDM component, and it has played a major role in propelling Uniphase—now JDSU—into their currently lofty position.

Perhaps we are paranoid, but IBM really seems to have something against compound semiconductors—first they dropped their GaAs program in favor of SiGe, and then they made this move. A little known fact: their 980nm pump laser was developed almost by accident. What they wanted was a high power 850nm diode that could be frequency-doubled to produce a 40mW blue laser for optical data storage.

4) Cree. In January 1998 we wrote an article suggesting that Nichia's lead in the blue LED field was so insurmountable that the most interesting question in this sector was who would be the #2 supplier. At that time Cree occupied that slot, with an estimated 21% market share, compared to 59% for Nichia. But, we suggested they probably would not be able to maintain their position.

How wrong we were! In 1998 Cree overhauled its LED production, switching over to a new vertical device structure that proved to be much cheaper to produce. The devices were also significantly brighter, closing the performance gap with Nichia. And the company moved very aggressively to capture the low-cost, high volume market, especially with regard to applications such as automotive interior lighting. From 1998 to 1999 they nearly tripled their output, and are now considered to have around 33% of the market (measured in terms of units), compared to Nichia's 40%. Meanwhile, Agilent and other former rising stars in the field appear to be holding back, likely because they are waiting for the outcome of a nasty patent fight being waged between Nichia and Toyoda Gosei over some fundamental aspects of GaN-on-sapphire technology.

5) (Tie) The Rapid Acceptance of HBT Technology/The Rapid Development of Blue LED/Blue Laser Products. Come on, admit it, you were surprised, too!

5th Anniversary

As Compound Semiconductor celebrates its 5th year anniversary, we'd like to take a moment and thank our advertisers. They make the whole enterprise possible. We don't have enough space to adequately acknowledge each of the more than 125 companies, but we would like to recognize the following for their significant support over the last two years.

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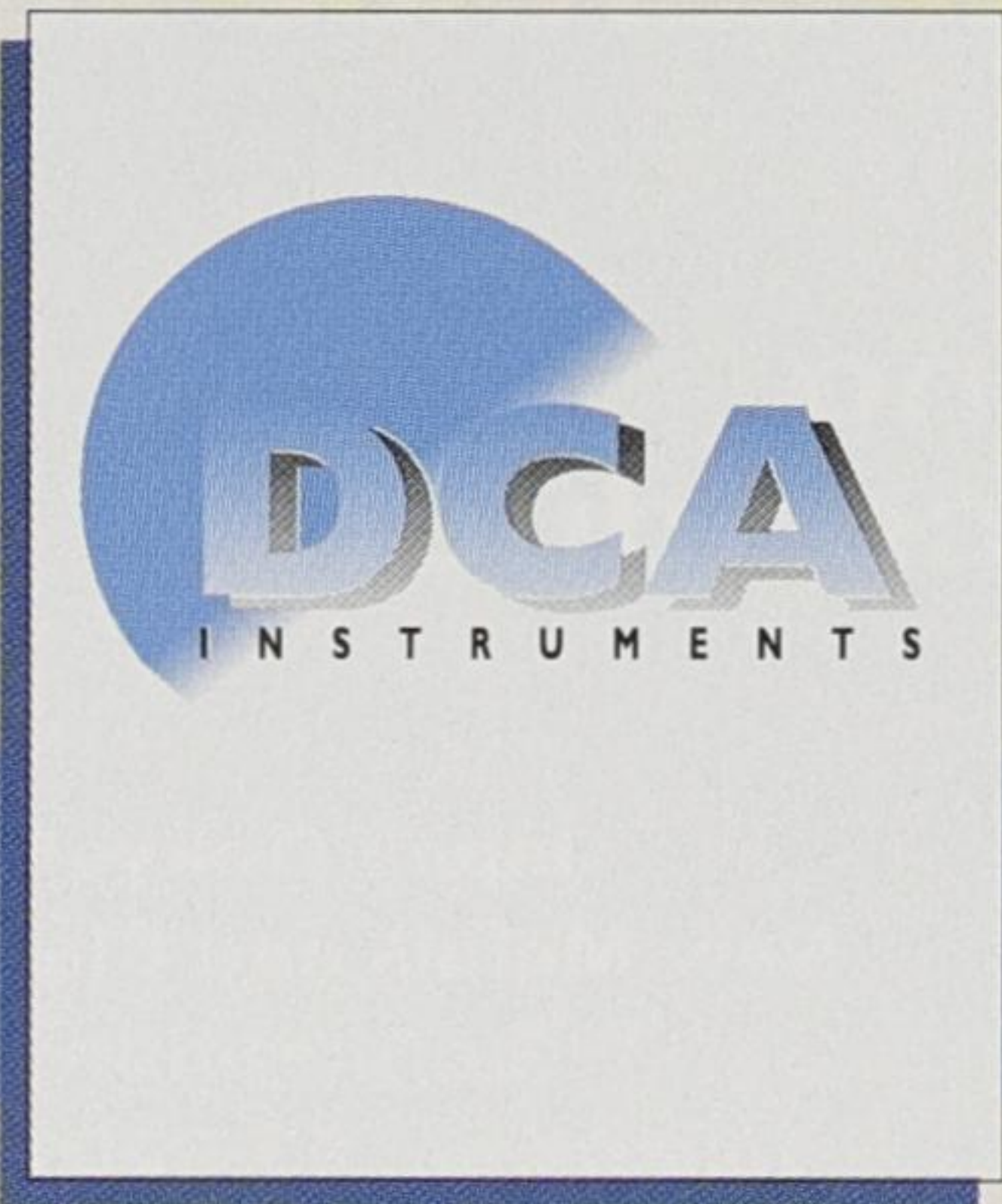
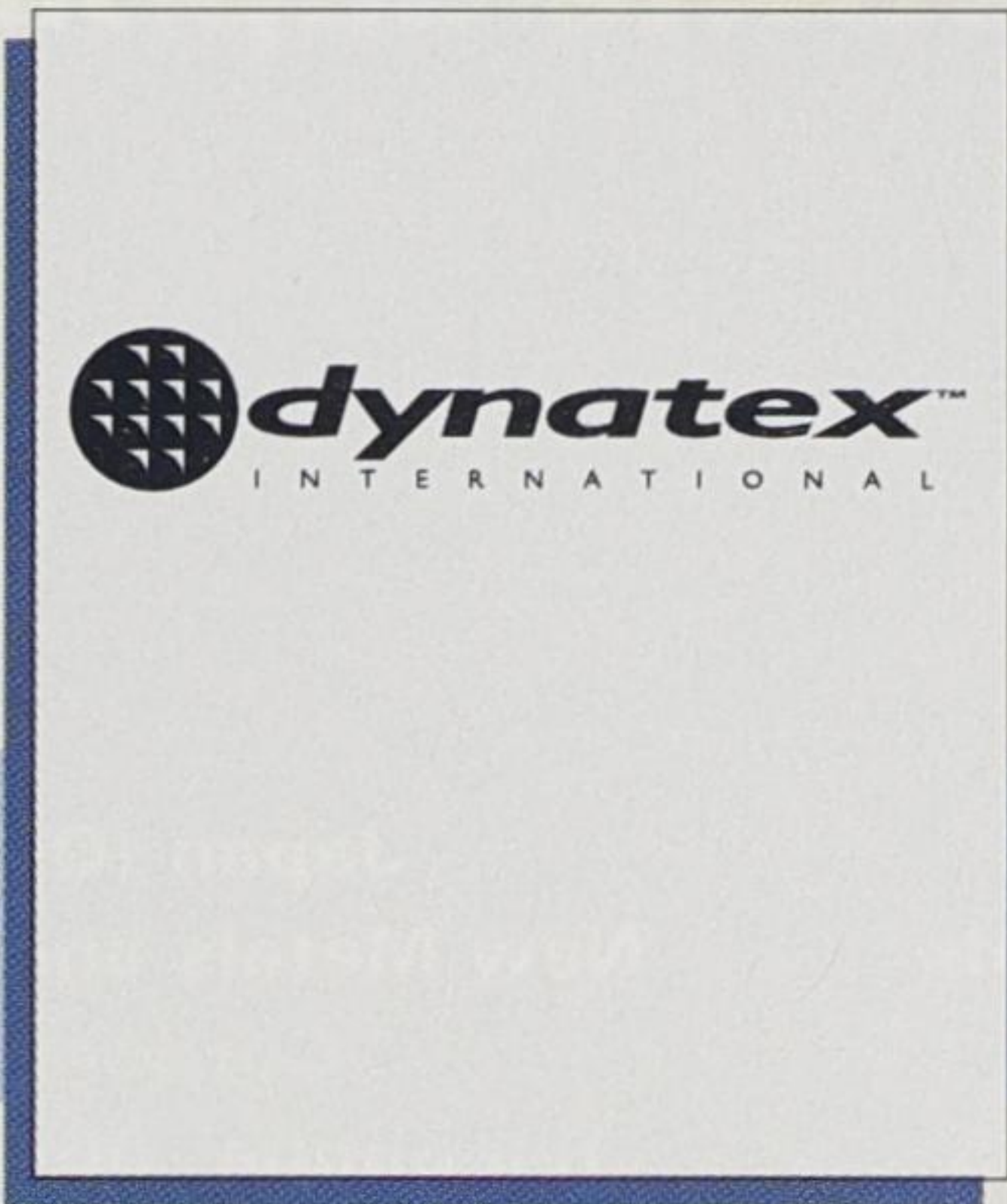
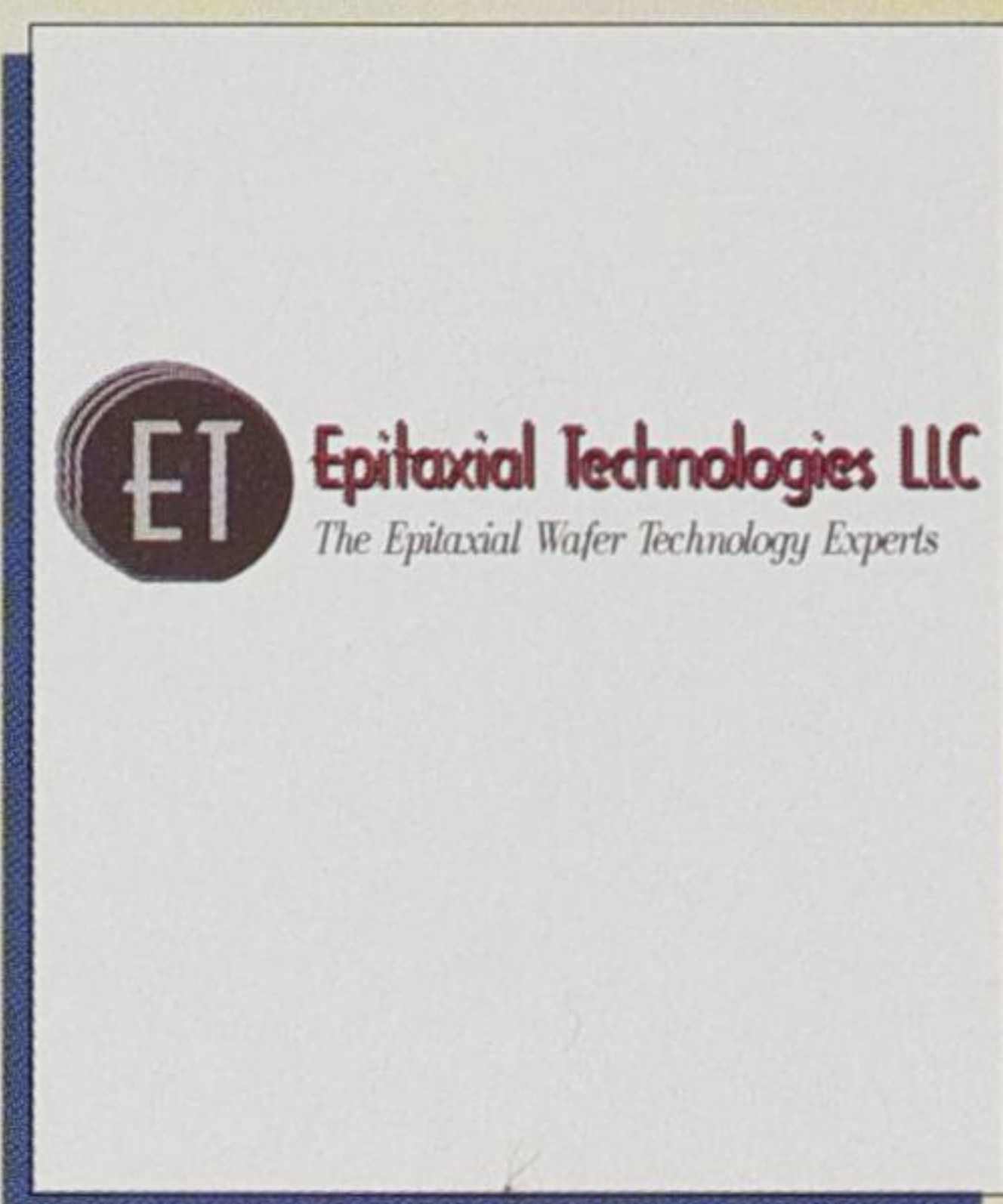
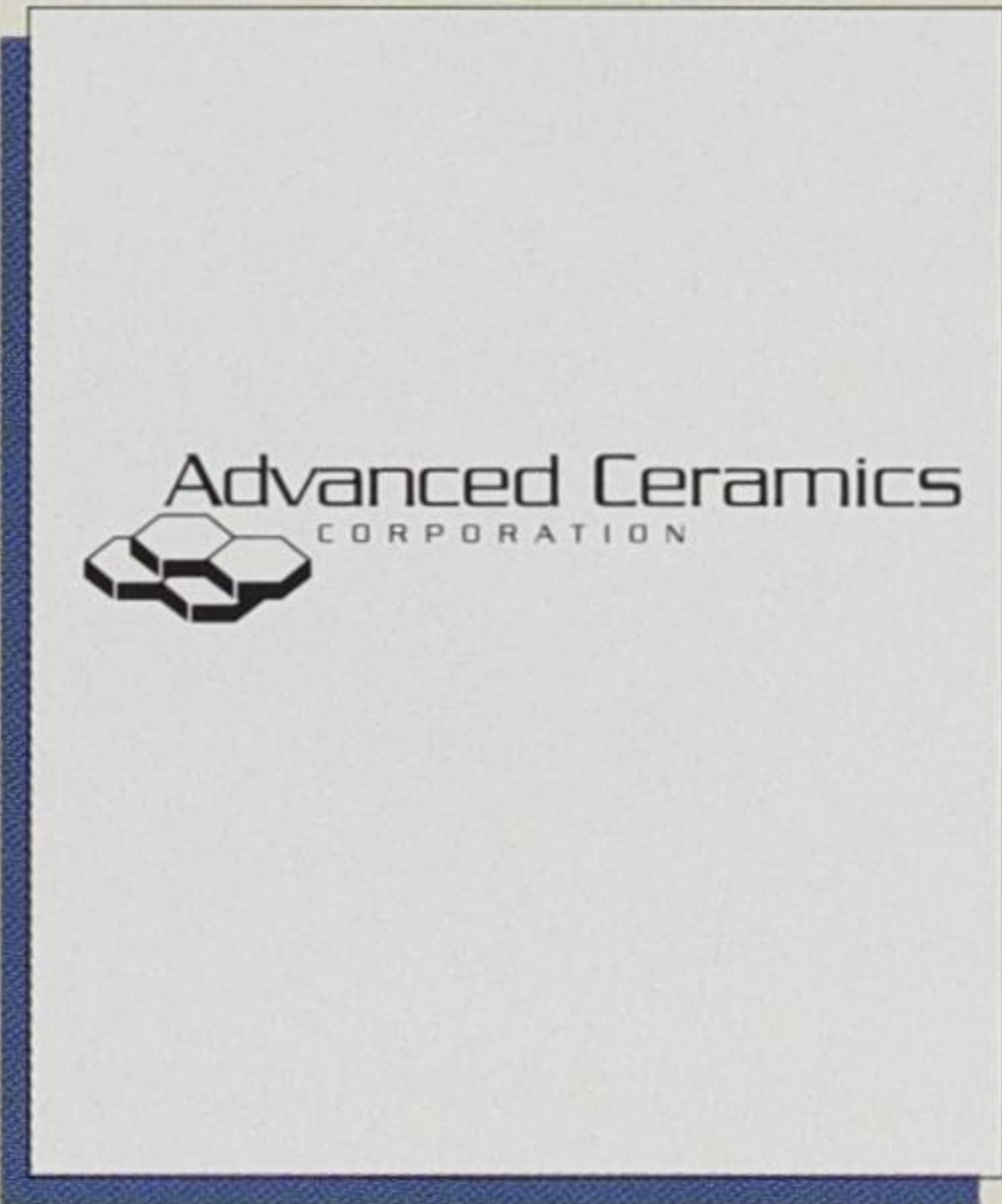
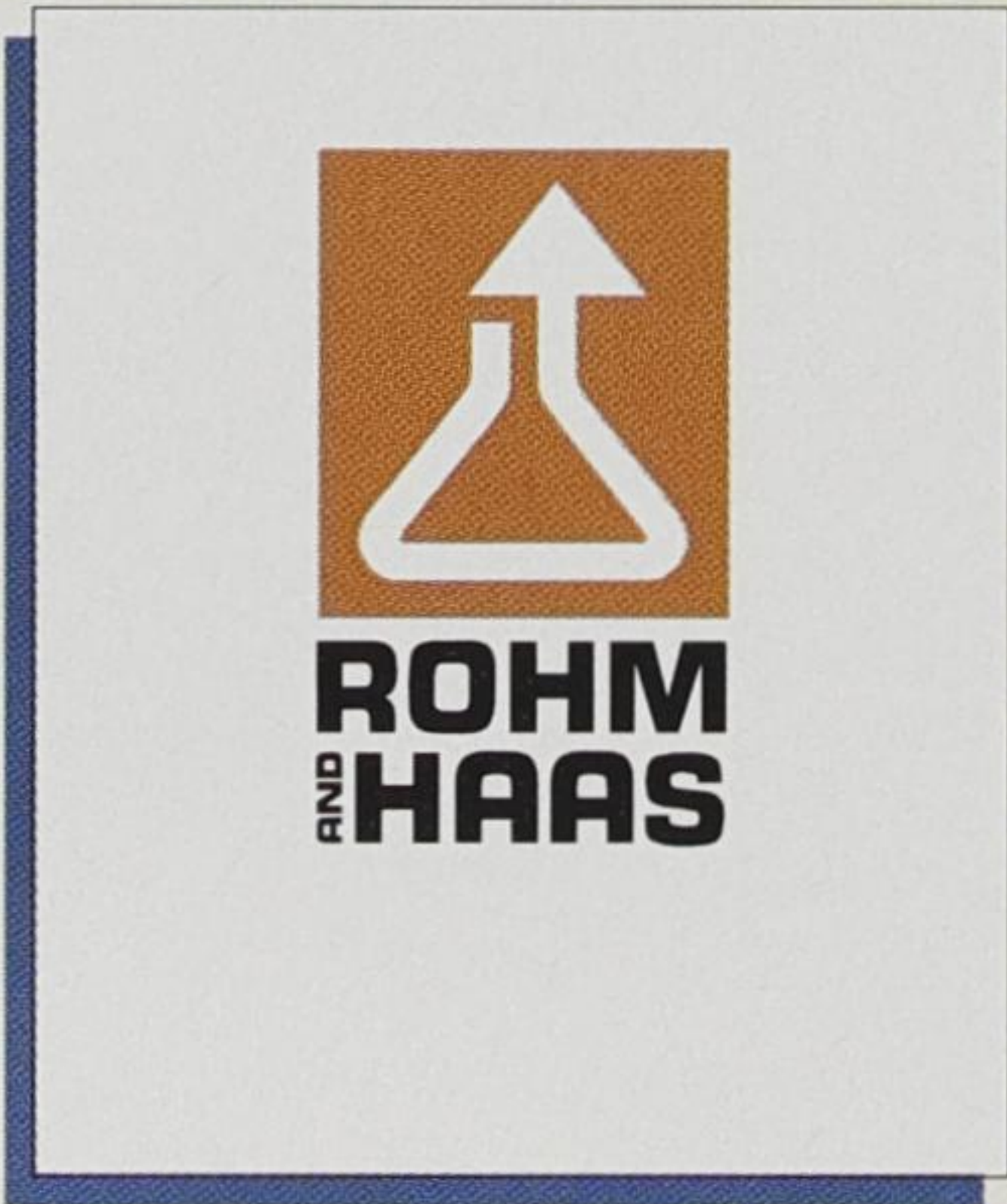
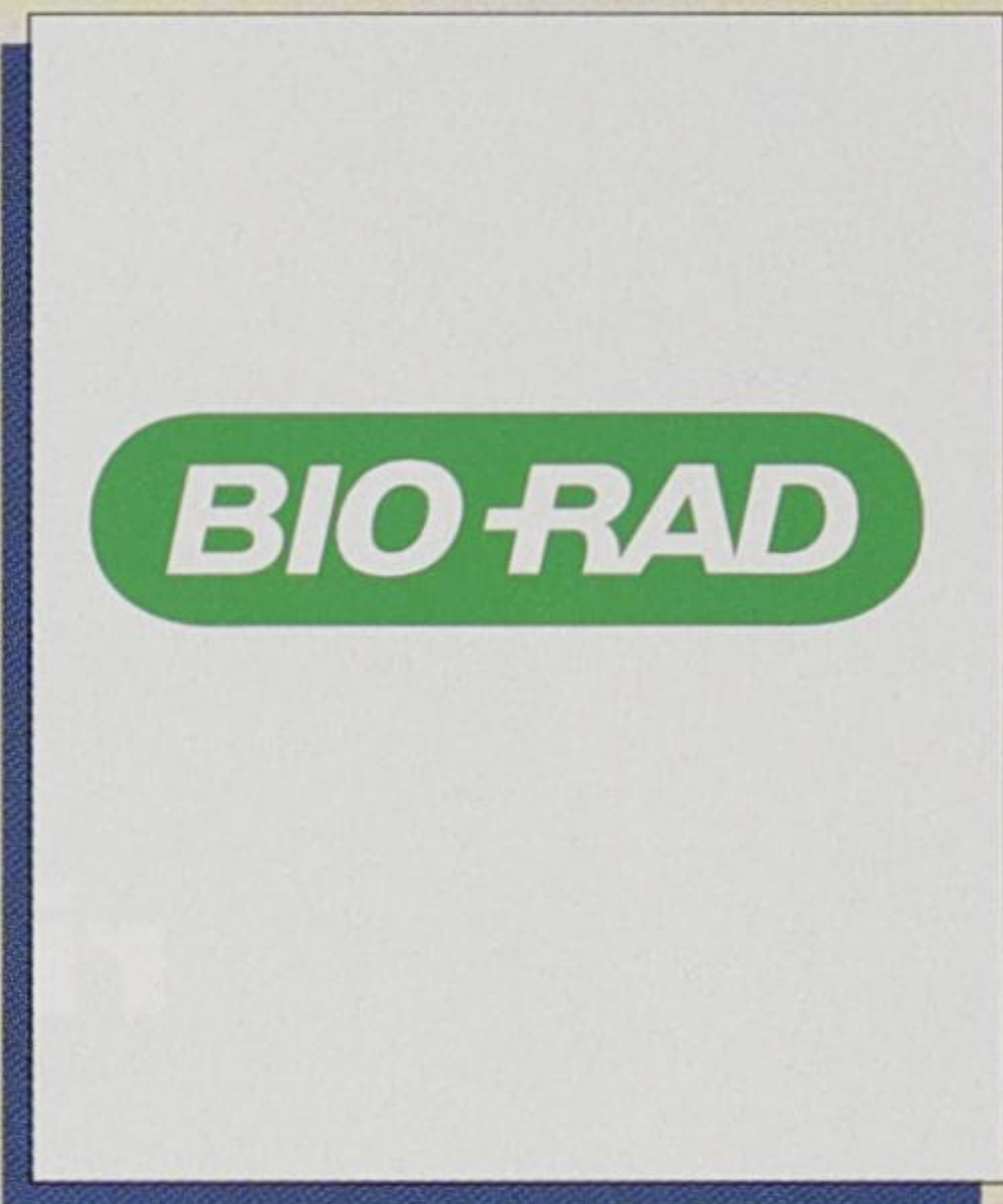
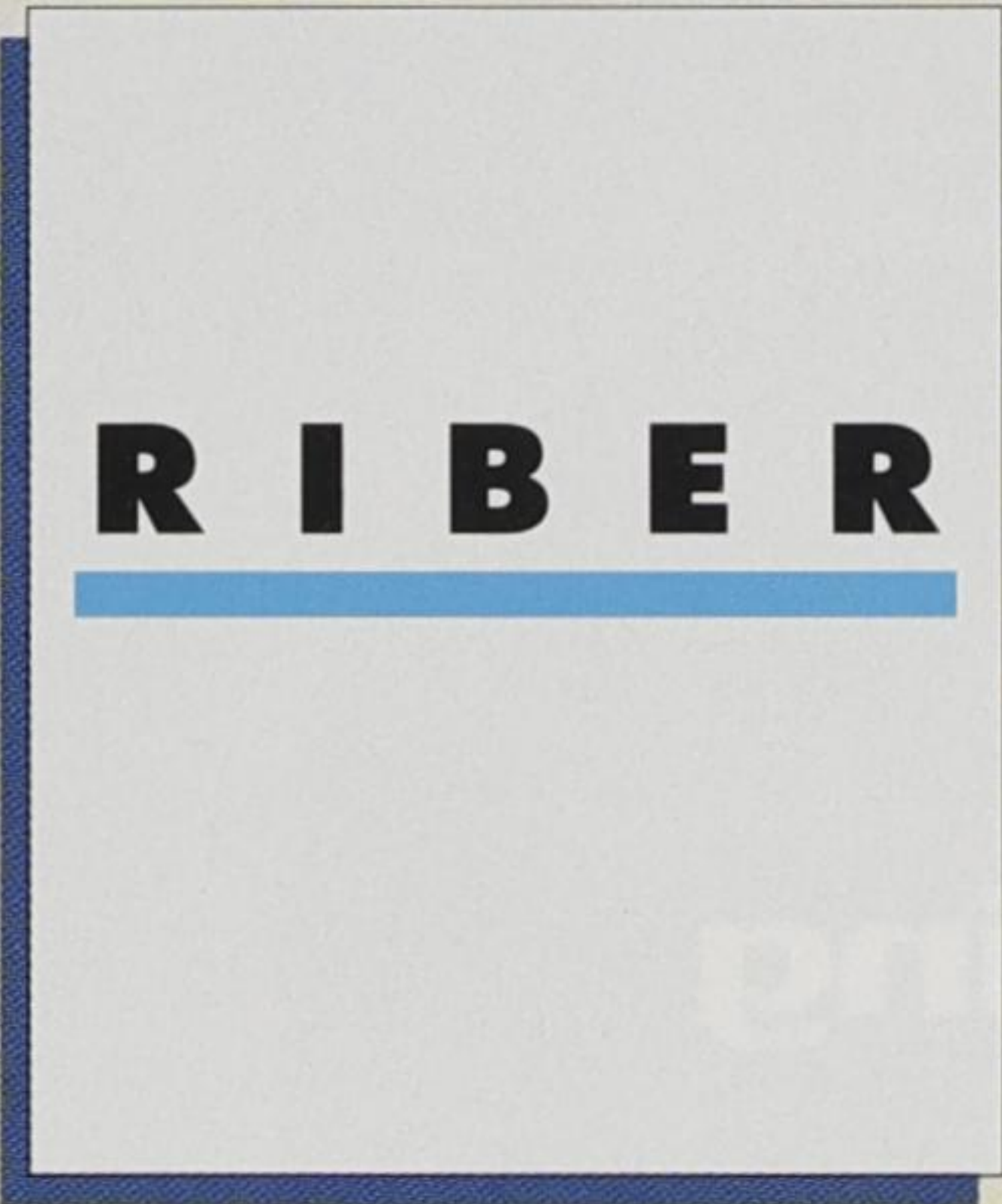
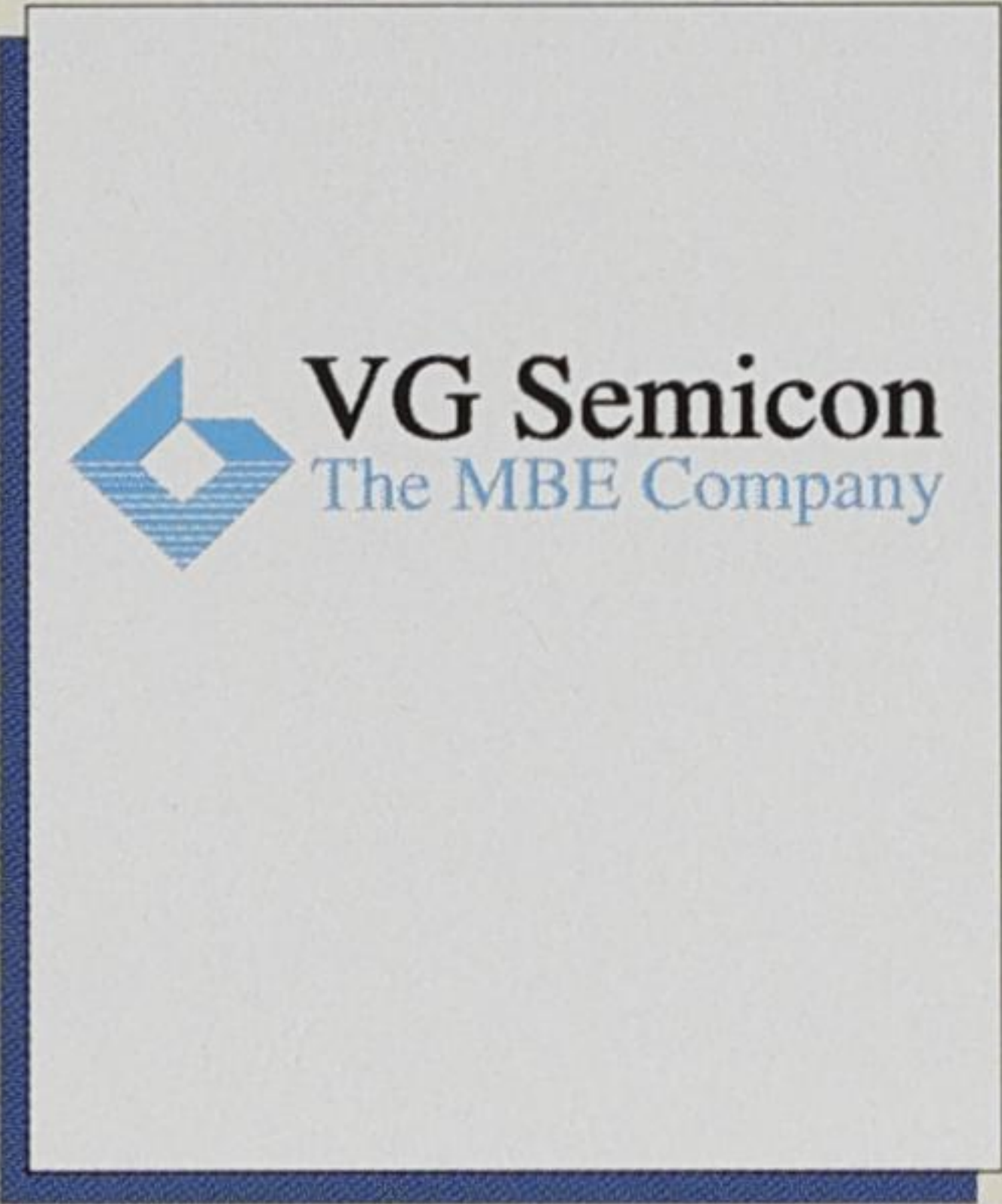
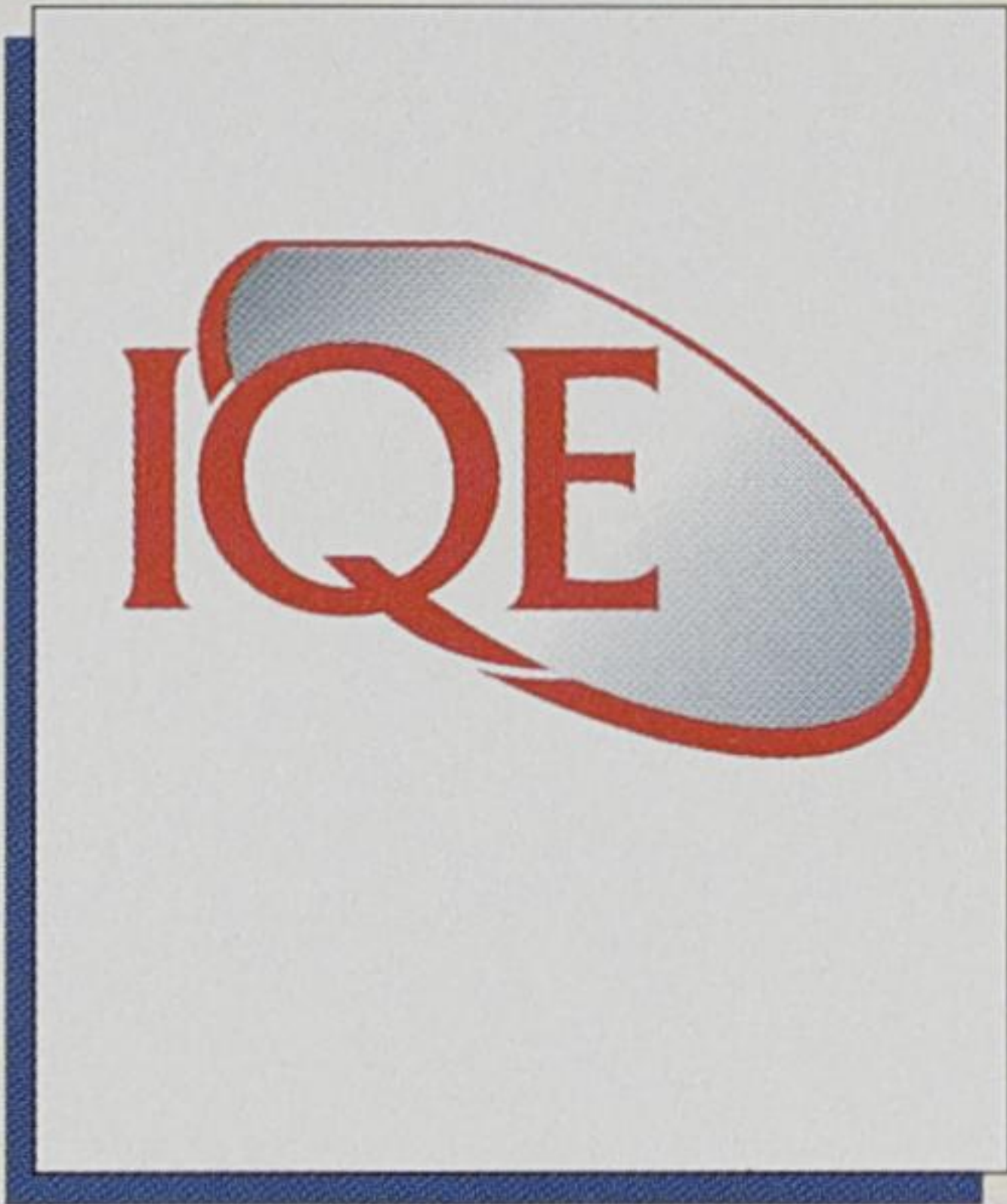
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2000 GaAs MANTECH Conference

Washington, DC

May 1-4, 2000

TIM WHITAKER

Reflecting the current growth in the GaAs industry, this year's MANTECH conference experienced a substantial increase in attendees over 1999. Among the 60+ exhibitors was a new Taiwanese company, **WIN Semiconductors**, which is currently building a 6-inch GaAs fab [see CS 6(4), p. 42]. In the manufacturing section of the program, Mark Wilson described the conversion of Motorola's GaAs facility to 6-inch operation—see page 6 of this issue for more details. Richard Lai described **TRW's** 0.1 μm HEMT MMIC process for high volume, low cost Ka-band LNAs for LMDS and commercial satellite applications. The process achieved 1.3 dB noise figure at 30 GHz and 2.0 dB noise figure

at 38 GHz, both with >20 dB associated gain. Excellent reliability was demonstrated: the mean time to failure at a channel temperature of 125°C was 6 billion hours, or 60,000 years. Also, **Filtronic's** plans to establish a high volume 6-inch PHEMT production facility in the UK, and a 6-inch R&D and MMIC prototyping facility in Santa Clara, were discussed [see CS 6(4), p. 43].

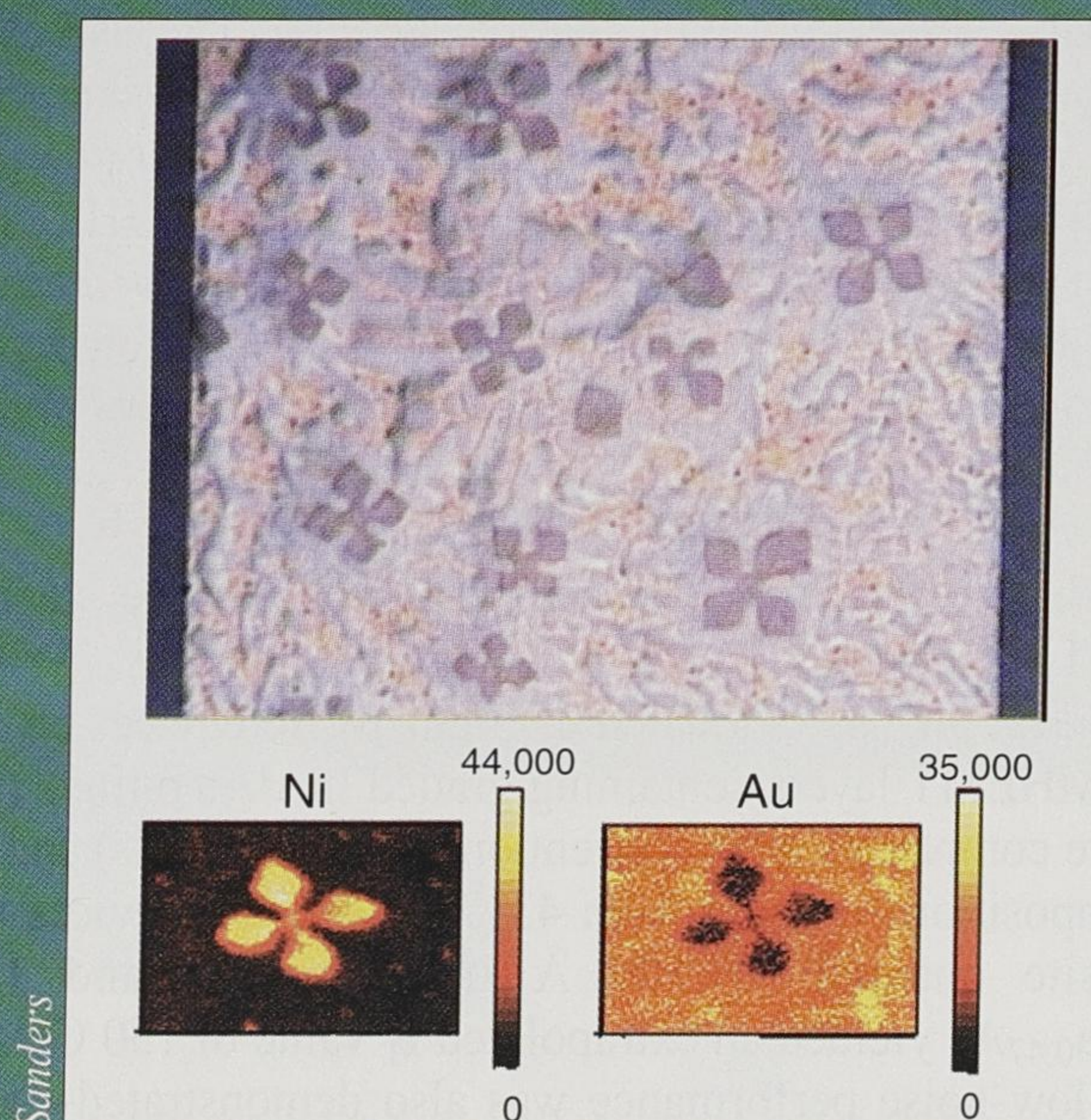
Plenary Session

Opening the conference, Mike Scott of **Nortel Networks** described compound semiconductor requirements in telecommunications networks. Since

fiber systems have stringent reliability requirements to meet 20-year service needs, reliability and performance dictate the choice of technology rather than cost. As volumes increase, driving down unit cost obviously becomes more important. Nortel fabricates InP-based optical devices using 2-inch wafers: despite challenges such as the lack of sophisticated automatic process equipment, yields from small discrete devices on 2-inch wafers can be very high. The need to perform several regrowths on partially processed wafers makes in-house epitaxial growth (and an extensive in-house analysis capability) a necessity. Nortel also has in-house capability to fabricate GaAs-based electronic devices, and chose to

The Ugly Picture Contest—Beautiful Art, Ugly Science!

For the second year, GaAs MANTECH held an “Ugly Picture” contest to highlight processing problems and their solutions. This year's winners were Sujane Wang and P.C. Chao of Sanders, a Lockheed Martin company, with their picture entitled “Beautiful Art, Ugly Science!” The photo shows a Ti/Al/Ni/Au ohmic contact on a GaN HEMT after alloying at 900°C. According to the Auger plots, the “flowers” have a very high Ni content, indicating imperfect NiAu alloy formation. By choosing a higher alloy temperature or a more appropriate Ni:Au ratio, it was possible to form a good NiAu eutectic. In this way, the ohmic contact resistance was reduced from 0.8 Ωmm to 0.2 Ωmm , and the “flowers” were eliminated.



adopt HBTs for 10 Gb/s products (modulators drivers, multiplexers and transimpedance amplifiers). Scott foresees a migration to higher data rates—20, 40 or even 80 Gb/s—which will probably require the introduction of InP HBTs. Tunable lasers will also be much in demand as the number of wavelengths in WDM systems increases to 160. Higher speed Si and SiGe devices are likely to displace their GaAs counterparts, especially at higher levels of integration, and only if costs are reduced and reliability targets can be met. [See MANTECH Digest of Papers, p. 3.]

Masumi Fukuta of **Fujitsu Quantum Devices** noted that there will always be a need for GaAs devices as long as they maintain a significant performance advantage over silicon. Both GaAs and silicon manufacturers continue to improve their process technologies to get or maintain their piece of the high-volume power amplifier market. GaAs has graduated from MESFETs to PHEMTs, AlGaAs HBTs and InGaP HBTs while silicon has moved from Si bipolar devices to LDMOS transistors to SiGe HBTs. Undoubtedly, said Fukuta, this race will continue for some time and the market will continue to accept the technology that offers the best combination of performance, price and timing. [Digest p. 7.]

Metamorphic HEMTs

A notable feature of this year's conference was the large number of papers on metamorphic high electron mobility transistors (MHEMTs), which combine the performance of InP with the manufacturability of GaAs. According to Colin Whelan and colleagues from **Raytheon RF Components**, MHEMTs offer distinct advantages over existing GaAs and InP HEMT technologies. The freedom to choose virtually any high value for the In content in the InGaAs channel provides for application-specific device optimization and high frequency performance. Furthermore, the

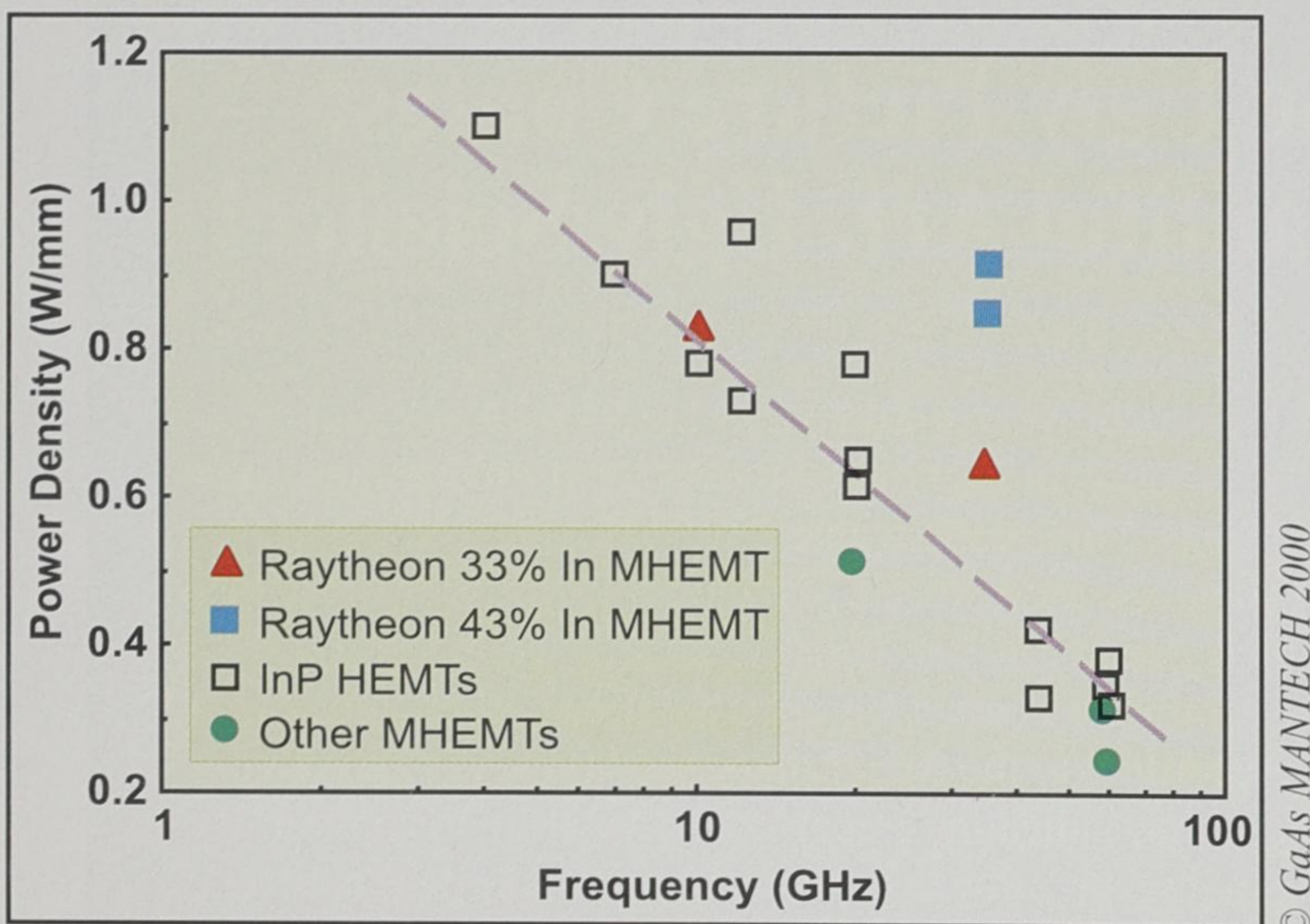


Figure 1. Comparison of recently published power density results for metamorphic GaAs HEMTs and InP HEMTs (for devices with >150 mm periphery). Courtesy of Colin Whelan, Raytheon RF Components.

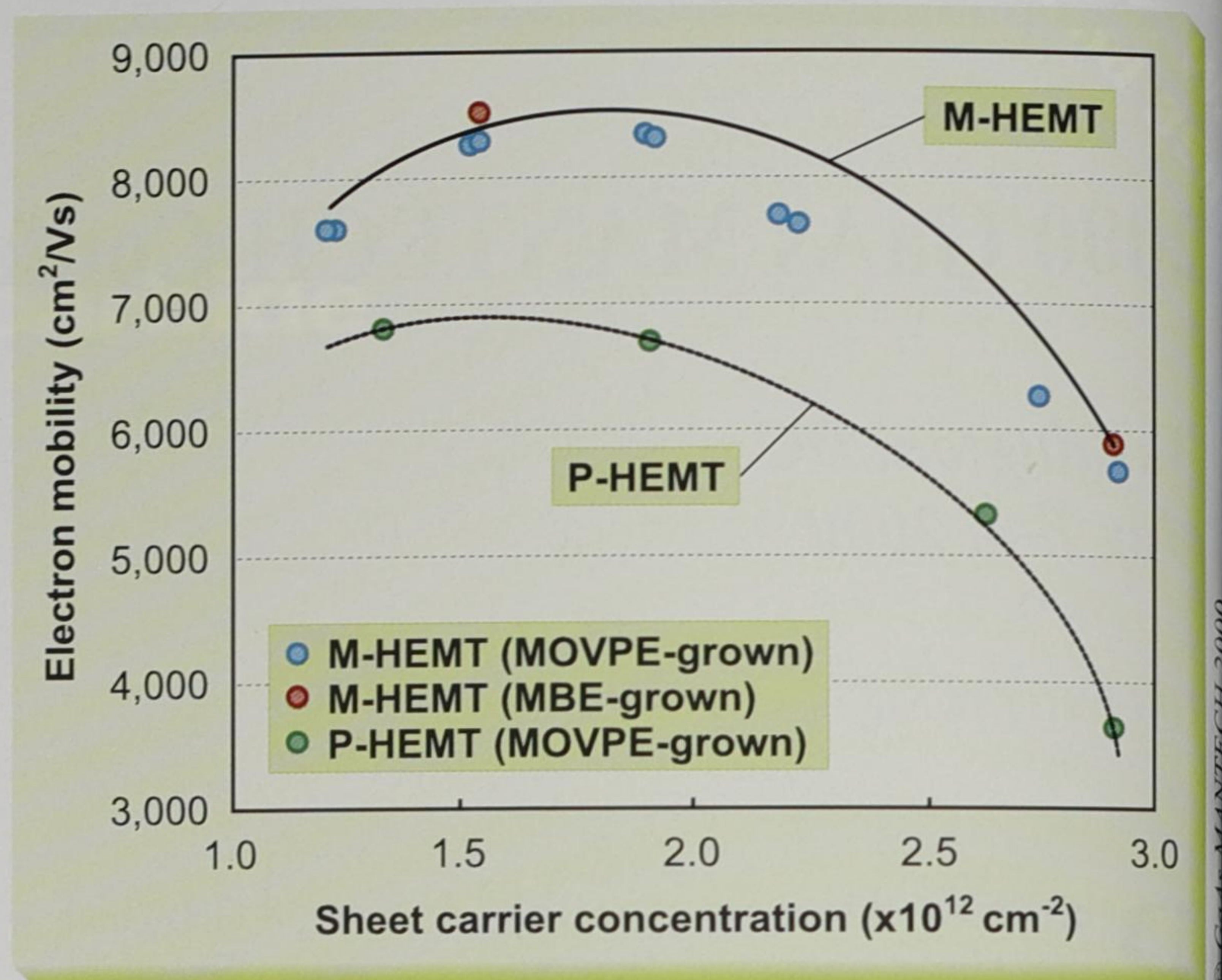


Figure 2. Electron mobility and sheet carrier concentration in $\text{In}_{0.36}\text{Ga}_{0.64}\text{As}$ MHEMT and $\text{In}_{0.20}\text{Ga}_{0.80}\text{As}$ PHEMT epitaxial wafers. Courtesy of Takeshi Tanaka, Hitachi Cable Ltd.

manufacturing economies of scale of a GaAs process—high volume, large wafer size—reduce the cost compared to InP.

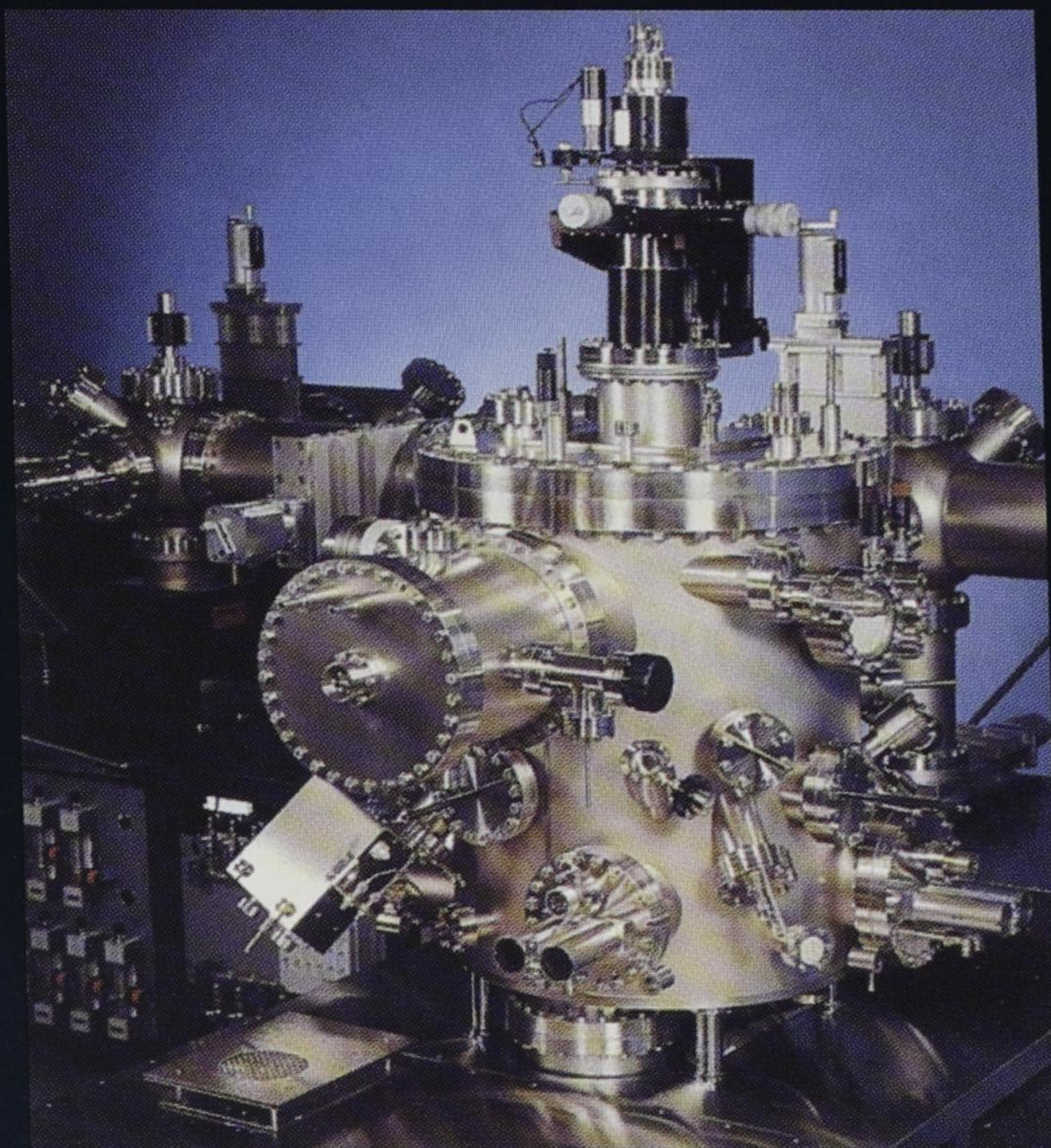
Raytheon has demonstrated 0.15 μm $\text{In}_{0.60}\text{Ga}_{0.40}\text{As}$ MHEMTs: when biased at 1 V and 90 mA/mm, the devices showed 0.24 dB noise figure with 16.2 dB associated gain at 12 GHz, and 0.61 dB noise figure with 13.8 dB gain at 26 GHz. These results compare favorably to state-of-the-art low noise InP HEMT results. Low noise amplifiers have also been demonstrated; a 3-stage 60% In MHEMT Ka-band LNA demonstrated less than 1.4 dB NF and >25 dB associated gain from 30–31 GHz.

Figure 1 compares published power performance of MHEMTs and InP HEMTs that have a periphery exceeding 150 μm (scaling device performance from smaller devices becomes questionable, especially with thermal effects). The use of relatively low In contents results in a higher on-state breakdown, enabling 5 V and 6 V drain biasing to be used for higher power density. Raytheon has demonstrated 820 mW/mm at 10 GHz and 640 mW/mm at 35 GHz using a 33% In channel and 6 V drain biasing. Furthermore, using a double recess structure for improved breakdown, a 43% In MHEMT achieved over 900 mW/mm at 35 GHz. [Digest p. 237.]

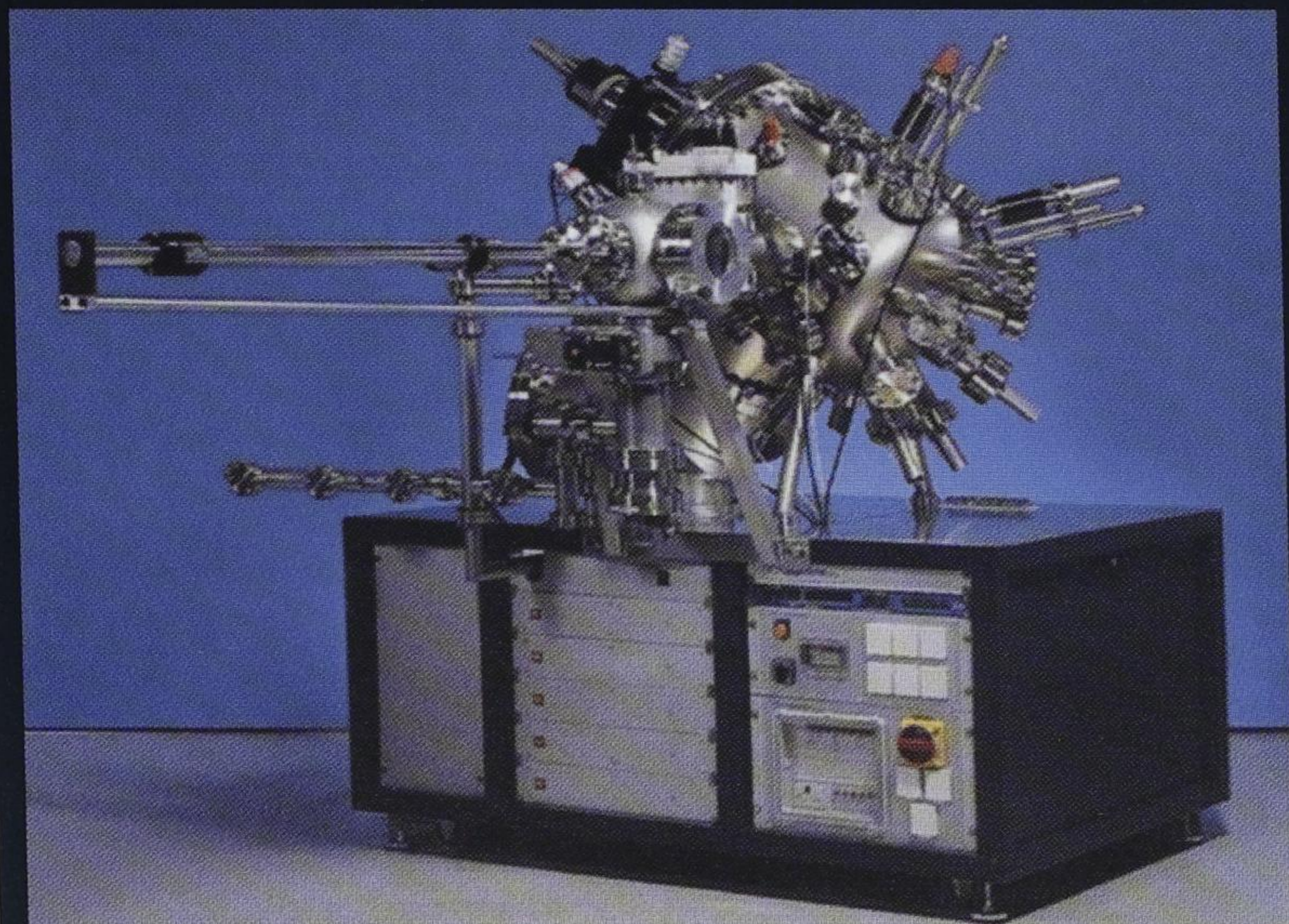
Both TriQuint and the Fraunhofer Institute described MHEMTs fabricated on 4-inch GaAs substrates. **TriQuint Semiconductor** has fabricated 0.15 μm T-gate devices on MBE-grown MHEMT layers containing graded InAlAs buffers (which are more compatible with conventional MBE systems) and channel compositions ranging from 43% to 63% In. Devices with a composite channel of 100 Å $\text{In}_{0.63}\text{Ga}_{0.37}\text{As}$ and 130 Å $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ yielded an extrapolated f_T value of 150 GHz. Excellent low noise performance was also demonstrated—a noise figure of 0.73 dB with an associated gain of 12.6 dB was measured for a 43% In MHEMT at 26 GHz. [Digest p. 225.]

MBE TECHNOLOGY

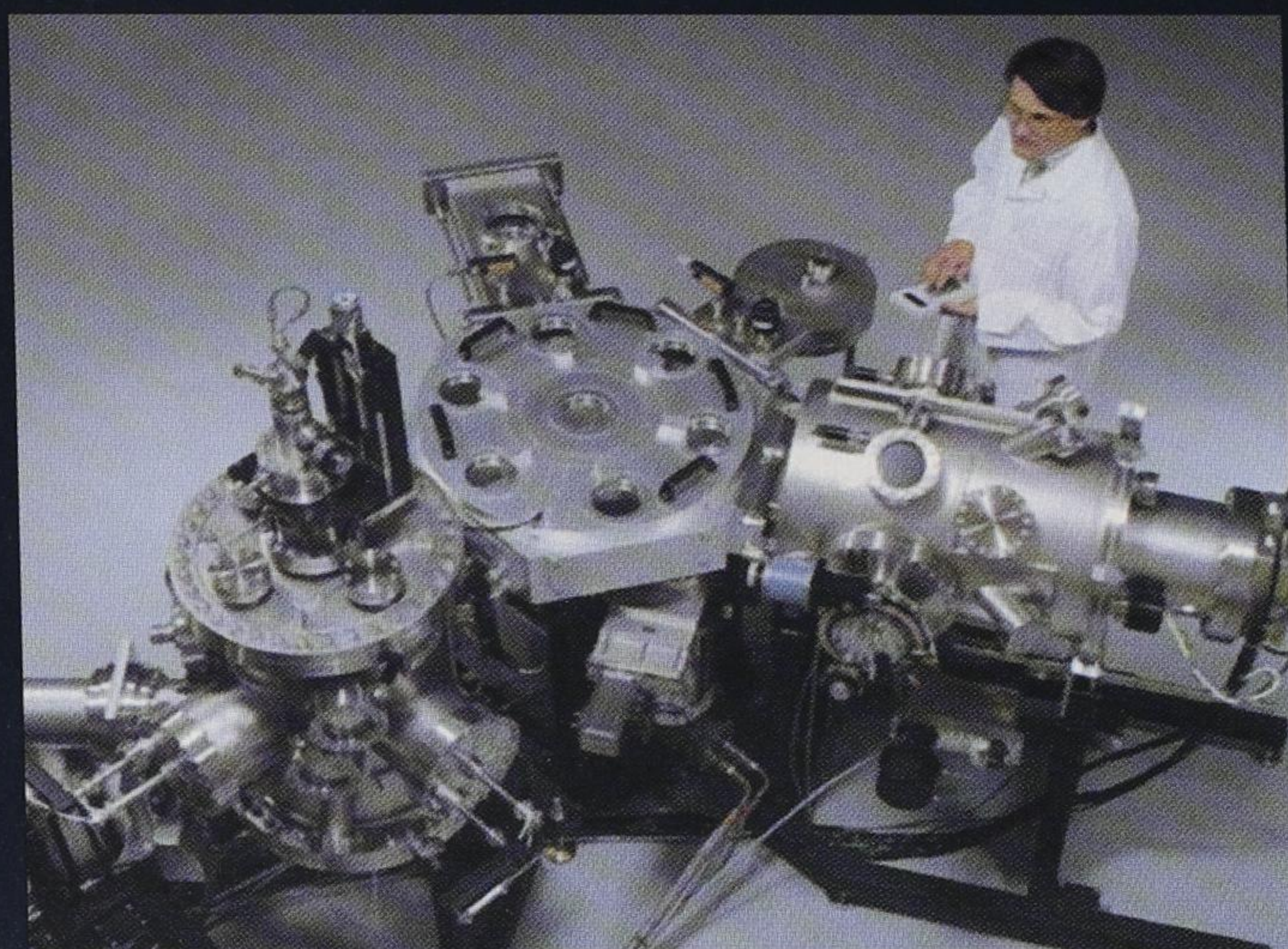
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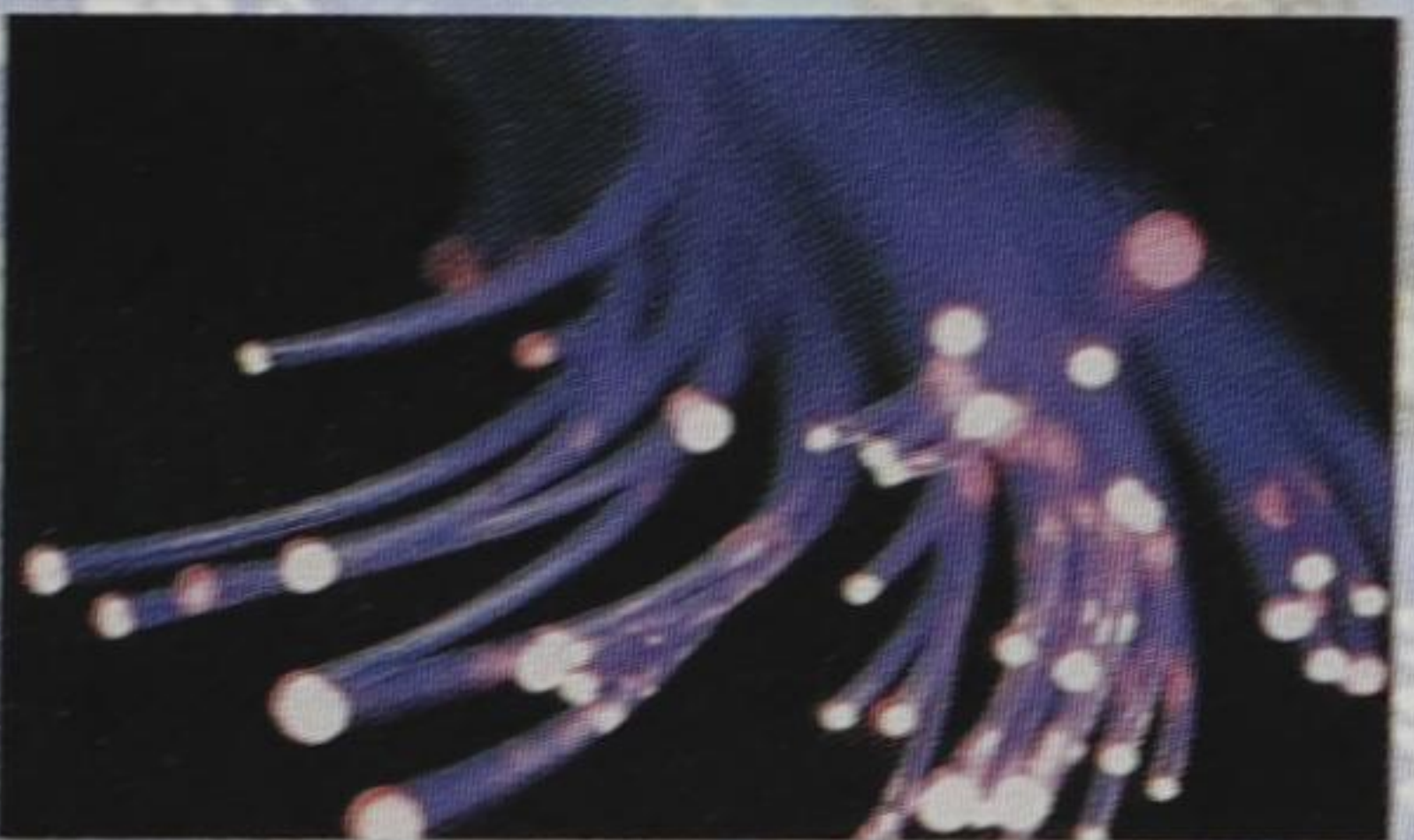
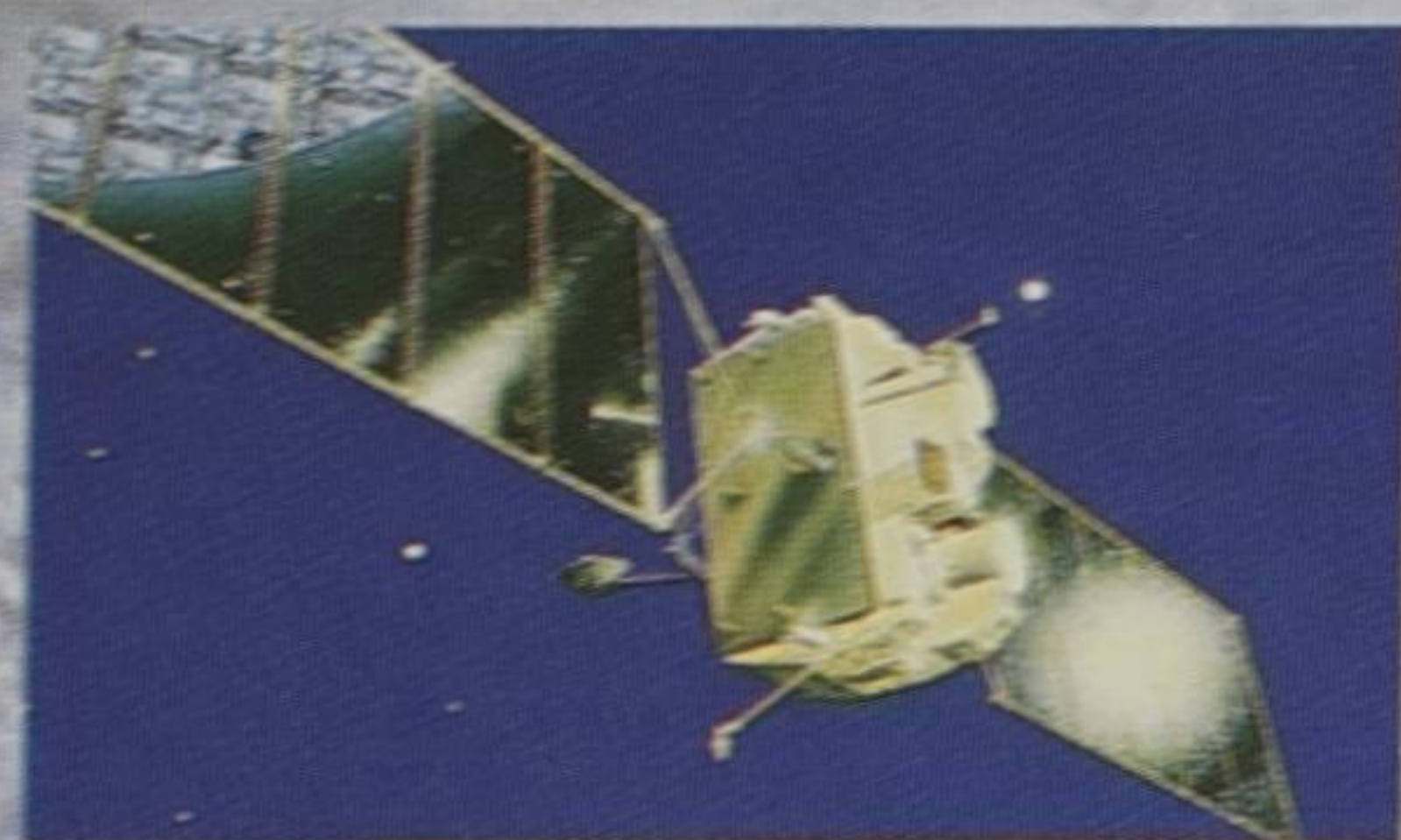
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The **Fraunhofer Institute for Applied Solid State Physics (IAF)** is developing an MHEMT MMIC production process on 4-inch GaAs using a $0.5\ \mu\text{m}$ gate length pattern defined by an i-line stepper. The authors feel this process, which has an f_T of 53 GHz and an f_{max} of 200 GHz, can compete with $0.25\ \mu\text{m}$ PHEMT products in the 2–77 GHz range. Two-stage W-band amplifiers fabricated using $0.15\ \mu\text{m}$ gate length MHEMTs were also described. These showed 18 dB gain and 30 GHz bandwidth along with excellent thermal stability—less than 8% gain degradation was observed after 2000 hours at 250°C . Similarly, $0.25\ \mu\text{m}$ MHEMTs had an activation energy of 2 eV and an MTTF of 2×10^6 hours at 150°C (or 4×10^7 hours at 125°C). The MMICs were also found to be insensitive to hydrogen gas, allowing them to be hermetically sealed without reliability degradation. [Digest p. 233.]

Sanders, a Lockheed Martin company, has developed a $0.1\ \mu\text{m}$ power MHEMT MMIC technology with performance comparable to that available using InP HEMTs, and cost equivalent to ~70% of the InP HEMT wafer processing cost. Sanders expects that the cost of MHEMTs will fall by a factor of 4 when the process is transitioned to a 6-inch manufacturing line. The device structure utilized by Sanders includes a patented AlGaAsSb strain relief buffer layer and an In mole fraction as high as 65%. At 20 GHz, an output power of 136 mW was obtained with a power added efficiency of 60.2% and a record 17.1 dB gain. This device also produced an output power density of 0.51 W/mm at V_{ds} of 3.5 V. At 60 GHz, the technology delivered 185 mW (0.31 W/mm) with 41.2% PAE and 6.9 dB power gain from a single-stage MMIC. [Digest p. 57.]

Until now, metamorphic HEMTs have almost exclusively been grown by MBE. Researchers from **Hitachi Cable** investigated the feasibility of MOVPE growth of MHEMT epitaxial wafers, and found that both the surface morphology and electrical properties were almost identical to those of MBE-grown wafers. The authors state that MOVPE offers advantages for mass production and for the growth of P-containing

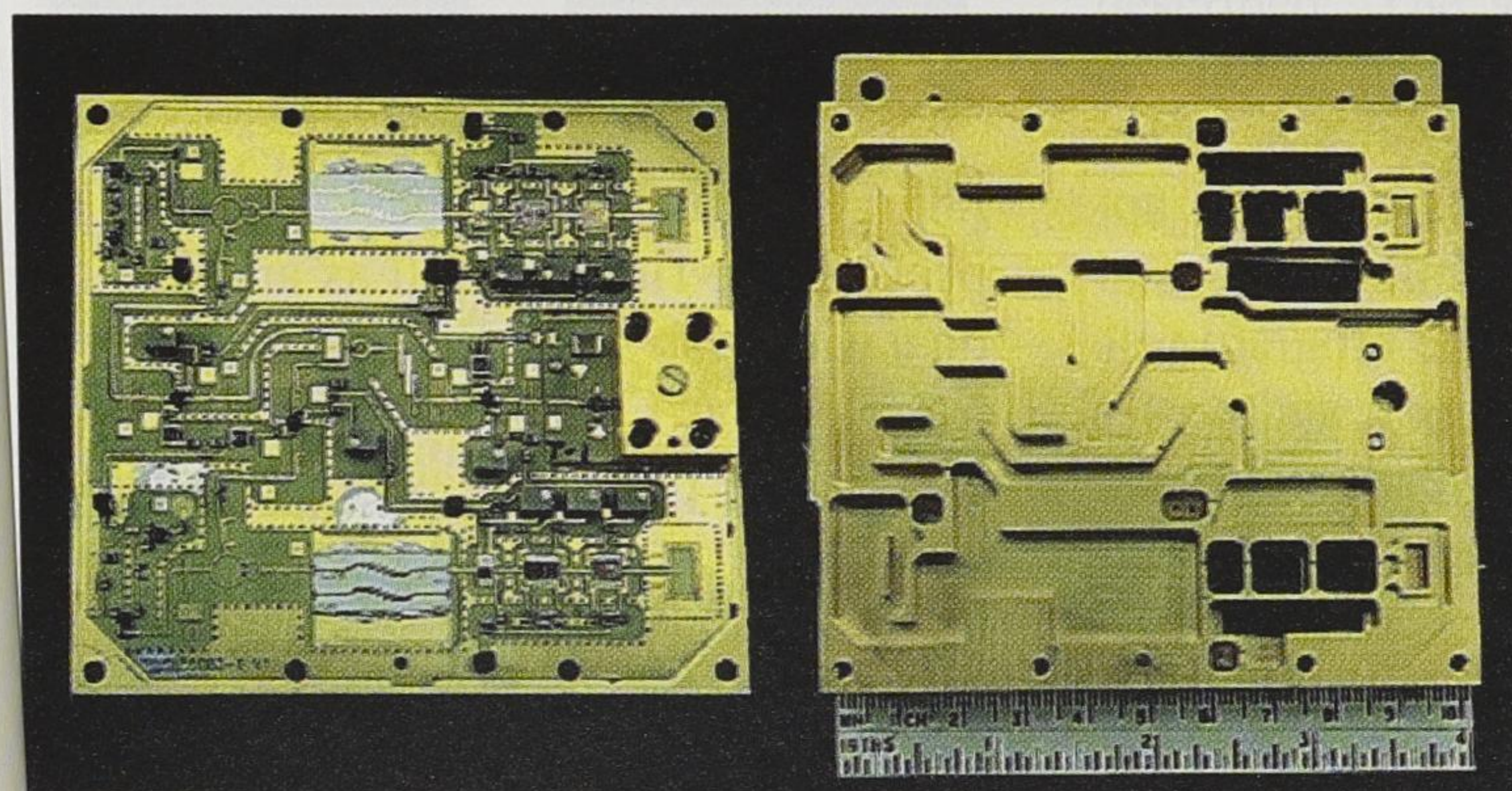


Figure 3. A dual-channel transmit function for a 19/29 GHz transceiver, showing (left) the RF electronics attached to a soft substrate circuit board and (right) the cover plate. The receiver was realized in a similar layout on the reverse side of the board. Courtesy of Roberto Alm, Raytheon RF Components.

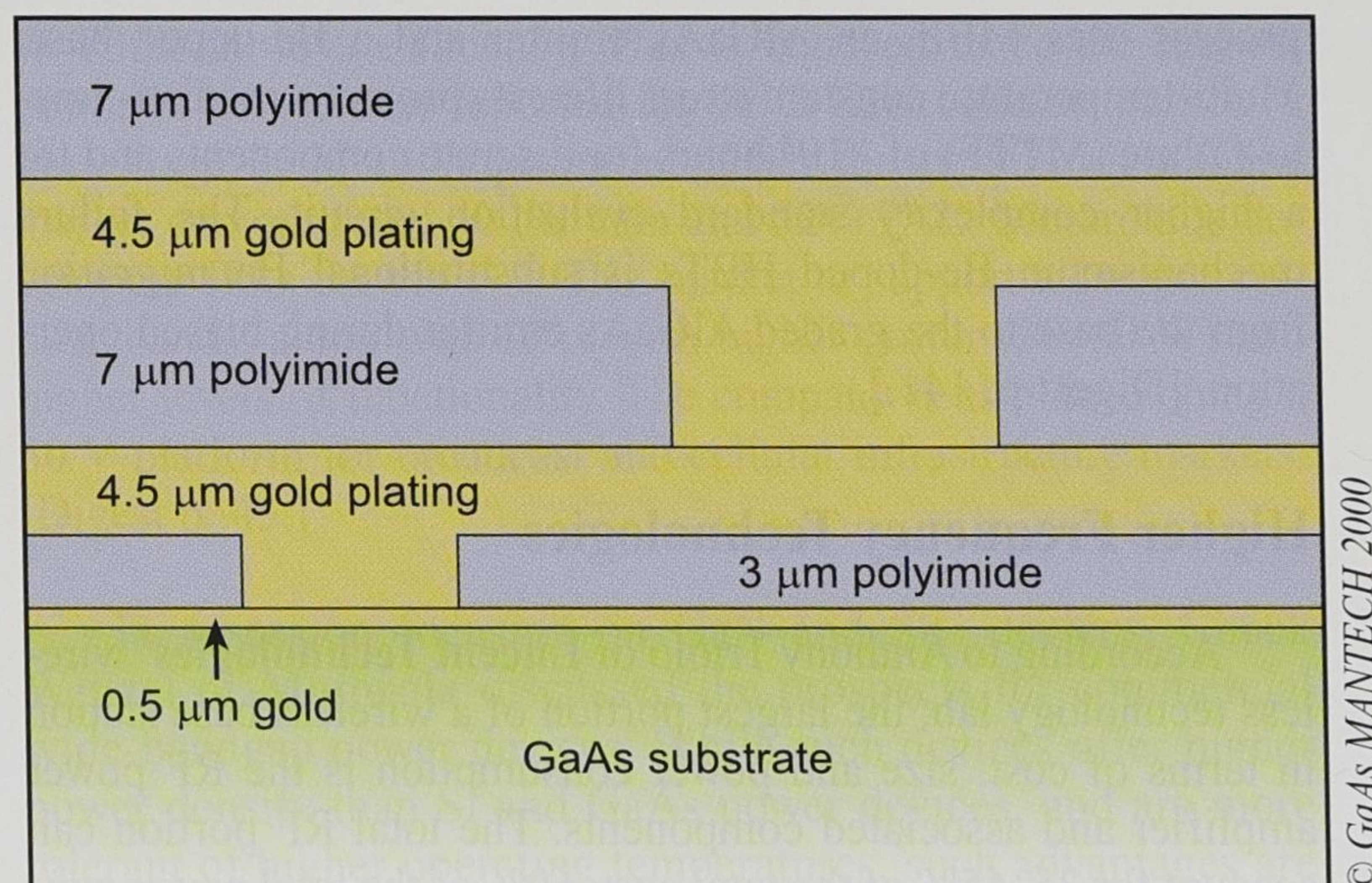


Figure 4. The multi-level plating (MLP) process adds a second layer of thick gold plating and a second layer of polyimide interlayer dielectric to M/A-COM's existing process for fabricating RFICs and MMICs. Courtesy of John Dilley, M/A-COM.

materials such as GaInP and InP, which could be used as etch-stop or surface-passivation layers. Identical structures containing a step-graded InAlAs metamorphic buffer layer and an InGaAs channel with 35–40% In were grown by both MBE and MOVPE. Figure 2 shows the similarity of channel conduction characteristics between the two MHEMTs and the superiority compared to a conventional $\text{In}_{0.20}\text{Ga}_{0.80}\text{As}$ PHEMT. [Digest p. 89.]

HBT Reliability

In a session on HBTs, **Agilent Technologies** described reliability results of InGaP-emitter devices. Even wafers with relatively poor reliability showed projected lifetimes at $T_J = 150^\circ\text{C}$ and $J_E = 0.6\ \text{mA}/\mu\text{m}^2$ exceeding 10^6 hours. The predominant failure mode was sudden and drastic β (DC current gain) degradation to $\beta \approx 1$. This failure mode has a relatively low activation energy, and devices can survive extremely long times under the most severe stresses. The activation energy was found to be ~1.2 eV. [Digest p. 131.]

Hitachi reported high-temperature bias stress tests on InGaP/GaAs HBTs with an emitter size of $2.5 \times 20\ \mu\text{m}^2$ at an emitter-base junction temperature T_J ranging from 360°C to 440°C and a collector current density J_c of $1 \times 10^5\ \text{A}/\text{cm}^2$. Both self-aligned and non-self-aligned HBTs showed the same dependence of the lifetime on T_J with the same activation energy of 2.0 eV. The results suggest that the observed degradation of current gain is related to minority carrier injection in the intrinsic base region near the emitter-base junction. [Digest p. 137.]

While Agilent and Hitachi both use MOVPE-grown HBTs with InGaP emitters and C-doped GaAs base layers, **TRW's** HBT

process uses MBE, an AlGaAs emitter and a Be-doped base. Multi-temperature constant stress lifetests project a median-time-to-failure (MTTF) of $>10^8$ hours for discrete components and for a higher complexity standard evaluation circuit. The failure mechanism in Be-doped HBTs is substitutional Be migration from the base to the graded AlGaAs emitter during biased operation. [Digest p. 141.]

Higher Frequency Technologies

According to Anthony Triolo of **Lucent Technologies'** wireless technology lab, the largest portion of a wireless base station in terms of cost, size and power consumption is the RF power amplifier and associated components. The total RF portion can account for 25–65% of the total cost, 60% of the total power consumption and more than 50% of the total size. Cost reduction efforts need to be concentrated on the RF subsystem in order to achieve significant savings. As cost is perhaps the biggest single reason to choose one device over another, a more expensive device must far outperform a less expensive device to be considered. A reasonable cost target for any RF power device is approximately \$1 per peak Watt. [Digest p. 49.]

Roberto Alm of **Raytheon RF Components** described the development of cost-effective front-end components for mm-wave satellite communications (SATCOM) ground terminal equipment and terrestrial point-to-point and point-to-mul-

tipoint systems such as LMDS. Given the projected volume for these systems, the overall product design—from MMIC design to final product assembly—must be compatible with high volume, low cost manufacturing methods. Figure 3 shows a dual-channel transmitter for a 19/29 GHz transceiver for K/Ka-band satellite and/or terrestrial LMDS communication systems. All RF electronics, including three amplifier MMICs per channel, were placed on a soft-substrate circuit board (shown at left), which was attached via sheet epoxy to the backside of a cover plate (shown at right). The body contains the DC bias circuitry and the compartment walls that provide the necessary isolation for circuit elements on each side. A 2 W, 29 GHz SATCOM transceiver module was also built and demonstrated. [Digest p. 53.]

Metals

John Dilley of **M/A-COM** in Roanoke (formerly GaAsTEK) described a metal interconnect process using two layers of thick plated gold and thick polyimide intermetal dielectric (see Figure 4). The so-called multi-level plating (MLP) process allows the fabrication of very low loss transmission lines and spiral inductors, along with other improvements in useful circuit elements. In addition, the MLP process enables chip size reduction by replacing distributed matching networks with high-performance lumped elements while simultaneously shrinking the size of these elements. Using this process, the

CONFERENCE

Workshop on Dry Etching for Compound Semiconductor Technology

Kassel, Germany
April 10, 2000

JÜRGEN DALEIDEN
University of Kassel

The workshop "Dry Etching for Compound Semiconductor Technology" took place at the Institute of Microstructure Technologies and Analytics within the University of Kassel, Germany. Since 1990, this workshop has

been a national German event with approximately 30 participants and 8 oral presentations. This year, the program was modified to include both oral and poster presentations, as well as vendor exhibits. The event attracted 50 participants from industry, university and research institutes.

The opening by Hartmut Hillmer and Jürgen Daleiden was followed by three invited talks. **Gerhard Franz** of **Infineon Technologies** (Munich, Germany) presented "Analysis and application of reactive Cl_2 -based plasma tech-

nology". Touching on basic research aspects in the field as well as applications on a wafer fab scale, the talk gave a good overview on Cl_2 -based plasma processing. Using plasma diagnostics such as Langmuir- and SEERS-probes, Franz found "islands of stability" where strong changes of the input parameters cause almost no change in the plasma parameters. These results could be very valuable to run stable processes in industrial etching applications. (Figure 1).

Ivo Rangelow of the **University of Kassel** gave an overview presentation on

cost of 10 W X-band power amplifiers was reduced significantly as a consequence of reducing the chip size by 50%.

Competing Technologies and Alternate Materials

Aaron Oki of **TRW** described the performance advantages of InP HBTs for high efficiency cellular and mm-wave power amplifiers, 40 Gb/s fiber-optic communications, and signal processing ICs [for more details, see CS 5(3), p. 28].

NTT Photonics also described work on InP HBTs: the company has developed a hexagonal-shaped emitter geometry aligned parallel to the primary flat of the wafer to suppress the periphery base leakage current originating from the side-wall of the InP emitter-mesa. In addition, a dehydrogenation annealing method was devised to activate the carbon acceptors of the In-GaAs base layer, which is passivated by hydrogen during MOVPE growth. A 6- μm^2 emitter HBT showed f_T and f_{max} values of 136 and 184 GHz, respectively. Several 40 Gb/s ICs—a 1:4 demultiplexer, a decision IC and a static 2:1 frequency divider—were fabricated using these non-self-aligned InP/InGaAs HBTs. [Digest p. 37.]

The advantages of silicon LDMOS (laterally diffused metal oxide semiconductor) for high power, high efficiency linear RF power amplifiers were described by **Motorola's** wireless infrastructure systems division. Device examples include a 28 V push-pull device designed for 2 GHz WCDMA, which delivered 220

W P3dB at 46% efficiency. This is believed to be the highest power Si-device ever reported for the 2 GHz cellular market. A three-stage 26 V, 10 W power amplifier for the 900 MHz GSM market demonstrated 40 dB gain and 52% PAE. Motorola is developing IPAs for the 1–2 GHz market to support all major cellular bands, along with IPAs with higher power (30–60 W) and higher levels of functionality. The company is also developing a 50 V platform for broadcast and cellular infrastructure markets. [Digest p. 43.]

In a session focusing on GaN and SiC devices, Chuck Weitzel of **Motorola** discussed the prospects for commercial wide-bandgap power devices. While such devices offer higher power density than Si and GaAs power devices, and are more tolerant of higher operating temperatures, such advantages are only achieved at operating voltages above about 10–20 V. This restricts wide bandgap devices to base station and infrastructure applications, a market valued at about \$600 million per year at present. There are a number of challenges: in particular, the quality and cost of SiC substrates and epitaxy will have to be improved significantly in order to achieve low die cost. [Digest p. 197.]

*The 2001 GaAs MANTECH conference will be held on
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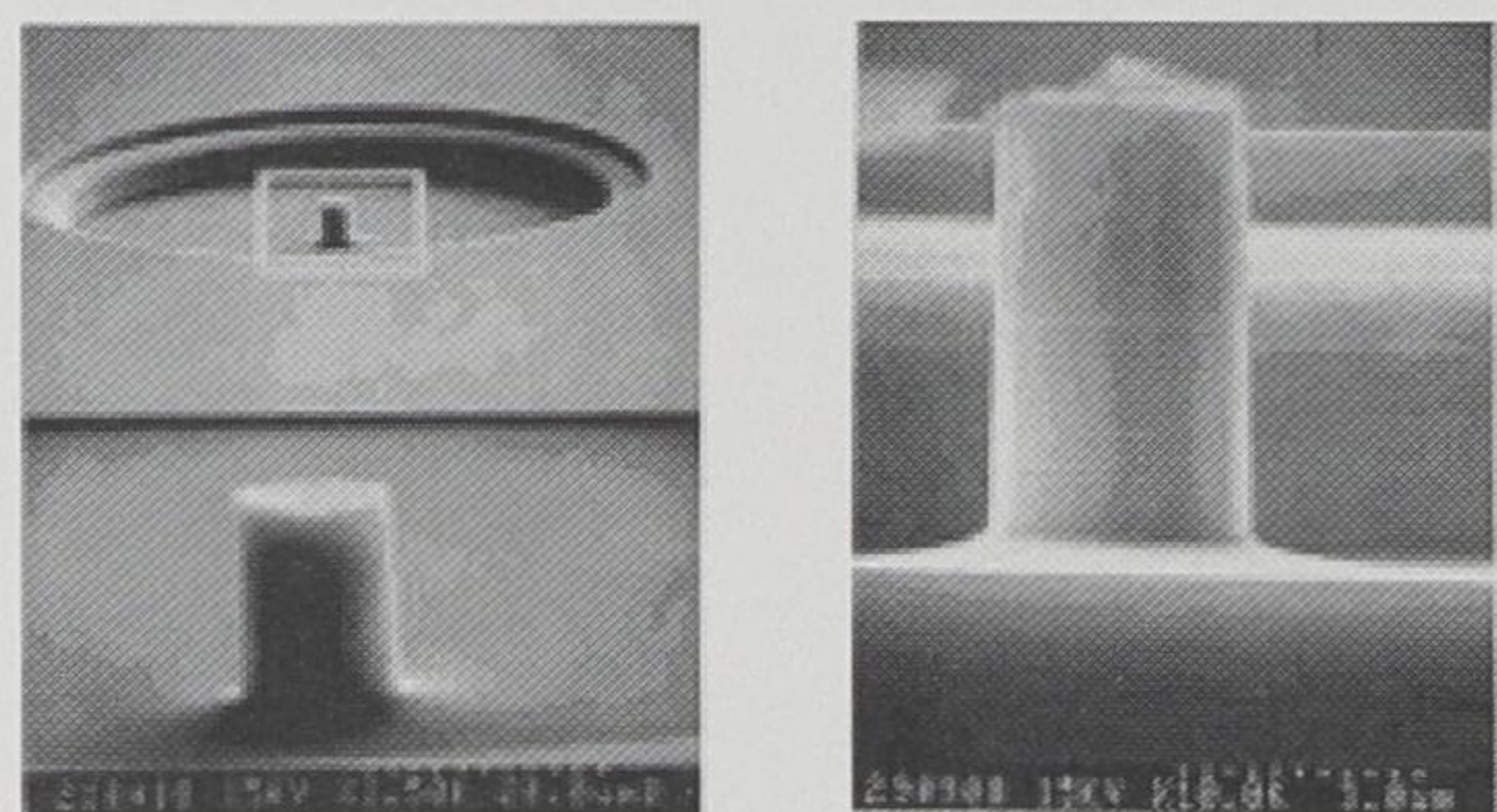


Figure 1. Etching of GaAs/AlAs stacks by $\text{Cl}_2/\text{BCl}_3/(\text{Ar}, \text{He})$. Very smooth side-walls of the structures were obtained using an optimized process to treat the photoresist after its development. It is shown that various end point detection methods can complement each other and enable etch depth monitoring with a depth resolution of significantly better than 50 nm at a total depth of more than 2.5 μm . Courtesy of Gerhard Franz of Infineon Technologies, Munich, Germany.

the subject of “Dry etching of silicon-based devices”. As it was experienced

many times before it is always good for the III-V experts to have “a look over the fence”. Impressive results of cryo etching and the gas chopping technique were shown (Figure 2).

Mike Cooke of **Oxford Instruments Plasma Technology** (Bristol, UK) described “The application of ICP processing in the fabrication of III-V semiconductor devices”. He gave examples for the system development and advanced applications in optoelectronics. Excellent results of ICP plasma processes for blue and red LEDs or laser diodes were presented.

The afternoon poster session and exhibition gave the opportunity for both scientific discussions and the exchange of practical experiences in the field of dry etching technology. All in all, the new format of the workshop was well accepted and discussions to expand the workshop to an international level were arisen.

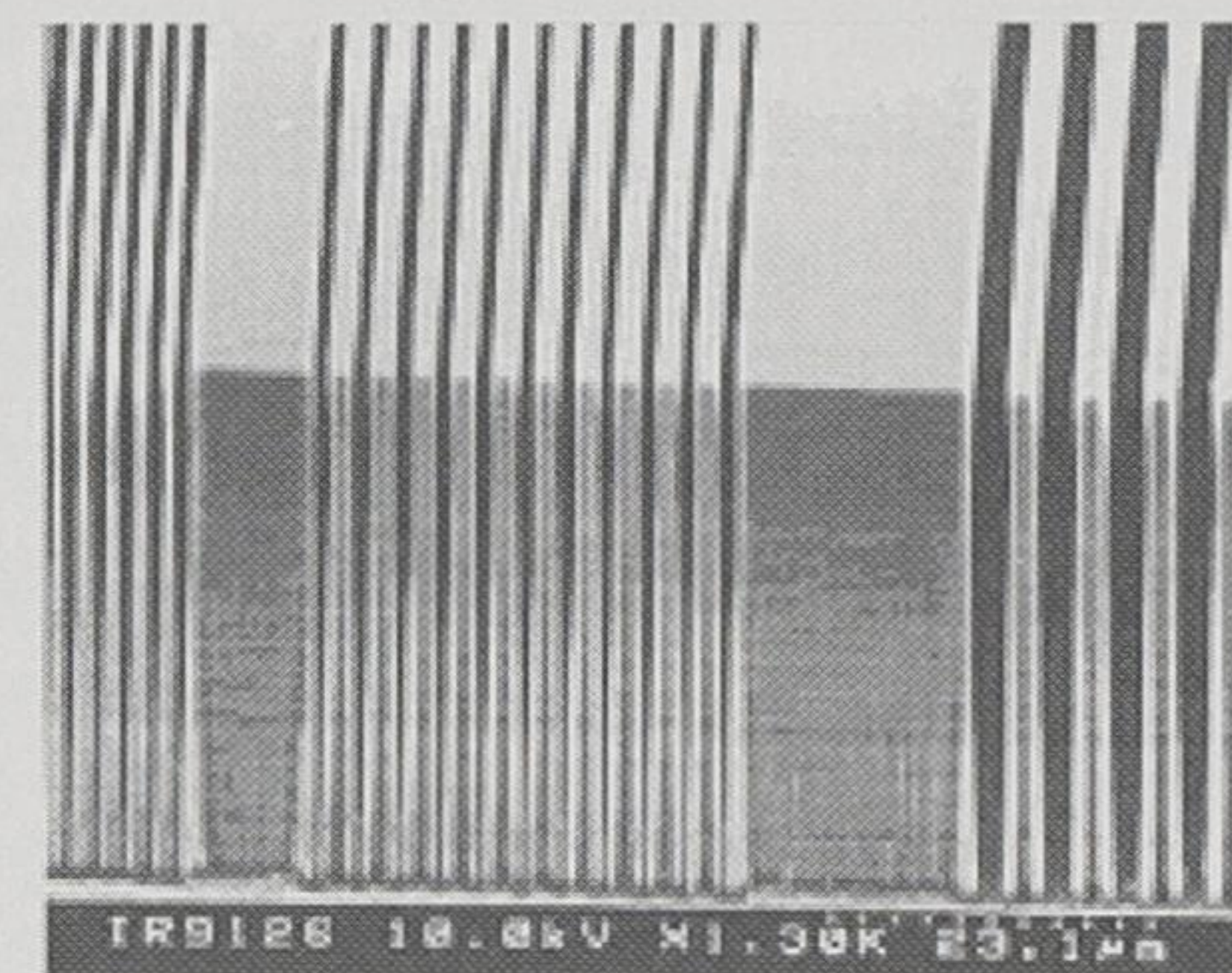


Figure 2. High aspect ratio etch results during silicon micromachining, obtained by the gas chopping technique. The gas flow of etching and deposition gas precursors is chopped, which results in controllable sidewall passivation and high anisotropy. Courtesy of Ivo Rangelow, University of Kassel, Germany.

For further details, or to discuss plans for future events, please contact Jürgen Daleiden. Email: daleiden@uni-kassel.de, phone: +49 (0)561 804-4470, fax: +49 (0)561 804-4488.

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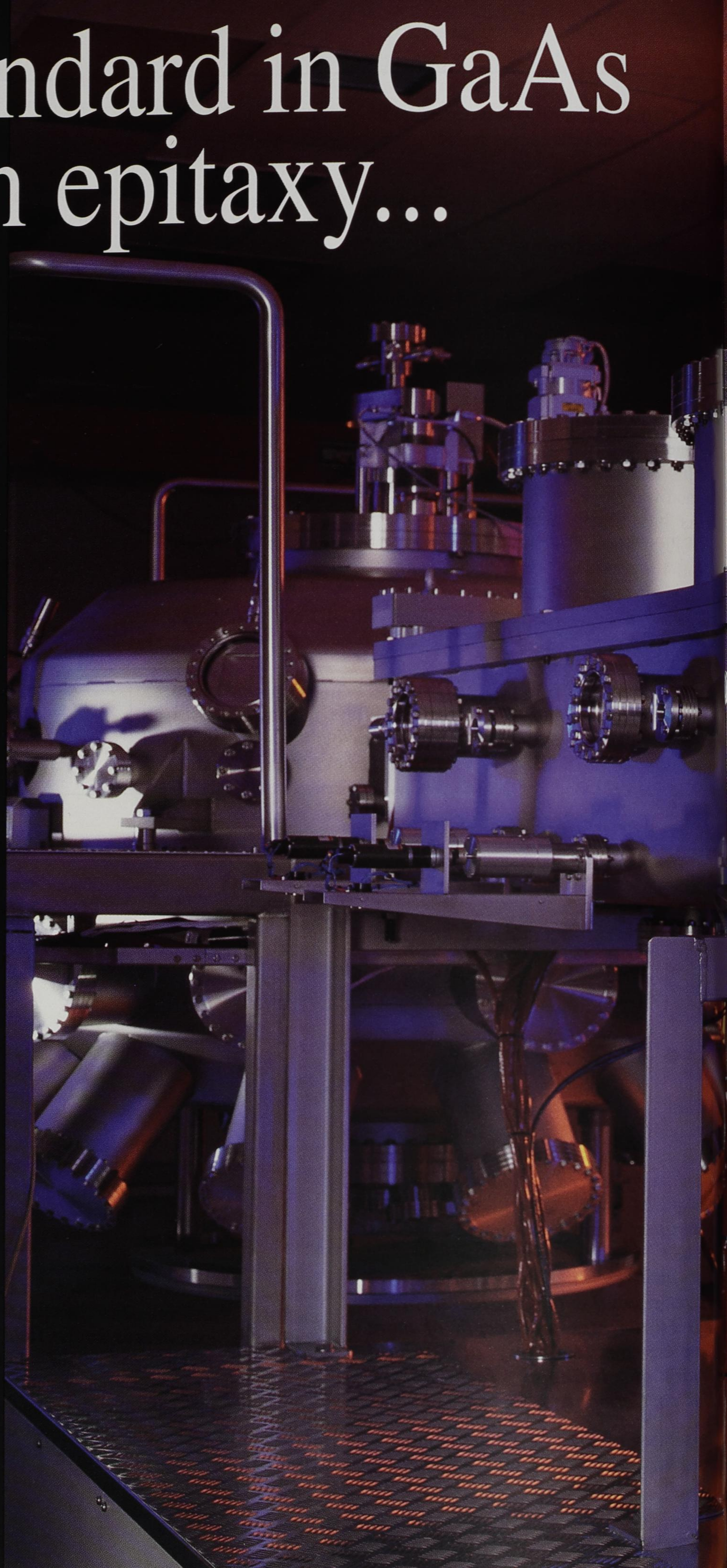
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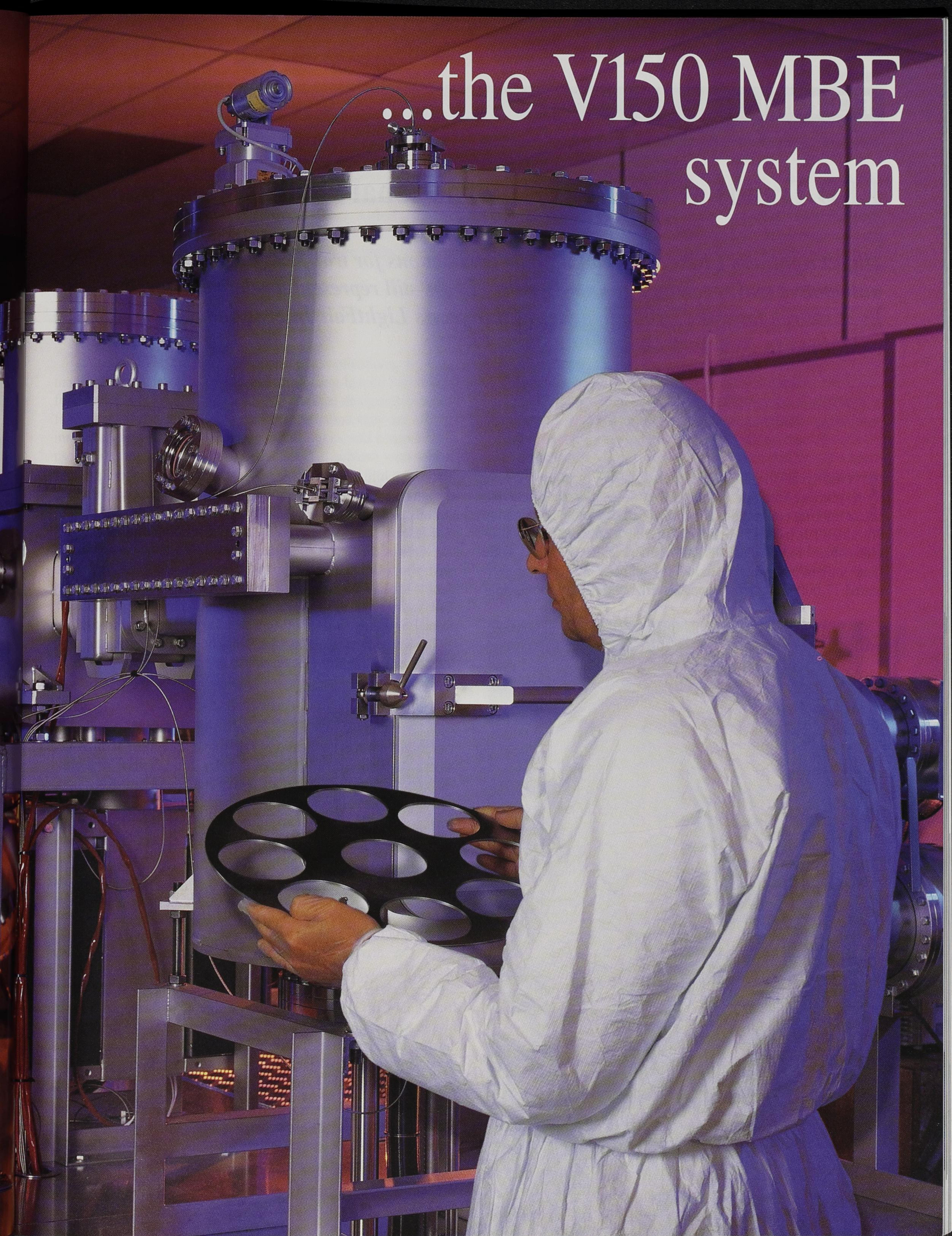
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LED Trends at LightFair International 2000

High brightness LEDs are enabling new applications for traffic signage, displays, automotive and specialty lighting. Even so, LEDs still represent a relatively novel light source for the 17,000 attendees at this year's LightFair International exhibition in New York City.

KATHRYN M. CONWAY*

Rensselaer Polytechnic Institute, Troy NY

Each year the LightFair International meeting gives a glimpse into the future of lighting, and each year the lighting community sees more LEDs. Held between May 9th and 11th in New York City, the LightFair exhibition provides space for as many as 400 companies to display a wide range of new and conventional light sources, attracting an estimated 17,000 architectural, engineering and design profession-

als. And while high brightness LEDs are enabling some product designers to move beyond indicators and signals and into applications for illumination, these devices remain a relatively novel and fascinating light source for many LightFair attendees.

One of the functions of the LightFair is also to recognize industry innovation in different branches of lighting. LEDs topped 3 of a total of 16 categories. In the specialty lighting category, TIR System's "LED Color Change Luminaire" and "Chipstrip" from LumiLeds Lighting (Figure 1) were honored. Meanwhile, Color Kinetic's "ColorPlay" LED lighting control software took the software category (see below).

Market Trends

Light source applications fall into two types: luminance, where the light source is viewed directly through glass or a plastic lens, such as traffic signals, brake lights and video displays, and illuminance, the case where we see the light reflected from a surface. Familiar examples of illuminance include street lighting, billboards and interior and office lighting, although these markets have yet to be significantly penetrated by LEDs.

In general, the market patterns for LEDs seem clear: luminance products precede illuminance products, outdoor products precede indoor products, and industrial products precede consumer products. Light output, luminance contrast and cost are the respective drivers of these patterns. For example, LEDs have nearly supplanted incandescent lamps in exit signs, but LEDs are newcomers to task lights for reading. Meanwhile, red LED traffic signals halt US traffic nationwide, but most shoppers have yet to see exhibition showcases glittering with LEDs. Audio fans are accustomed to taking cues from LED display panels, and drivers now see their automotive instrument panels back-lit with LEDs: but few people carry LED flashlights.



Figure 1. LumiLeds' chip-strip lighting can be used as decorative illumination on the edge of strip mall shops and buildings.

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The reasons for these patterns link directly to the output of LEDs. As higher light output LEDs are introduced, fewer devices are needed per product, which helps control cost. Alternatively, more light output can be achieved with the same number of LEDs, making the product more attractive for situations where more light is needed, even if the cost is higher. Although home gardeners can now affordably brighten their plants at night with solar-powered LEDs, they probably will not be replacing their kitchen lights with LEDs for years to come.

Substitute, Then Innovate

When LEDs are used in particular applications, lighting manufacturers first tend to apply them as long-lasting substitutes for a more familiar lamp. Then, as industrial designers become familiar with the device's unique characteristics, they are able to innovate, producing more sophisticated optics and controls that use LEDs in ways that would be difficult to achieve with incandescent or fluorescent sources. For instance, the first exit signs and traffic signals to use LEDs arrayed many narrow-beam units in a matrix, with each LED directly visible to the viewer. Newer products take advantage of very high brightness LEDs with distinctive beam spreads, arranging and recessing them in optically optimized reflective chambers, with the individual units hidden or indistinguishable. This trend has so far been evident in life safety and automotive products, but judging from this year's LightFair winners, the next wave of design creativity will focus on customized light sources for more niche applications, and on digitally-addressed LED products for stylish, upscale retailing and the entertainment industry.

The Path to White

LightFair attracts viewers who know the basics about light: they agree that in the world of additive color, $R + G + B = W$, or in plain English, mixing the primary colors of red, green and blue makes white light. What surprises some, however, is the LED alternative of $B + Y = W$, or the mixing of blue and its complement yellow to make white light. This method has already been successfully implemented, for example in the LED-based car map light developed by Gentex [see CS 6 (2), p. 43].

Indeed, both semiconductor and lighting professionals have a great deal of experience with chips... but of two different sorts! From the semiconductor point of view, what matters most is the material composition and structure of the chip that emits light. From the lighting industry perspective, what matters most is what the customer sees when comparing paint chips—small colored samples that are used as an industry standard comparison of how a light source renders an object.

Common to the two industries is the vexing problem of creating a spectral power distribution that will satisfy the discerning viewer of the paint chip, yet minimize the engineering and production expense of the semiconductor chip. This is reminiscent of the struggle to liberate fluorescent lamps from their old (and bad) reputation for making “ugly, greenish-looking white” light,

and the effort to introduce people to the much more attractive modern lamps that employ tri-phosphor technology and electronic ballasts.

Yes, the semiconductor industry can make “white” light with blue or UV LEDs doped with yellow-emitting phosphors, but the design community will snub any type of product that yields poor rendering of complex colored objects. Color rendering is a very complicated and important consideration—the perception of color reflected from a surface can shift radically if the light source is changed. Problems occur when using light sources that are poorly matched to the color reflectivity of the surfaces to be illuminated. For example, a white LED that only emits light in blue and yellow wavelengths would be a poor choice for illuminating red roses, or cosmetics.

With lighting designers' strong concerns about color, it was no wonder that there were more than a few cool exchanges overheard about white LEDs! Some of the comments ran thus: “That's not really a white LED, is it? It looks too blue! What's the color temperature?” and, “Let me know when you've got a product that has better color rendering.” Even so, interest in their energy-saving potential and long life did lead many attendees to ponder when they would see an LED lamp that could really replace the light bulb. The answer lies hidden on the path to the LED product that will eventually produce white light that is both visually satisfying and economical, a path that may stretch 10 to 15 years into the future.

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Figure 2. Color Kinetics' cove lighting fixture for architectural and decorative use; the modular design allows strips of different lengths containing all control electronics to be added, making it possible to install the systems in tight recesses and curved areas. The company also produces an LED lighting fixture that uses software to control up to 16.7 million colors for dynamic lighting and coloring effects.

Measured Language

Before any new light source fully enters the mainstream illumination market, all parties must agree upon nomenclature and standard measures: designers, researchers, manufacturers, and standards-setting organizations. Professionals in the lighting and the semiconductor industries are just beginning to get to know each other—and each other's technical vocabularies. Furthermore, LEDs differ in many ways from most of the light sources that designers conventionally use, so a common language and methods of testing are just beginning to evolve.

In particular, LEDs are very small, long-lived, strongly monochromatic and exhibit relatively narrow beam spreads compared to most common incandescent, fluorescent and high-intensity discharge lamps. Also, the electrical operation of LEDs is quite versatile, depending upon the control gear and the lighting application. New generations of high output LEDs are being introduced more frequently than conventional light sources, making some types of products nearly obsolete before test results can be distributed and independently verified. Lighting designers and manufacturers will need assurances that the new LED light sources are indeed performing as promised. Some will demand the ability to test and bin LEDs in their own facilities, a need anticipated by some testing equipment manufacturers exhibiting at LightFair.

Looking Ahead

No doubt we can look forward to even more entrants and colorful competitors from LEDs next year, when the LightFair International 2001 moves to Las Vegas (May 30–June 1).

LED Lighting Products on Show

With recent developments in the brightness and output of LEDs, the number of outdoor applications for these devices has proliferated to include large video-rate displays, message boards and traffic control lighting. However, more and more manufacturers are putting LEDs to use in specialty products such as outdoor building lighting, architectural lighting, large structure indicators, hand-held torches, garden and retail lighting. Many of these applications are driven by the LED's robust nature and low power consumption, in addition to considerable maintenance savings that result from their longevity, which can exceed 100,000 hours or 10 years of continuous operation. Below are some of the LED products that were on show at Lightfair.

Outdoor and Architectural Lighting

Modular International of Pittsburgh, PA exhibited small, recessed flush-mounted upward LED lamps for pathway, riser, or garden lighting with a power consumption in the range 0.5–7 W. The company also makes wall-mounted markers for security, signals or décor. Larger products include an 8-inch lamp that consumes 20 W, which is also available with a pierced cap to achieve a "sparkle" effect or for directional indicators. Modular says its customers include hotels, casinos, and parking complexes, and some of its products have been used in London's Millenium Dome.

Permlight, a Tustin, CA-based enterprise supplies low power replacements for neon. The company offers a small LED light module that installs into standard channel letters and consumes just 0.4 W, and into 24-inch high letters that require 4.4 W. Permlight's light tubes employ red LEDs in UV-resistant polycarbonate outer tubes and consume 0.8 W per linear foot.

LumiLeds Lighting, the joint venture of Agilent and Philips Lighting based in San Jose, CA, recently unveiled its LED Rail, a neon replacement that uses a string of LEDs mounted on a patented rail system designed for installation inside channel letters and band lights. A red LED is capable of illuminating a 20 ft. section with one controller. The company's Chipstrip contour lighting uses LEDs encased in UV resistant polycarbonate. These strips are designed to replace neon and provide decoration to the contours of buildings (see Figure 1). Lumileds' systems are available in red, amber and yellow using AlInGaP devices and blue and green using InGaN LEDs.

Cove lighting is also an important architectural application for LEDs. Boston-based **Color Kinetics**' cove lighting fixture (Figure 2) allows lighting in inaccessible locations with low maintenance costs. Also, because LEDs are efficient and produce little heat, problems that could be associated with heating in confined spaces are avoided. The cove fixture projects a soft-edge strip of light at a 100° beam angle, and segments are available in 6 and 12-inch lengths. A 12-inch segment costs approximately \$180.

Life Safety Products and Signage

Life safety products represent an important application for LEDs. The rugged construction, low power requirements and vibration-insensitive nature make these devices well suited as lighting for helmets and safety clothing, in addition to direction and warning signs. **Pathway** (Old Saybrook, CT) supplies a

range of red and green exit signs using LEDs mounted on a convenient slide-out circuit board. **Beghelli** of Miramar has developed red and green fixtures for signage, and offers a unit with white LEDs to illuminate a European-styled pictogram of a person running toward an exit.

Standard Enterprises offers a range of Wattman lamps used as replacements to retrofit exit signs presently using incandescent or fluorescent light sources. The Charlottesville, Virginia-based company also offers a wall-mounted LED signal light in blue, green and red, which the company says is used by energy services companies, shopping malls, casinos and other entertainment complexes. **Targetti-Tivoli** (Santa Ana, CA) supplies glare-free illuminated step lights and seat-mounted lights capable of reducing power consumption by 70%–80% compared to miniature incandescent lamps.

Illumination Polymer Technologies is a Naperville, Illinois-based manufacturer of LED-based clothing illuminators.

These devices are capable of operating for 600 hours with standard batteries. The company's Polybrite line consists of a yellow reflective polymer with embedded red LEDs, which is flexible and can be used for self-illuminating armbands, belts and vests.

Display and Task Lighting

Display and decorative retail lighting represents an exciting new development that benefits from the ability of output and color of LEDs to be rapidly switched to produce complex lighting effects, in addition to providing low-wattage incandescent replacements. Additionally, task lights such as flash lamps and reading lights are robust and require much less power than incandescent sources, leading to considerable battery savings, or the ability to take advantage of solar power.

An example of a decorative and/or retail application comes again from **Color Kinetics**—its LED control soft-

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ware allows designers to create lighting and dynamic effects with up to 16.7 million colors. The company's ColorBlast indoor and outdoor LED fixture (see Figure 2) contains 108 red, 85 green and 85 blue LEDs (from Nichia and Agilent), and is capable of flooding a wall up to 10 feet in height.

Vancouver-based **TIR Systems** also has a color changing light fixture using programmable LED technology. The company's module diffuses light into 4- or 6-inch diameter sections of plastic pipe (Figure 3). At less than 50 W of power consumption at full light output for white and around 30 W for saturated colors, this system also uses RGB

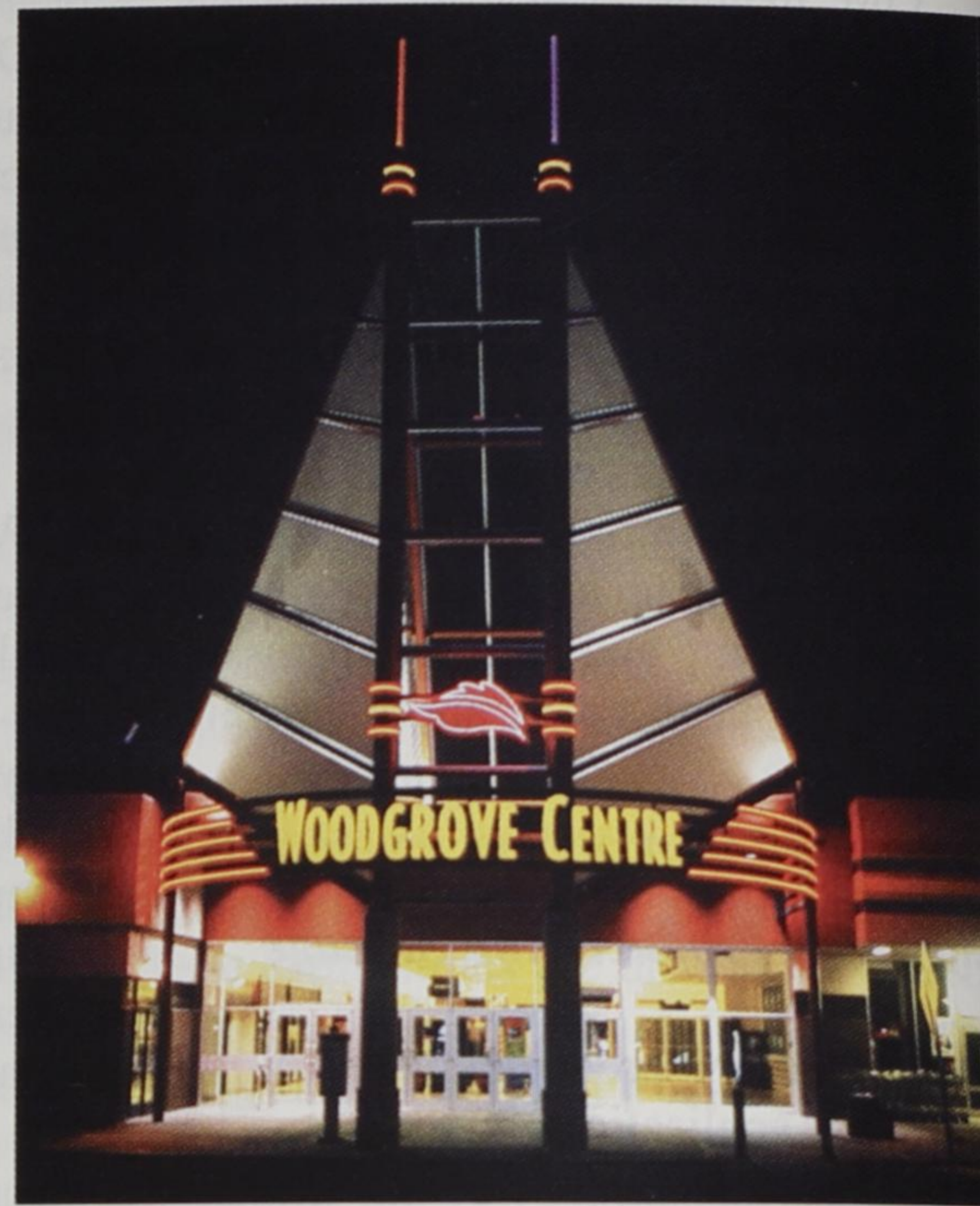
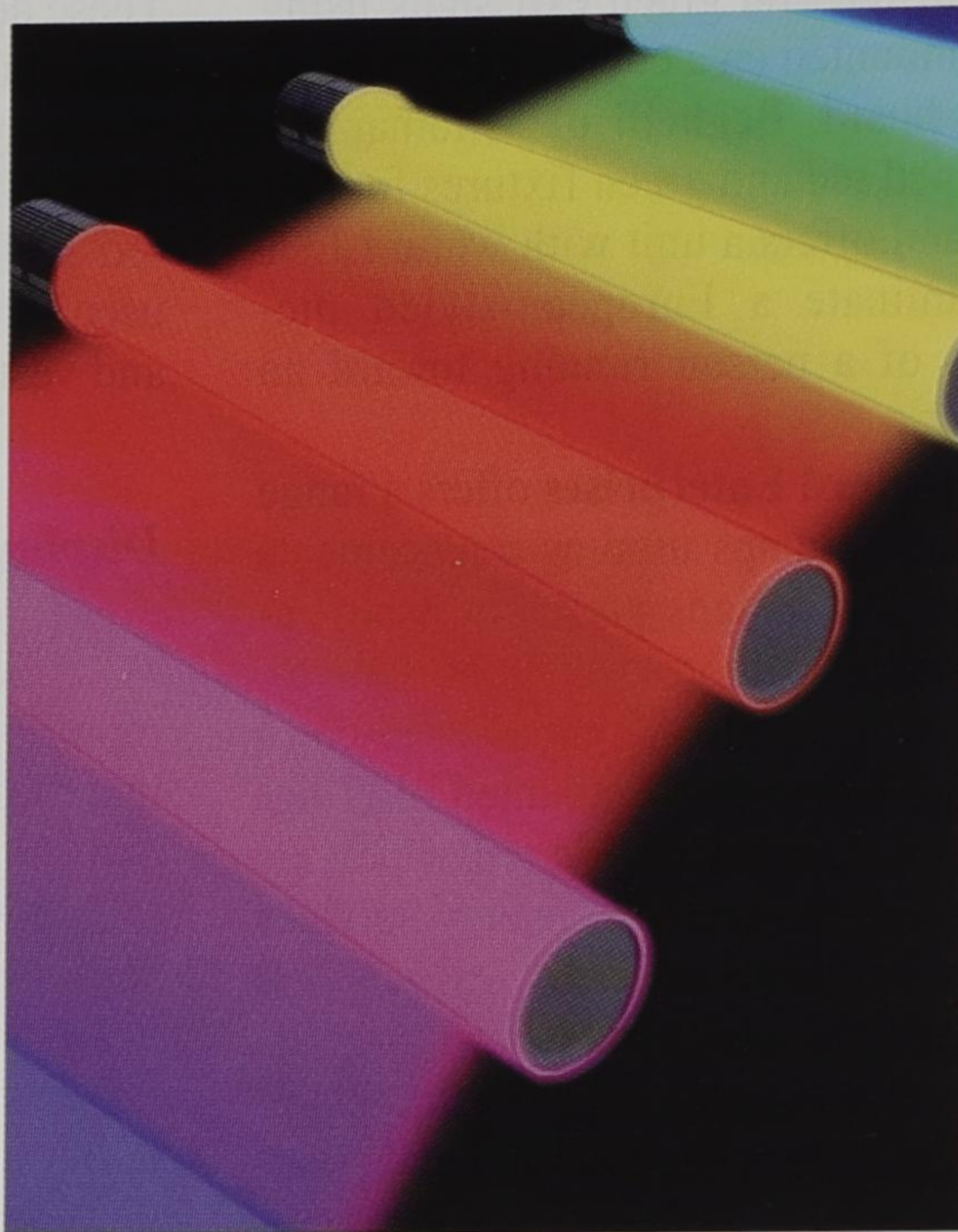


Figure 3. The LED color change module from TIR Color Systems produces light in 4- or 6-inch diameter plastic pipes, and also enables RGB color mixing in strobe or color wash modes for building decoration.

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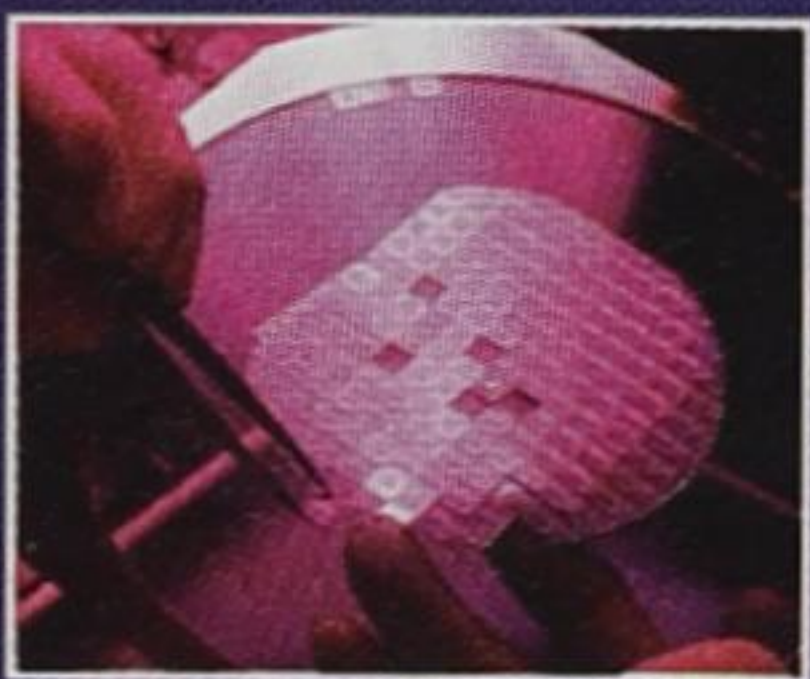
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(red-green-blue) color mixing to provide retail and architectural highlighting (Figure 3).

General LED Light Sources

LumiLeds also displayed its new Power LED Light Engine. This system features customized configurations of LEDs mounted on a metal core printed circuit board. Each board can contain 1, 2, 12 or 18 LEDs in red or amber AlInGaP, or blue or cyan based on InGaN, with luminous efficiencies from 1.7 lm/W for blue to 20 lm/W for red. Advance Transformer, now a division of Philips Electronics North America Corporation, has teamed up with LumiLeds to supply electrical system drivers for these LED engines, and to distribute products. LumiLeds will also collaborate on value-marketing its products with Dialight, the largest producer of LED traffic lights in the United States (see page 18).

Osram Opto Semiconductors of Regensburg in Germany displayed a full range of colors and also GaN- and InGaN-based white LEDs. These devices were featured in packages including Mini-, Power- and Multi-TOPLEDS, SIDELEDs and CHIPLEDS. Osram's TOPLED configuration can be used for indoor applications such as screens or displays, where the observer may be only a few feet away and high resolution is needed. For this case Osram Multi-TOPLED employs a single package containing red, green and blue LEDs spaced very closely to obtain high resolution. These devices are primarily aimed at the automotive market, but show potential for general illumination applications.

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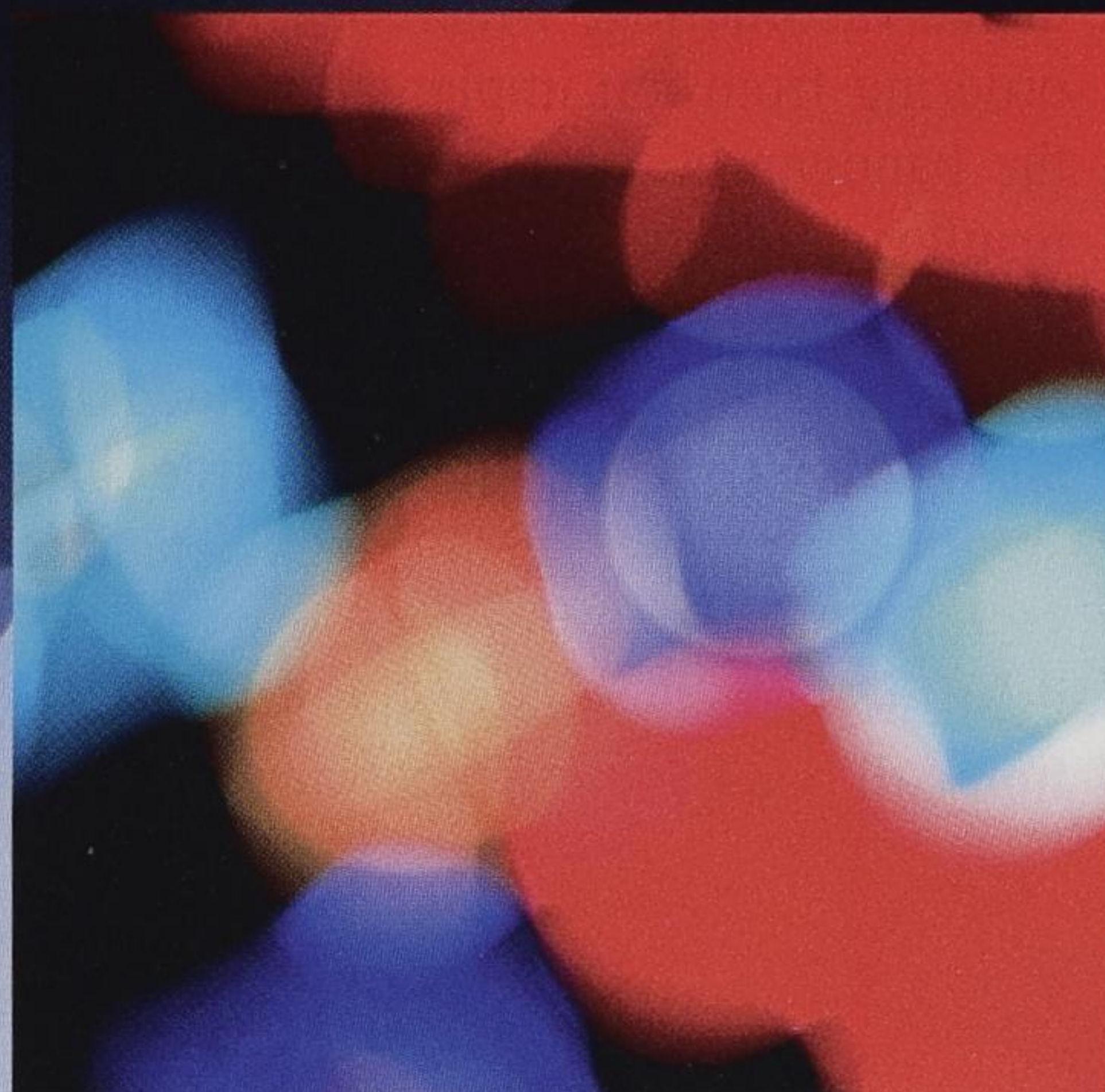
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ADC's Epitaxial Mirror on Facet Process Improves 980 nm Pump Laser Reliability

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This year's Optical Fiber Communications conference (OFC) saw the emergence of several new manufacturers of 980 nm pump lasers—ADC, Mitsubishi Electronics and Multiplex. Each company has developed a proprietary method to coat the facets of their laser structure to protect the devices from catastrophic optical mirror damage.

The first pump lasers used in erbium-doped fiber amplifiers (EDFAs) operated at 1480 nm and took advantage of high reliability InP-based technology derived from 1550 nm devices. The introduction of GaAs-based 980 nm pumps resulted in lower noise figures in the amplifiers, but there were problems associated with the reliability of the shorter wavelength devices.

Most 980 nm pumps use AlGaAs in the cladding layers around the InGaAs/GaAs QW active region. Surface oxidation of the Al-containing layers and the resulting high surface recombination velocities leads to band bending at the laser facets. Light is absorbed within a region several diffusion lengths wide at the facet. The absorption leads to heating at the facet, which eventually causes catastrophic optical mirror damage.

Reducing COMD

Several approaches have been developed to protect laser facets from catastrophic optical mirror damage. The earliest was the E2 process developed by IBM, in which silicon is deposited onto the laser facets by e-beam evaporation. This facet passivation step prevents oxidation and associated problems due to heating, but the passivation material is strongly

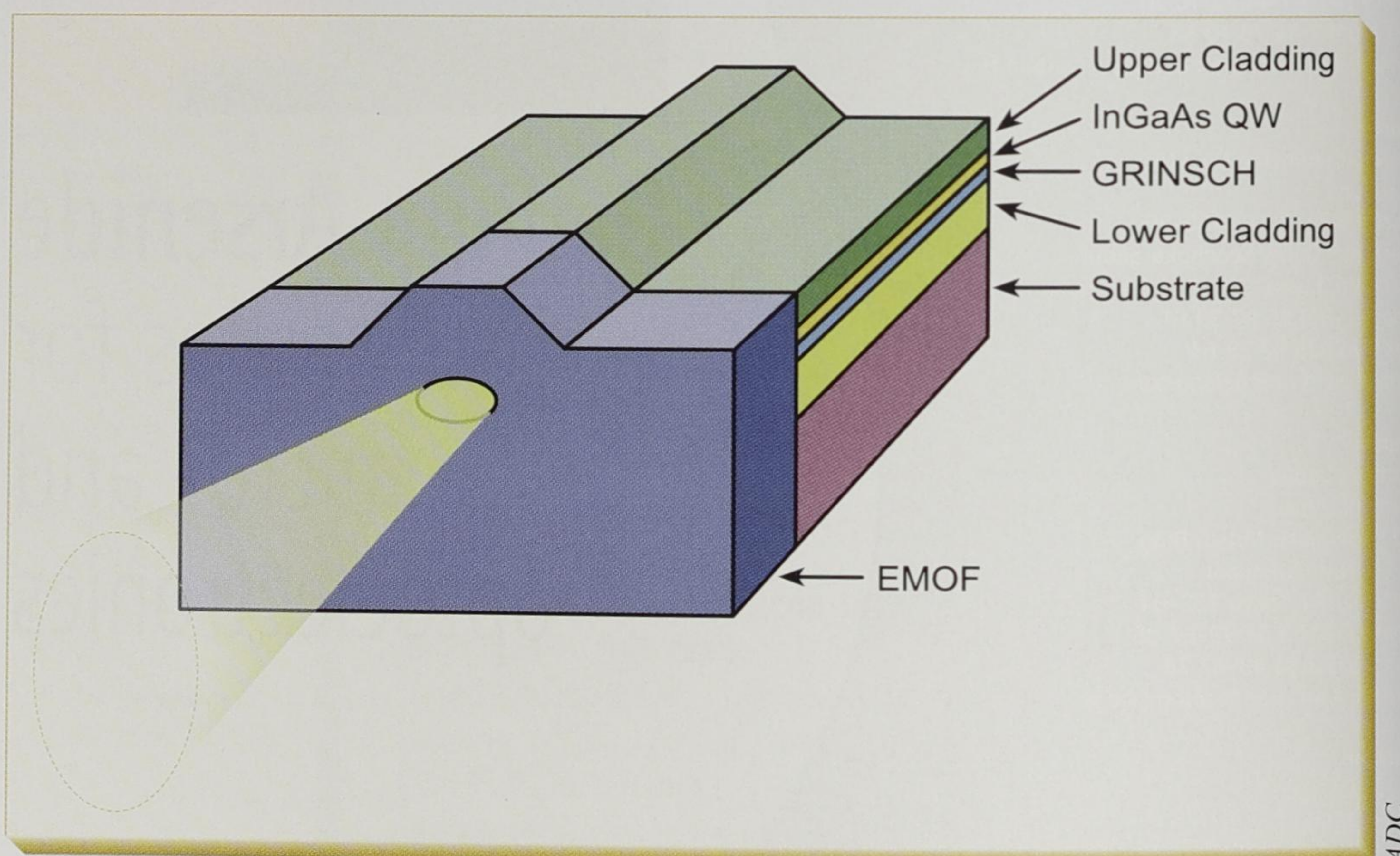
absorbing at 980 nm. One important feature of this process is that the reliability of the device has a roughly cubic dependence with output power, apparently due to heating in the neighborhood of the front facet.

Another approach is impurity-induced disordering, which uses local disordering from ion implantation to widen the bandgap at the facets. Although this results in reduced absorption at the facets, the bandgap shift is small and the fabrication process is relatively complicated. It is also possible to fabricate Al-free laser structures using the InGaAsP material system. These devices are less efficient than InGaAs/AlGaAs devices and oxidation still occurs, but at a slower rate.

While improvements continue to be made to the power handling capability of the facets, this remains a major issue for manufacturers of 980 nm pump lasers.

The Epitaxial Mirror on Facet Approach

ADC's approach is to use MBE to grow a layer of single crystal material onto the facets. According to Prabhu Thiagarajan, Head of Reliability at ADC, the process—termed Epitaxial Mirror on Facet or EMOF—virtually eliminates catastrophic optical mirror damage. "In our reliability tests we have been unable to find a power dependence of reliability



Schematic of a 980 nm pump laser fabricated by ADC. The ridge waveguide structure features a single InGaAs quantum well, and is grown by MBE. In order to restrict the onset of catastrophic optical mirror damage, the facets are cleaved under vacuum and a non-absorbing epitaxial mirror layer is deposited in a batch process termed "Epitaxial Mirror on Facet (EMOF)".

or failure rate," he says. The lasers can be pulsed above 2.5 A, producing a calculated optical power density over 100 MW/cm², without effect. In addition, the devices can be cycled indefinitely with high current to the point of rollover and back again without any degradation to the laser performance.

The EMOF process is performed under UHV conditions after most other processing steps have already been carried out. "We load a rectangular section of wafer into the UHV system and cleave it into bars," explains Mark McElhinney, Director of Engineering. "Then all the bars are placed in a cassette, and we grow the mirrors on each bar simultaneously." As a batch process, this differs from other processes in which the bars are coated individually, one at a time. "We can run several cassettes without breaking vacuum, and the yields are extremely good," he adds.

Since metallization, dielectric deposition and most other processing steps have been carried out prior to mirror growth, the growth temperature must be kept low. Fortunately, says McElhinney, the nature of the mirror material and the (110) orientation of the facet both lend themselves to a low MBE growth temperature. Until various applied-for patents are issued, ADC declines to name the material, although it is known to have a wide bandgap to avoid problems with optical absorption. The thickness of the mirror is based on the need to achieve 9% optical reflectivity for the front facet.

ADC's Products

ADC sells both 980 nm chips and modules. The company operates a fully integrated facility in White Bear Lake, Minnesota, which was obtained through the acquisition in June 1999 of Spectracom, a start-up laser manufacturer that originally developed the EMOF process. ADC carries out epitaxial growth and chip fabrication, burn-in and testing, as well as module assembly and packaging.

The 980 nm chips fabricated by ADC have demonstrated output powers of 350 mW ex-facet, while modules have achieved fiber-coupled power as high as 250 mW. As noted above, the reliability of the lasers has no output power dependence, so the FIT rate applies to the highest power devices. "We have achieved around 400 FIT after 5000 hours for 350 mW ex-facet or 250 mW into fiber," says McElhinney. "We believe that our reliability figures are the best available for such high powers."

ADC has logged well over a million device hours internally, and is in the process of accumulating field hours now that it has started to deploy sizable quantities of devices to telecom customers. Long-term reliability is a crucial feature of 980 nm pump lasers, especially for submarine applications where there is a high barrier to entry for new manufacturers. However, ADC is confident that its EMOF process will provide a strong advantage in the 980 nm pump laser market.

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VCSELs: Driving the Cost Out of High Speed Fiber Optic Data Links

DAVE WELCH

W. L. Gore & Associates

*Presented at the Key Conference on
Compound Semiconductors
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VCSELs offer both performance and cost advantages over traditional edge-emitting lasers. Following strong investment by the U.S. government, universities, and industry in the late eighties and early nineties, VCSELs are now being manufactured in high volume by a number of suppliers. The main application at present is gigabit-speed communications, while technology advances are opening up other markets at higher data rates and longer transmission distances.

The VCSEL Advantage

Essentially, VCSELs are very high performance lasers that can be produced much like low cost LEDs. VCSELs have a low divergence circular output beam and very stable performance characteristics over temperature. They can be modulated at high data rates, and can have threshold currents of less than a milliamp in some cases. In addition, VCSELs offer the manufacturing advantages of wafer-scale fabrication and test, and the practical ability to produce either small or large arrays.

Although VCSELs can be manufactured at relatively low cost, the real advantage comes in the ease of packaging these devices. For example, the low divergence circular beam enables improved coupling tolerances. Also, high-speed operation is achieved at low power, which minimizes problems with crosstalk and heat dissipation.

Another important aspect of VCSELs is that the stable performance over temperature allows the monitor photodiode feedback loop to be eliminated in many applications. This not only eliminates the monitor photodiode, it also simplifies the IC and package designs, with important cost implications. Furthermore, non-hermetic packages are now available and the ability to produce uniform, low cost arrays with good temperature stability has enabled the development of low cost, parallel optical modules (see Figure 1).

VCSELs were successful at entering the communications market because of the strong demand created by the need to transition from 100 Mb/s applications like Fast Ethernet to 1 Gb/s applications like Gigabit Ethernet and Fibre Channel. The perfor-

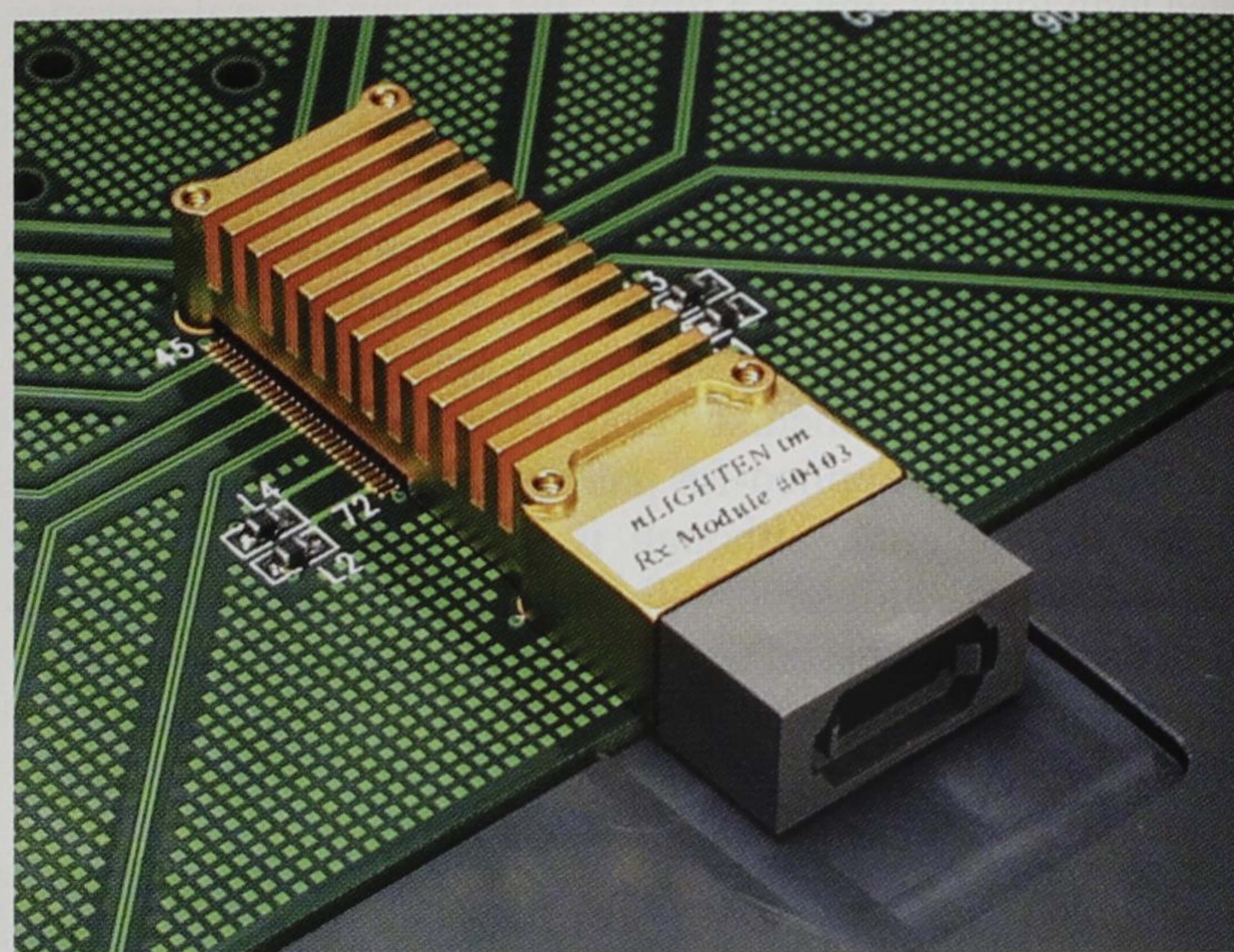
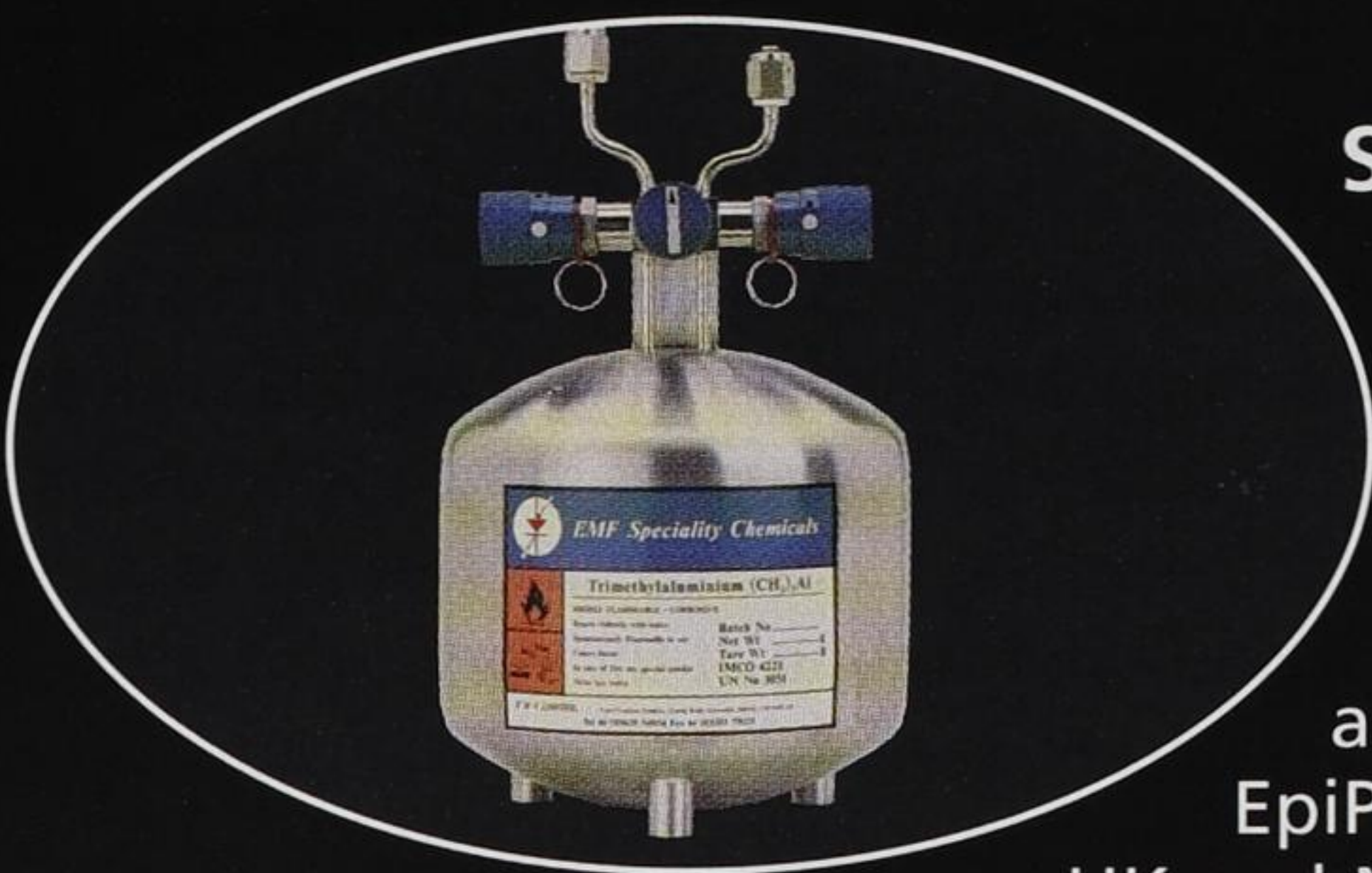


Figure 1. Gore's nLIGHTEN™ parallel optical modules contain 12-channel arrays of VCSELs and detectors, for an aggregate bandwidth of 15 Gb/s. The modules are only about three-quarters of an inch wide, allowing many modules to be incorporated onto a card edge.

mance of LED sources that had been used for 100 Mb/s applications was not able to match the speed requirements of the emerging standards, so a new source technology was required. One interesting point is that VCSELs went head to head with CD lasers in the early stages of the Fibre Channel and Gigabit Ethernet markets. At the time, VCSEL production volumes were very low, while the CD lasers were being produced in high quantities. Despite this, VCSEL manufacturers were able to enter the market and be cost competitive at an early stage. Customers were attracted by the performance and reliability advantages of VCSELs, as well as the promise of scalability to higher data rates. Today, the vast majority of high-speed, short wavelength transceivers use VCSELs, and production is now at the level of million of units per year.

Products and Markets

The first commercial VCSEL product was introduced by Honeywell in 1996. The VCSEL was offered in a traditional TO can, primarily for use in transceiver modules for Fibre Channel and Gigabit Ethernet. In these applications, transmission distance is



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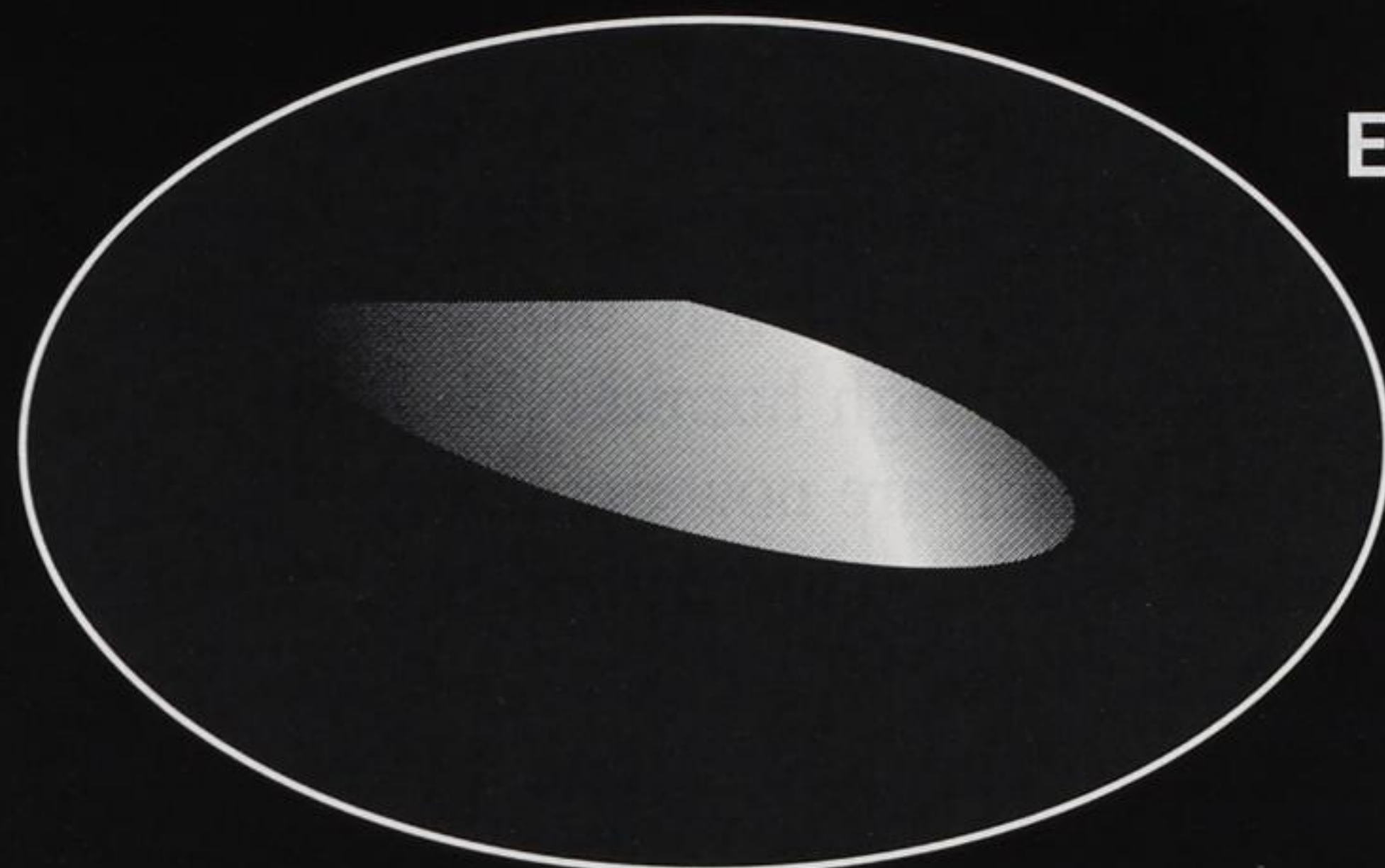
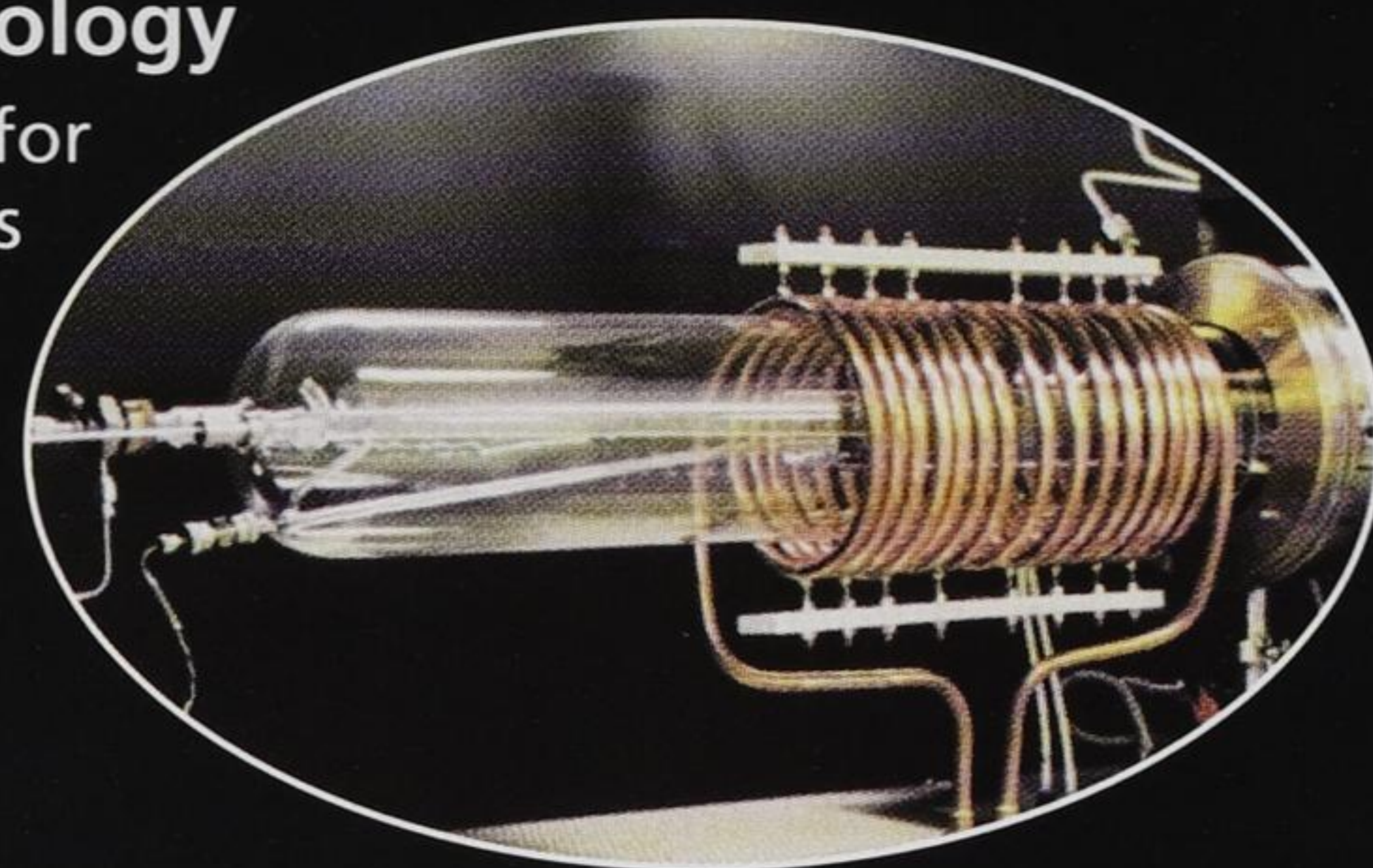
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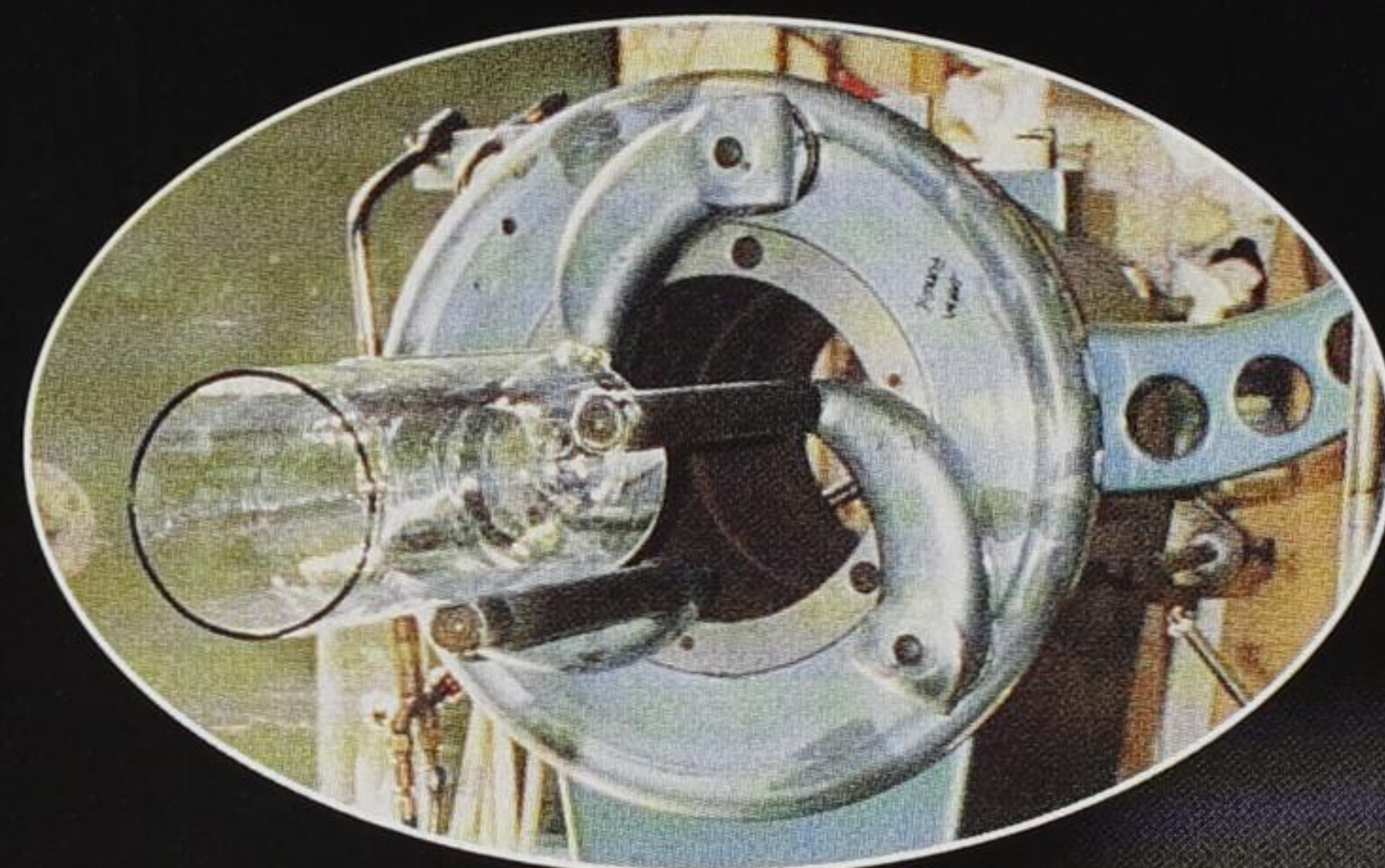
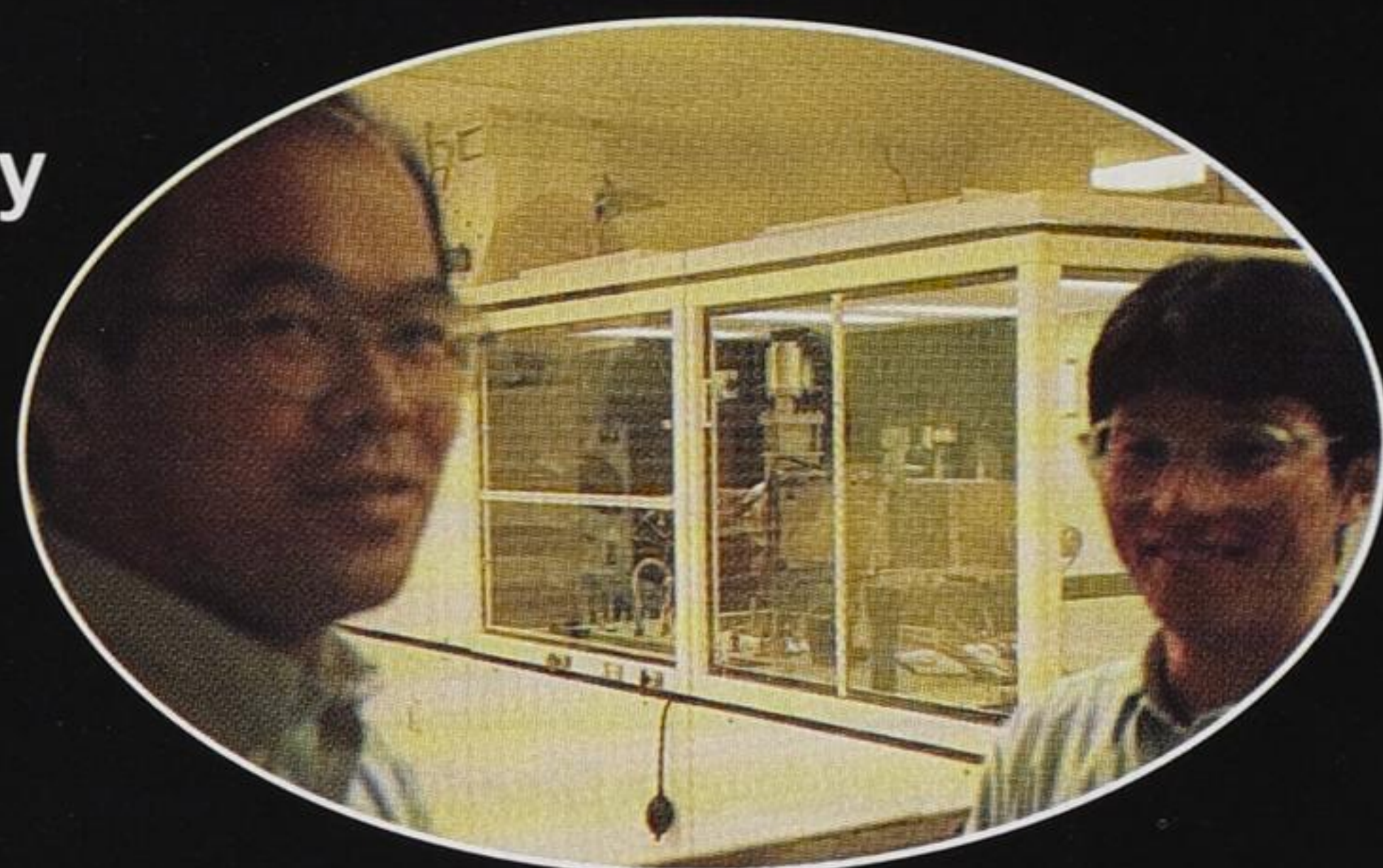


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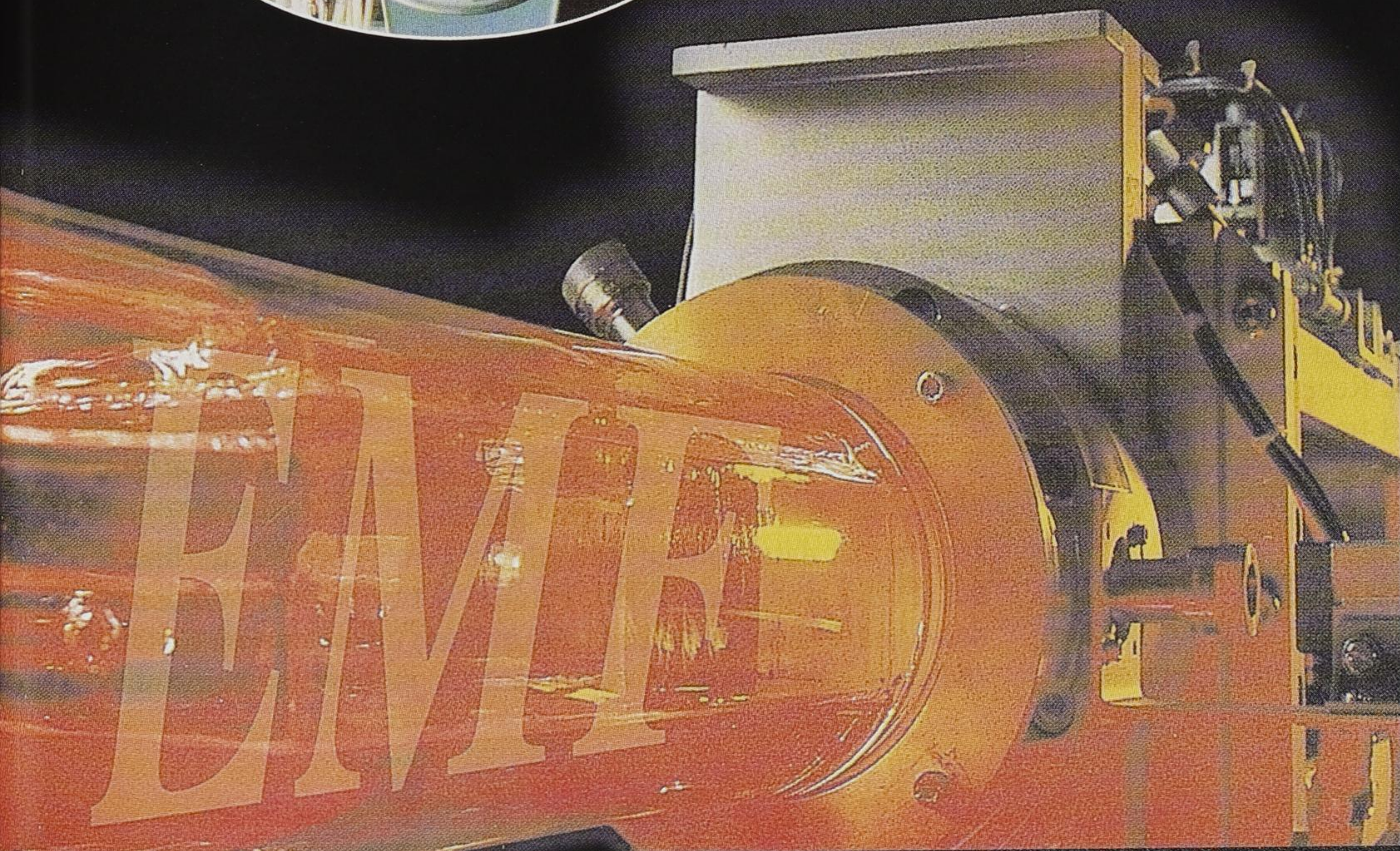
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12.5 Gb/s Eye Pattern

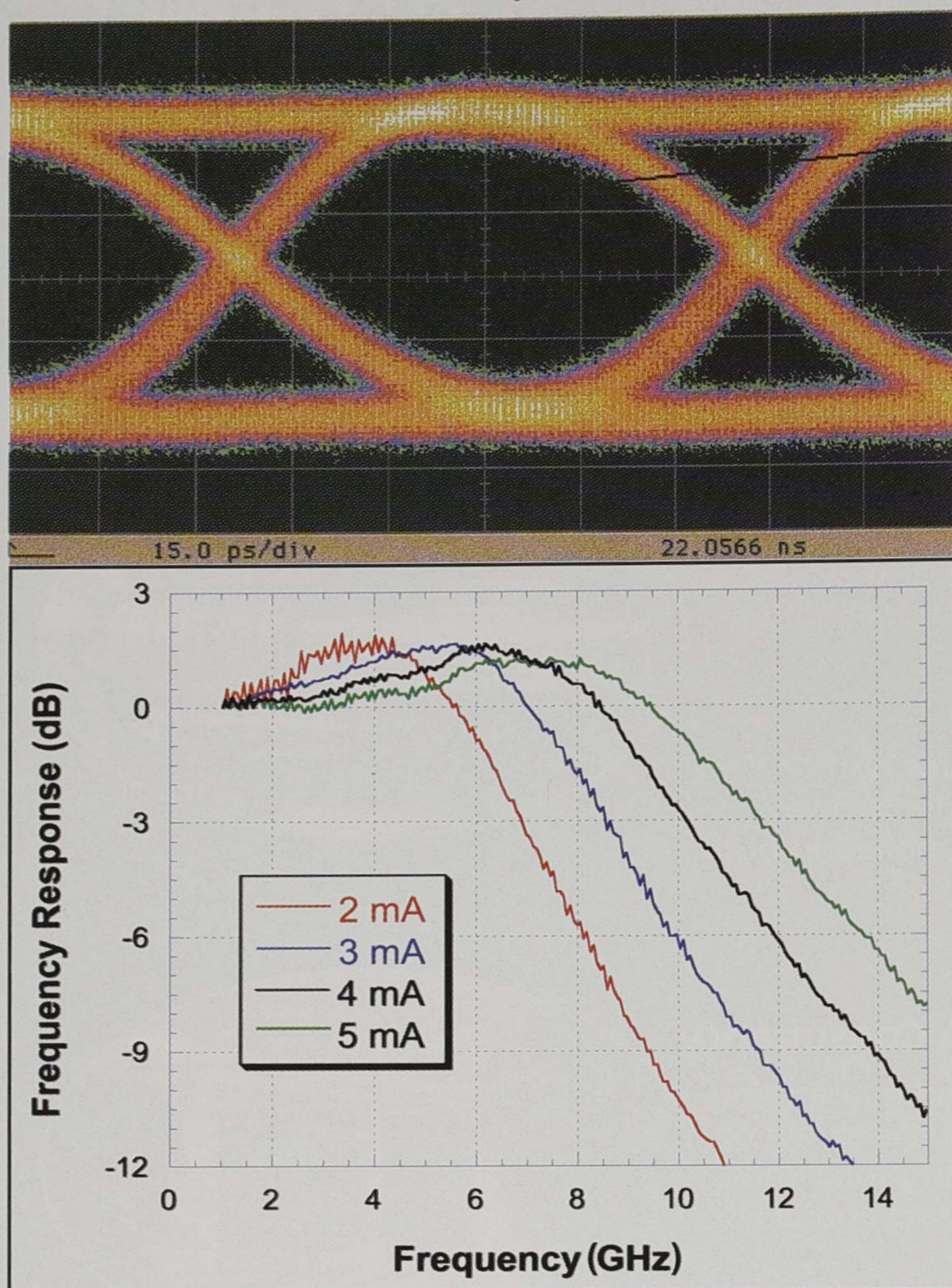


Figure 2. Gore's oxide-confined VCSELs show an open eye diagram at 12.5 Gb/s and operate from a very low modulation current of less than 5mA.

less than 300 meters. Honeywell conducted early reliability studies that were very helpful in getting VCSELs accepted within the standards community and by customers. By accumulating a large amount of data, Honeywell showed that VCSELs could typically offer reliability improvements over CD lasers. Today Gigabit Ethernet and Fibre Channel transceivers are available from a large number of suppliers.

An important development in the last year or two has been the introduction of small form factor transceivers at approximately half the size of standard products, allowing the incorporation of more transceivers onto each network card.

The gigabit market is growing at a rapid rate, and will continue to do so for the next several years. Recent data from *Electronic* states that the gigabit Ethernet transceiver market was worth about \$600 million in 1999, and will grow to over \$2 billion by 2004. Other projections suggest that this figure will be even higher.

There are a number of emerging opportunities for VCSELs, particularly in the area of multi-gigabit networking, where VCSELs are being developed for emerging standards such as 2X

and 4X Fiber Channel and 10 Gigabit Ethernet. Parallel optical products for Very-Short-Reach (VSR) applications have reached the market and are gaining support in industry groups such as the Optical Internetworking Forum (OIF). For these applications, the development of oxide-confined devices and arrays is crucial. Long wavelength VCSELs operating at the single-mode telecom transmission wavelengths (1.3- and 1.55- μ m) will move the cost benefits of VCSELs to longer distance applications. Also, there are a number of emerging applications for VCSELs in areas relating to WDM.

Oxide-Confined VCSELs

First generation VCSELs, including many of today's standard products, are fabricated using ion implantation. This process creates a resistive area that funnels the current into the active region. The second generation of VCSELs use oxide confinement to provide both current guiding and index guiding for improved efficiency. Oxide VCSELs are grown with a high aluminum content buried layer, which is subsequently oxidized under conditions of high temperature and high humidity to form the device aperture. Oxide devices, which are now commercially available, operate at higher speeds and have lower threshold currents than the ion implant VCSELs. Oxide VCSELs also exhibit improved temperature performance. The advantages offered by oxide VCSELs enable low cost, higher speed LAN transceivers. These devices also allow the fabrication of highly uniform arrays, enabling multi-channel, parallel optics applications.

Figure 2 illustrates the performance of oxide-confined VCSELs manufactured by Gore. In an uncooled package, the devices can be directly modulated at a rate of 12.5 Gb/s with a very low modulation current. As the networking environment moves towards higher speeds, the transmission distance in standard multi-mode fiber shrinks dramatically (see Figure 3). To address this problem, new multimode fibers have been developed that are optimized for lasers emitting at 850 nm. Gore has been on the leading edge of working with companies including Lucent, Corning and Alcatel, who have been developing this fiber to create next generation multimode systems.

A demonstration combining Gore's 850 nm VCSELs and Lucent's high bandwidth fiber showed 10 Gb/s transmission across a distance of 400 meters. Subsequent experiments have shown that a 12.5 Gb/s signal can be transmitted across nearly a kilometer. These are laboratory-type experiments, but they indicate that robust transmission can be achieved through several hundred meters of multimode fiber using VCSELs.

Parallel Optical Interconnects

One of the major challenges in emerging high-speed networks is the ability to cost-effectively manage the huge amounts of data flowing through the central offices and Internet service providers (ISPs). Parallel optics is a very attractive solution for short-distance (<300 meters) links between routers, switches, and transport equipment. A number of companies

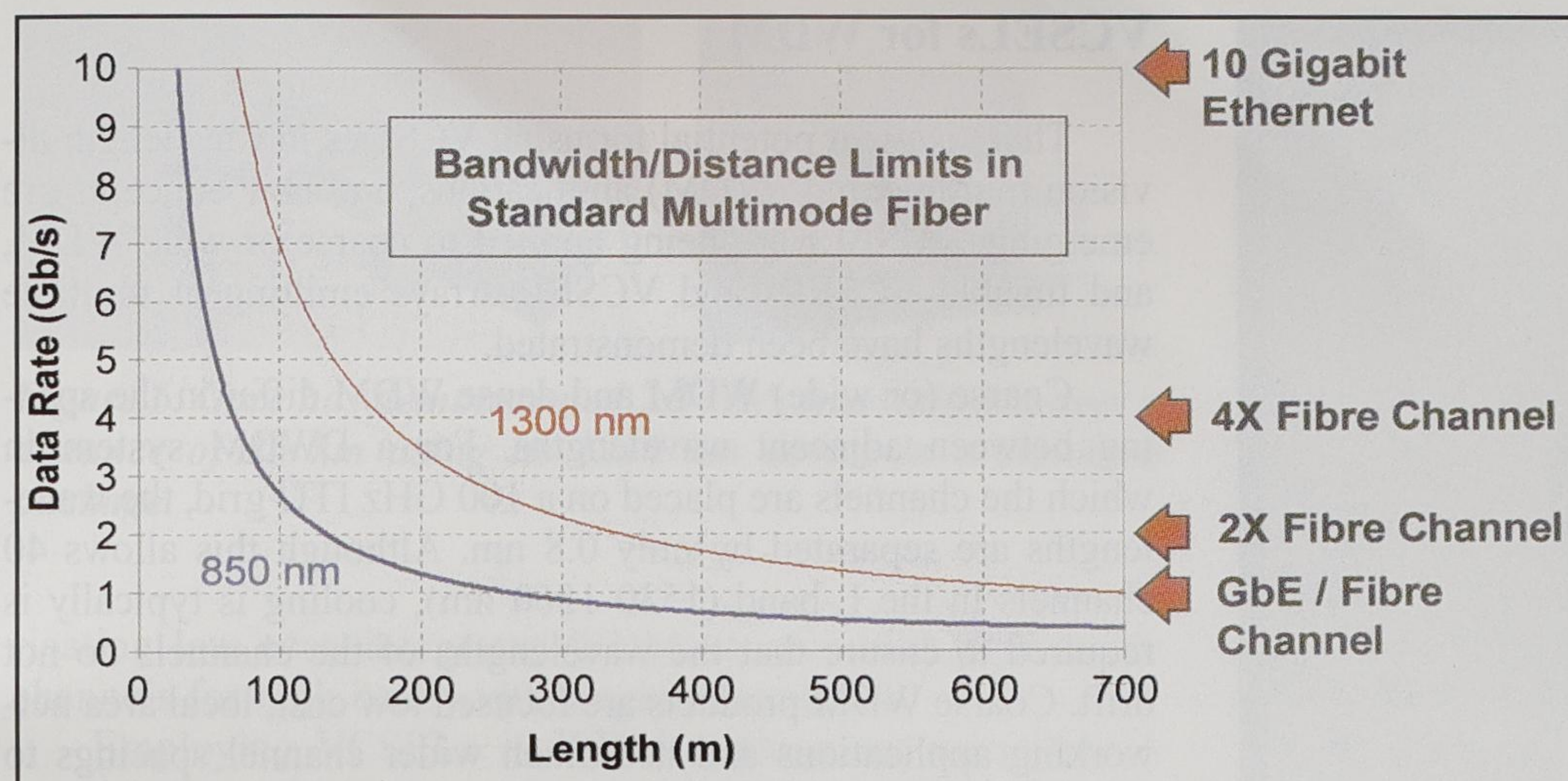


Figure 3. Bandwidth/distance limits in standard multi-mode fiber: the transmission distance is severely restricted as the data rate increases (Data based on the Gigabit Ethernet link model in 160 MHz/km fiber.) Several vendors have developed new fiber optimized for 850-nm transmission, and 12.5 Gb/s transmission over 1 nearly km has been demonstrated.

have introduced multi-channel transmitter & receiver products, utilizing arrays of VCSELs and detectors connected by ribbon fiber. Early implementations of this technology have 12 channels with 1.25 Gb/s per channel, equating to an array with an aggregate data rate of about 15 Gb/s. It is important to note that this solution costs a few hundred dollars, compared to the thousands of dollars required to implement today's OC-192 (10 Gb/s) serial links.

Gore is in the process of commercializing its nLIGHTENTM parallel modules. The modules are only about three-quarters of an inch wide, allowing many modules to be incorporated onto a card edge (see Figure 1). Both Gore and Infineon produce parallel optical modules compliant with a multi-source agreement that provides for footprint-compatible modules in an effort to speed the market acceptance of these products.

Gore's nLIGHTENTM parallel modules were incorporated into a system displayed by Cisco Systems at the recent Optical Fiber Communications Conference (OFC). The Very-Short-Reach (VSR) parallel optical interface is being promoted within the Optical Internetworking Forum as a leading choice for OC-192 (10 Gb/s) transmission at distances up to 300 m. In

this application, an ASIC converts the incoming 16×622 Mb/s signal into a 12×1.25 Gb/s signal for transmission across the 12-channel ribbon fiber.

A key part of making low cost parallel modules is the availability of a suitable VCSEL array technology. Gore VCSEL arrays are designed to have very stable performance over temperature at the actual operating current of ~5 mA (see Figure 4). This simplifies the system design, and eliminates the need for a monitor photodiode feedback loop. The VCSELs are scalable to high data rates so that in the future, low cost, hundred gigabit connections over very short distances is a viable concept.

Life test data for Gore VCSELs operating at 100°C with a drive current of 5 mA shows no failures after more than 2500 hours of test time. A large-scale reliability test is currently being performed, and the results will be available shortly.

Long Wavelength (1.3 μ m and 1.55 μ m) VCSELs

VCSELs operating at the transmission wavelengths of single-mode fiber (1.3 μ m and 1.55 μ m) will extend the cost benefits of VCSELs into the single-mode domain, enabling longer transmission distances and opening up new applications. This will move VCSELs from local area networks (LANs) with transmission distances of several hundred meters into access networks, campus backbones, metropolitan area networks (MANs) and wide area networks (WANs) with multi-kilometer transmission distances.

Despite strong demand for long wavelength VCSELs, the technology has developed relatively slowly due to fundamental materials challenges. Good mirrors can be grown on GaAs substrates, however it is very difficult to grow active regions emitting at 1.3 μ m on GaAs. Conversely, good active regions can be grown on InP substrates, however high reflectivity InP-based mirrors are extremely difficult to fabricate. There has been, and continues to be, a large effort to try to address these problems through fundamental materials research. Thus far, however, the best devices have used wafer fusion to combine materials of different lattice constants into one structure.

Gore has combined wafer fusion with an integrated, optical pump to produce the world's best long wavelength

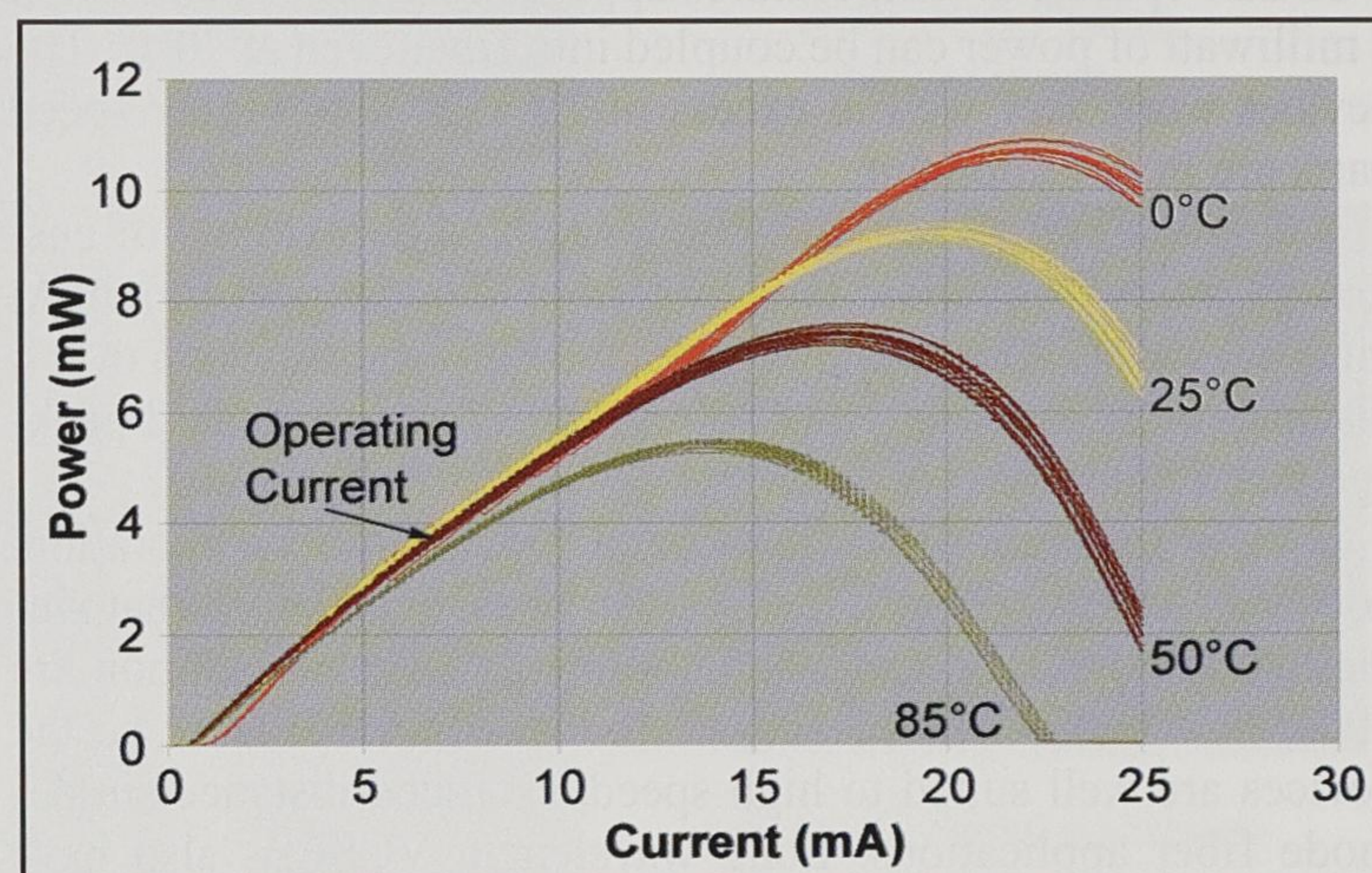


Figure 4. Gore's VCSEL arrays are designed to have very stable performance over temperature at the actual operating current of ~5 mA. This simplifies the system design, and eliminates the need for a monitor photodiode feedback loop.

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VCSELs (see Figure 5). The Gore structure has several major technical advantages resulting in higher single-mode powers and improved performance over temperature. Gore's 1310 nm VCSELs operate at temperatures approaching 100°C, and about a milliwatt of power can be coupled into fiber even at 70°C. The devices work very well in excess of 2.5 Gb/s and higher speed parts are in development.

Gore's VCSELs are now being sampled to a couple of customers, and will be more broadly available in the near future. At this year's OFC, Gore demonstrated 2.5 Gb/s transmission over a distance of 25 km using its 1300 nm device in a standard package (see Figure 6).

VCSELs are normally associated with multimode operation, however long wavelength devices can be designed such that single longitudinal mode and single transverse mode operation are obtained. The linewidth is similar to that of a DFB laser, so the devices are well suited to high speed, extended distance single-mode fiber applications. Long wavelength VCSELs also have major coupling advantages (see Figure 7). 1300 nm VCSELs have a low divergence, circular beam profile that enables more than 80% of the light to be coupled into single-mode fiber without lensing, creating very obvious advantages with regard to package design.

VCSELs for WDM

There is great potential for using VCSELs in wavelength division multiplexing (WDM) applications, and new concepts are emerging. VCSELs are being applied to coarse or wide WDM, and tunable VCSELs and VCSEL arrays emitting at multiple wavelengths have been demonstrated.

Coarse (or wide) WDM and dense WDM differ in the spacing between adjacent wavelengths. For a DWDM system in which the channels are placed on a 100 GHz ITU grid, the wavelengths are separated by only 0.8 nm. Although this allows 40 channels in the L-band (1530-1560 nm), cooling is typically required to ensure that the wavelengths of the channels do not drift. Coarse WDM products are focused low cost, local area networking applications and use much wider channel spacings to simplify product design. Channel spacings of 10- to 25-nm are employed, and because VCSELs drift less than 0.1 nm/°C the products can effectively operate uncooled, from 0–70°C without channel overlap.

Blaze Network Products has developed an eight-channel coarse WDM transceiver using VCSELs with wavelengths ranging from 790 nm to 860 nm. Plastic, molded components combined with broad wavelength filters enable the optical mux and demux functions to be accomplished at low cost.

Tunable VCSELs have also been demonstrated. CoreTek (now part of Nortel) has combined a VCSEL technology with a MEMS mirror that can be moved in order to tune the cavity. About 40–50 nm tuning and 5 mW of coupled power has been achieved in this manner.

Finally, Gore has demonstrated VCSEL arrays containing four devices emitting at different wavelengths in the 1550 window. Using this technology, the possibility exists for fab-

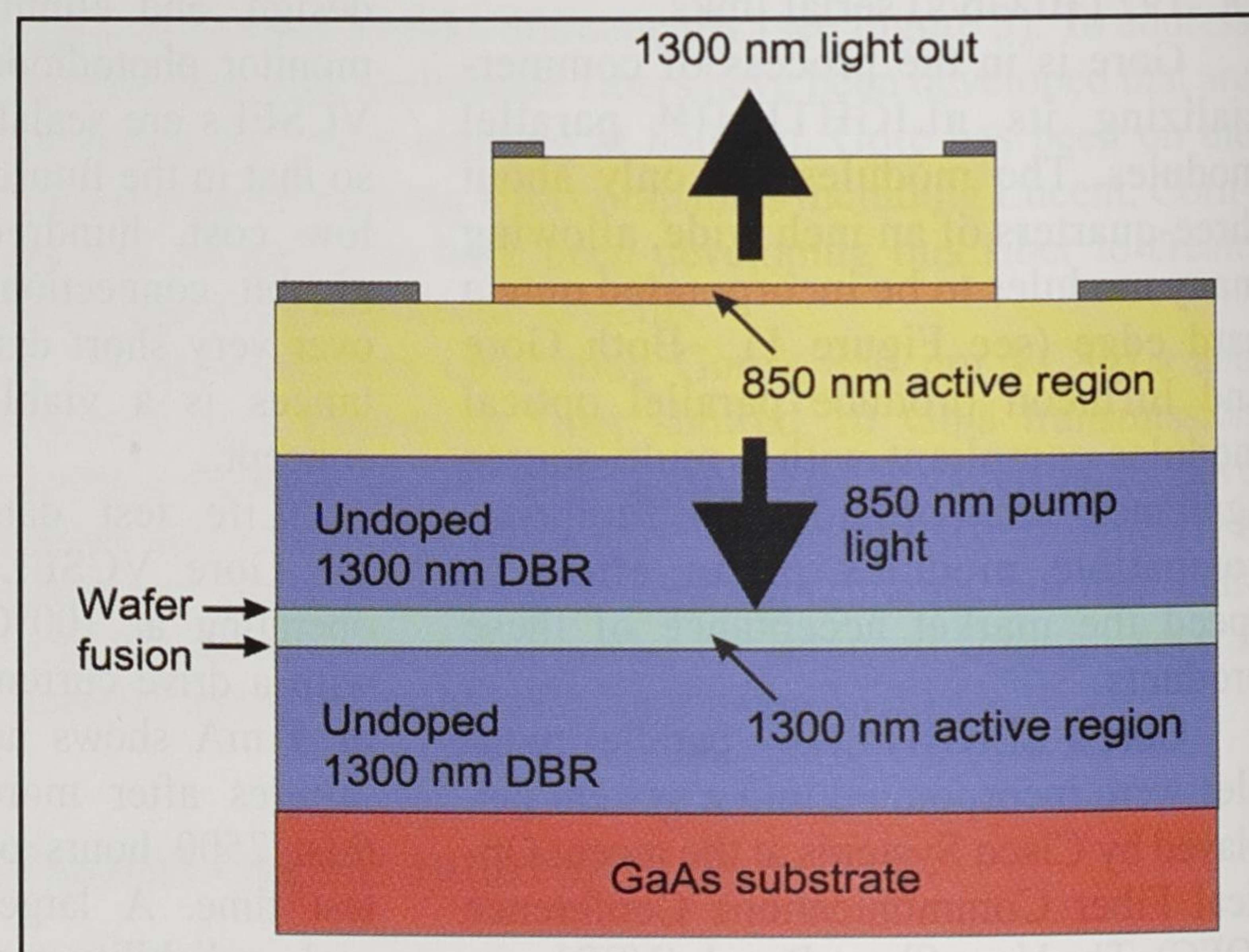


Figure 5. Schematic structure of Gore's 1310 nm VCSEL, which uses wafer fusion and optical pumping to overcome materials challenges at these wavelengths. The device has demonstrated CW performance at 95°C, a modulation speed of 7 Gb/s, and single-mode output powers of >1 mW.

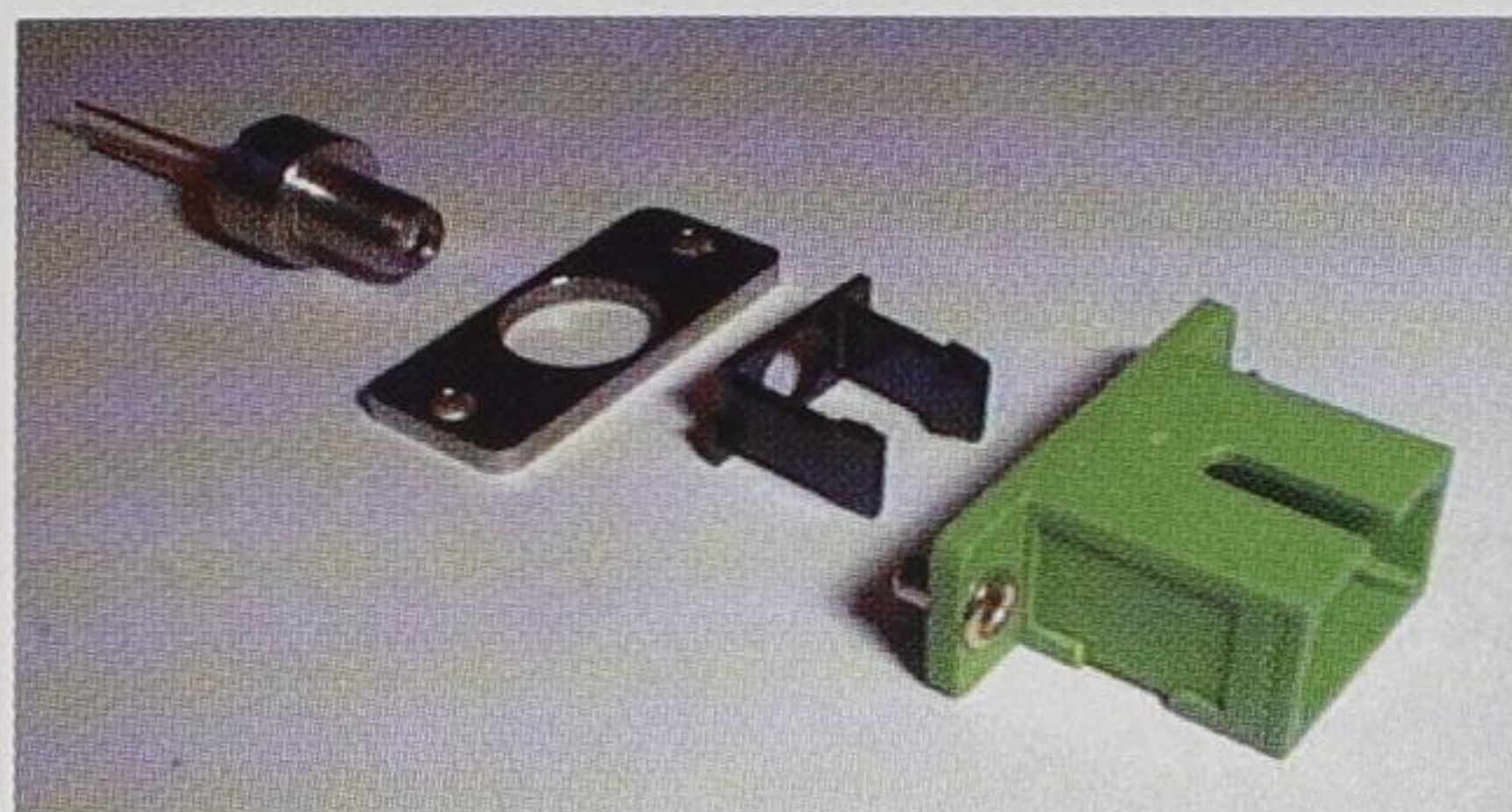


Figure 6. Gore has demonstrated 2.5 Gb/s transmission over a distance of 25 km using its 1310 nm device in a standard package.

ricating low cost, integrated WDM sources with 4, 8 or 16 channels for high bandwidth single-mode links.

Employing VCSELs in WDM applications area should prove to be a fertile ground for innovation and future development.

Summary

For certain applications, VCSELs have fundamental advantages over other types of lasers. No longer lab curiosities, VCSELs are in volume production from multiple suppliers, and technological advances continue to enable new applica-

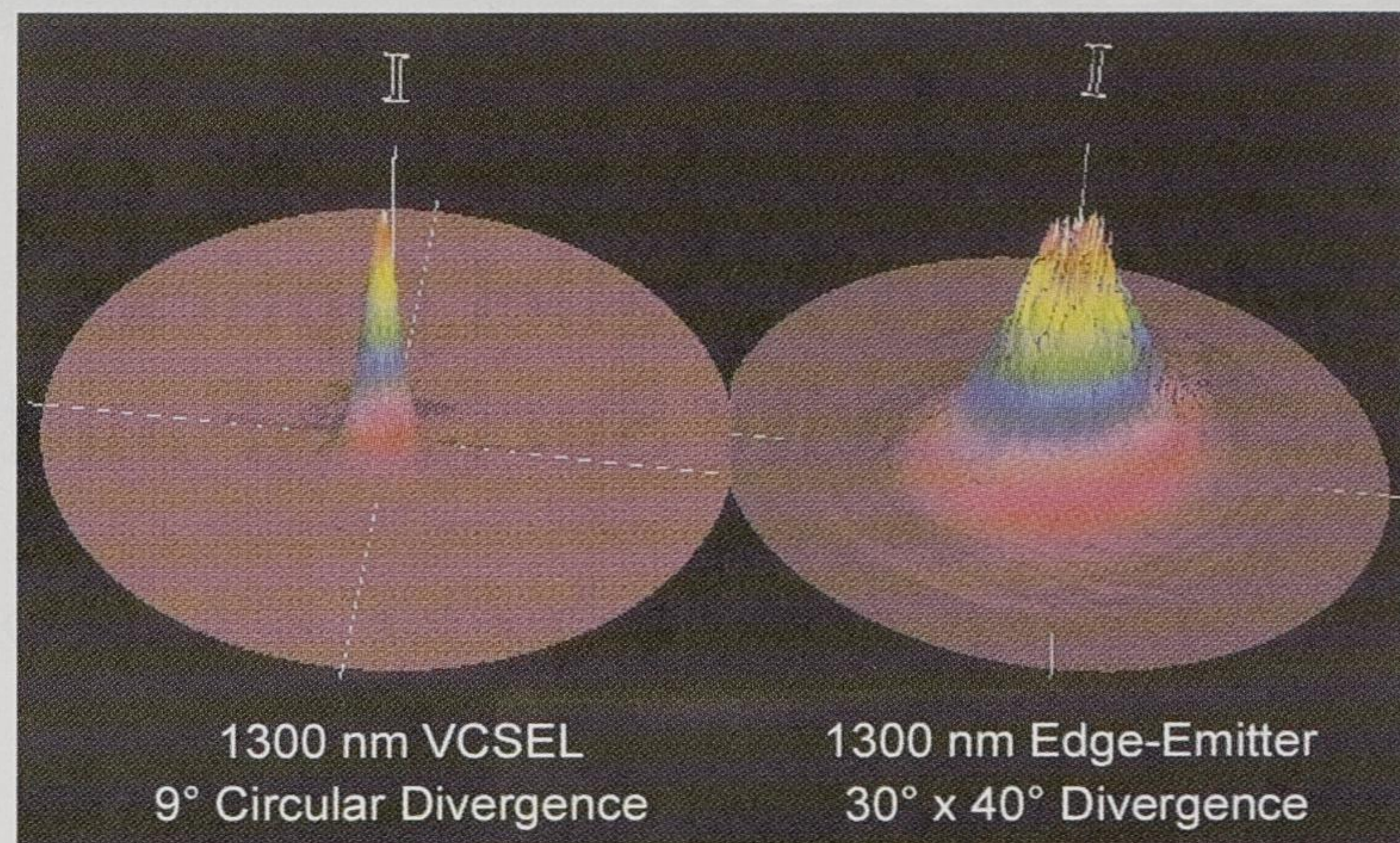


Figure 7. Compared to edge-emitting lasers, the circular output beam from Gore's 1310 nm VCSEL leads to improved fiber coupling.

tions. Oxide-confined VCSELs have already enabled higher data rate products and parallel optical interconnects, while longer wavelength devices hold the promise of longer transmission distances over single-mode fiber. Finally, there is a great deal of potential to utilize VCSELs for WDM-related applications.



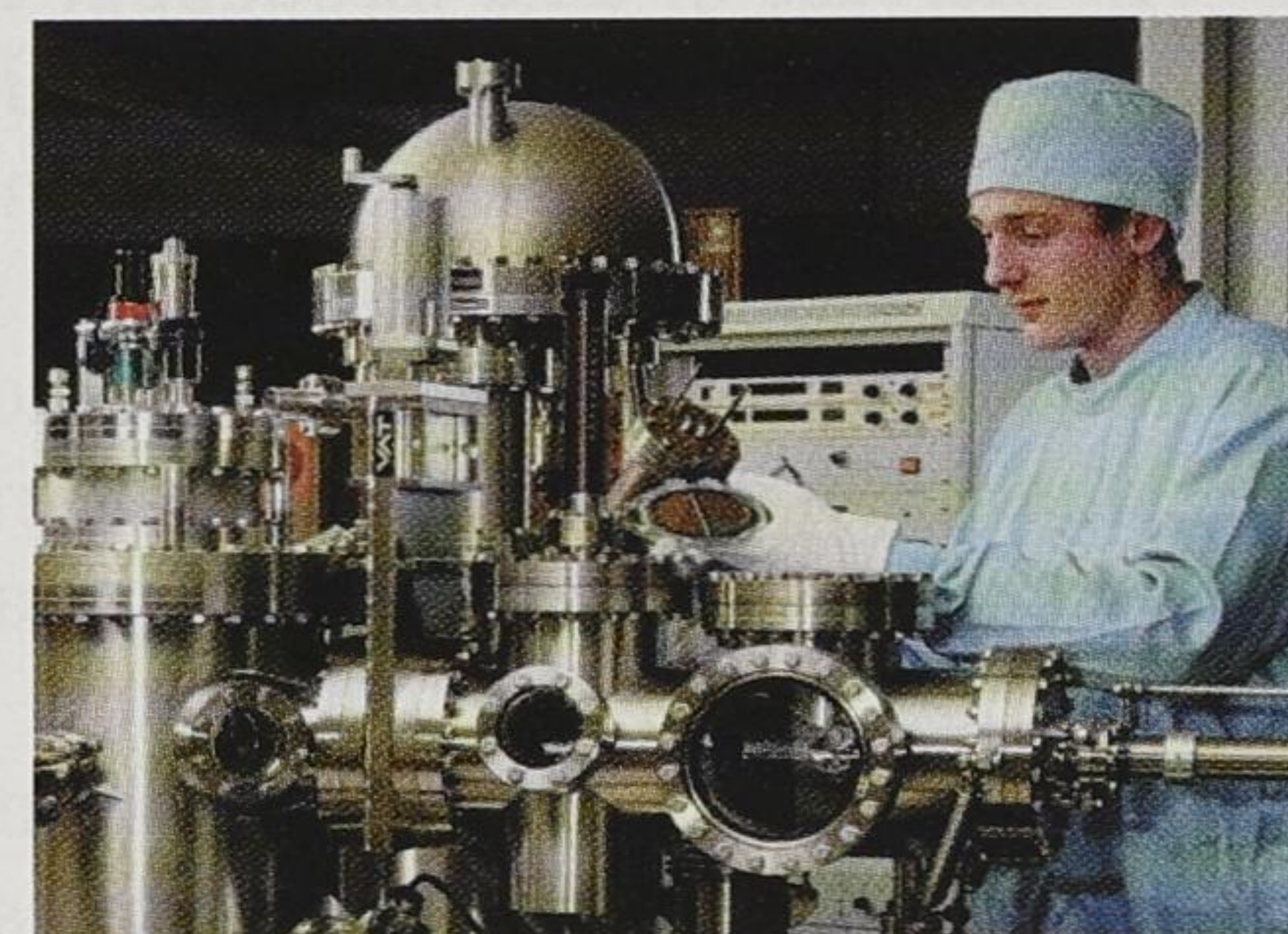
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High-Speed Parallel Optical Interconnects Based on Vertical-Cavity Surface-Emitting Lasers

FELIX MEDERER*, RAINER MICHALZIK and KARL JOACHIM EBELING

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These days, every article on optical communications takes a good start by bowing to the enormous information desires of mankind. In a joyous mood, the beneficiaries of this trend then analyze that the majority of the uncountable Terabits per second flowing through the fiber strands of the global telecommunication networks are generated in individual computer systems which are often interconnected through local networks. More specifically, an estimate of 80% of this traffic is said to originate in the Ethernet format. Indeed, the current high-speed version called Gigabit Ethernet (GbE) is the main commercial success story of the vertical-cavity surface-emitting laser (VCSEL).

Attractive features of VCSELs include on-wafer testing similar to that of electronic chips, simplified mounting technology related to the pig-tailing of light emitting diodes, high-speed modulation capability at low driving currents, temperature insensitive output characteristics, and natural parallel arrangement in one- or two-dimensional arrays. Inexpensive graded-index multimode fiber (MMF) based transceivers operating in the 850 nm wavelength region are employed for a variety of tasks like in-building backbone links or interconnection of telecom gear in central offices.

An increase of data throughput compared to single channel modules of, for example, up to 30 Gbit/s is nowadays achieved with 12-channel parallel optical links [1] connected through MMF ribbon cables at the expense of somewhat reduced link lengths. These already well established technologies are utilized at a rather high, namely the rack-to-rack, interconnect level and little by little feel their way to the board-to-board realms.

Fortunately for the component suppliers, the acceptance threshold concerning the application of optoelectronics in the box, i.e. inside computer systems, seems to be gradually decreasing, which has its root cause in the continuous progress of very-large-scale integrated (VLSI) silicon technology in terms of integration density and clock rate. Coming along with the penetration into lower interconnect levels like board-to-board, MCM-to-MCM, or even chip-to-chip, the competition with traditional and often inexpensive electrical wiring solutions is getting more intense. System engineers do not consider implementing optical

interconnections because they finally found out that photons are sexier particles than electrons, but simply because electrical wiring technology is having a hard time to meet the more and more stringent performance requirements.

Thus, optical technology is given a chance if it can provide a notable combined advantage concerning features like data throughput, cost, interconnect density, power dissipation, immunity against electromagnetic interference, and reliability. As pointed out clearly by the SIA [2], the electrical interconnection bottleneck is awaiting us down the road, so that optoelectronics is among the candidates that are given serious consideration. Amidst various approaches, many people nowadays agree that cheap VCSEL technology is the real key enabler. In this paper we will give a brief overview over recent high-speed VCSEL interconnect activities at Ulm University, ranging from conventional MMF links down to the intraboard and chip-to-chip levels.

Basic Layout of High-Speed VCSELs

Figure 1 shows the schematic cross-section of an oxide-confined top-emitting AlGaAs/GaAs-based VCSEL for ultra-high speed 850 nm wavelength optical interconnects. The layer structure is grown by molecular beam epitaxy on GaAs sub-

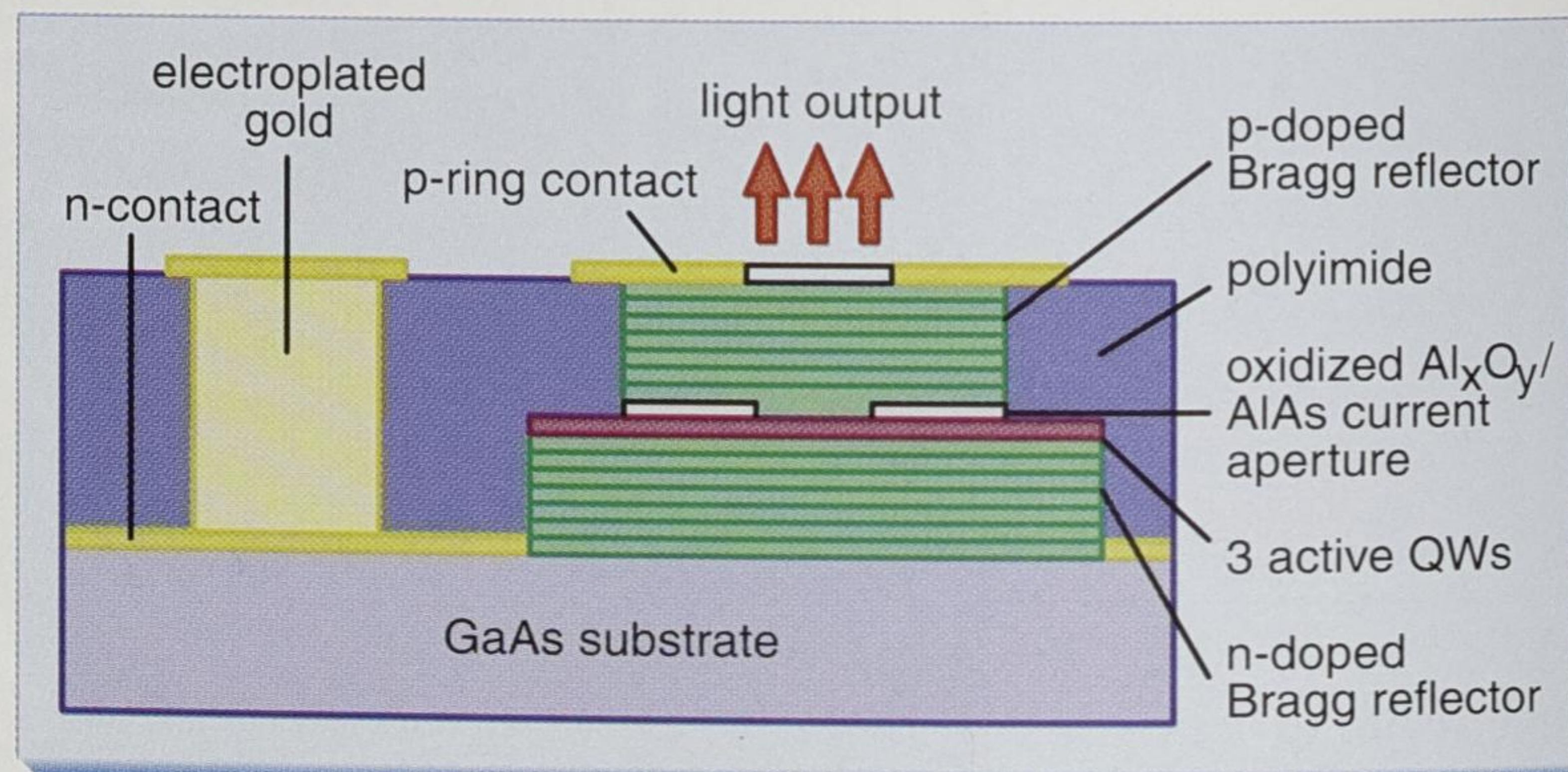


Figure 1. Schematic layout of a low-parasitic, top-emitting VCSEL.

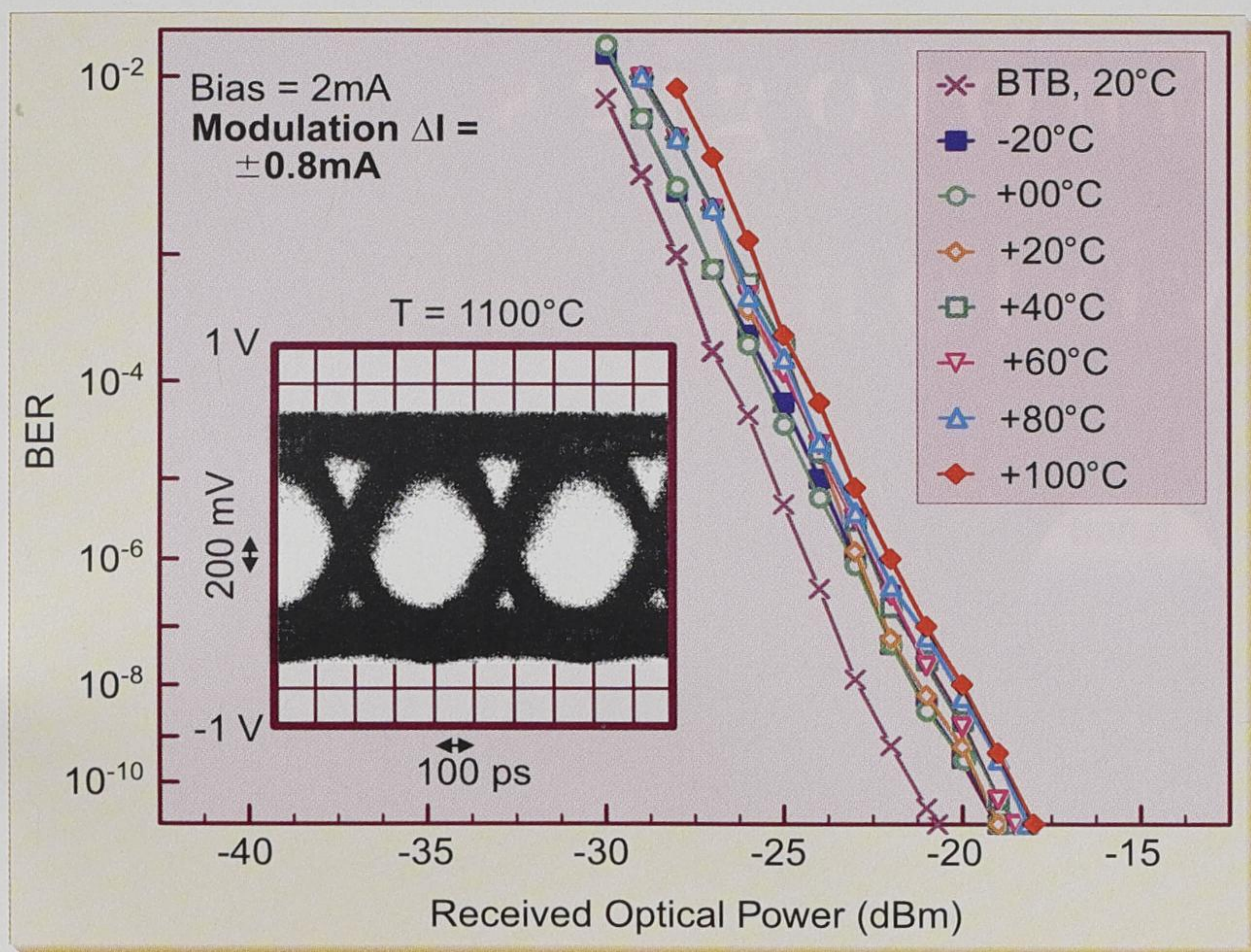


Figure 2. Temperature dependent bit error rate (BER) characteristics at 2.5 Gbit/s for 250 m MMF transmission and eye diagram at 100°C for a BER of 10^{-11} in the inset [5].

strate. The active region is composed of three 8 nm thick GaAs quantum wells (QWs) embedded in carrier confinement layers and bottom and top Bragg reflectors. VCSEL modulation bandwidth is often limited by electrical parasitics. In order to reduce the low-pass filter effect of series resistance and parasitic capacitances on the modulation bandwidth, devices with small mesa diameters are desirable. For the present example, upper mesas of 20 μm diameter are formed by chemically assisted ion beam etching. After selective wet oxidation of the 30 nm thick AlAs layer current aperture, the mesas are passivated and a second etching step gives access to the n-doped GaAs substrate on which a large-area n-contact is evaporated. The surface is planarized with polyimide and a coplanar contact layout is put on top that allows wire bonding to a transmission line or alternatively flexible testing with a microwave probe tip. Measured electrical 3-dB bandwidths easily exceed 12 GHz for small-signal modulation [3]. For aperture diameters below about 4 μm , the VCSEL emits in a single fundamental mode closely resembling a gaussian field profile. Highest reported output powers are in the 5 mW range [4]. For larger diameters, lasing occurs in several transverse modes. Both types of VCSELs can be designed for 10 Gbit/s operation.

Temperature Insensitive Data Transmission with Multi-Gb/s Throughput

The temperature behavior of VCSELs can be influenced by adjusting the position of the cavity resonance (determined through the layer thicknesses during epitaxial growth) relative to the gain peak of the quantum wells. Temperature insensitivity of the threshold current is obtained through red-shifting of the cav-

ity, i.e., by placing the laser emission on the long-wavelength side of the gain spectrum. The physical reason behind this behavior is that with increasing temperature, the refractive index change of the semiconductor layers results in a cavity mode shift of about 0.07 nm/K, whereas the gain spectrum shifts at a higher rate of about 0.3 nm/K due to bandgap reduction. In a red-shifted VCSEL, emission wavelength and gain peak thus approach each other during ambient temperature rise, which can partially compensate for increased losses or even lead to a reduction of the threshold current.

Especially for low-cost transceiver modules, it is of paramount importance to ensure reliable operation over a wide temperature range without external laser cooling. To investigate the modulation behavior, we have thus performed data transmission experiments at 2.5 Gbit/s data rate over a -20°C to $+100^{\circ}\text{C}$ temperature range while maintaining constant bias and modulation voltages [5]. Non-optimized conditions were chosen by selecting a non red-shifted VCSEL showing a continuous increase of threshold current from 0.3 mA at -20°C to 0.79 mA at $+100^{\circ}\text{C}$. The single-mode device emits at around 830 nm wavelength with a side-mode suppression ratio exceeding 30 dB.

The results of the transmission experiments for back-to-back (BTB) testing and 250 meter MMF transmission are summarized in Figure 2, where different symbols denote the various temperatures. For all temperatures, BERs of better than 10^{-11} are achieved for 2.5 Gbit/s data transmission over 250 m MMF without any indication of a BER floor. The maximum power penalty compared to BTB equals 3 dB for transmission at 100°C . The inset of Figure 2 displays the eye pattern recorded at

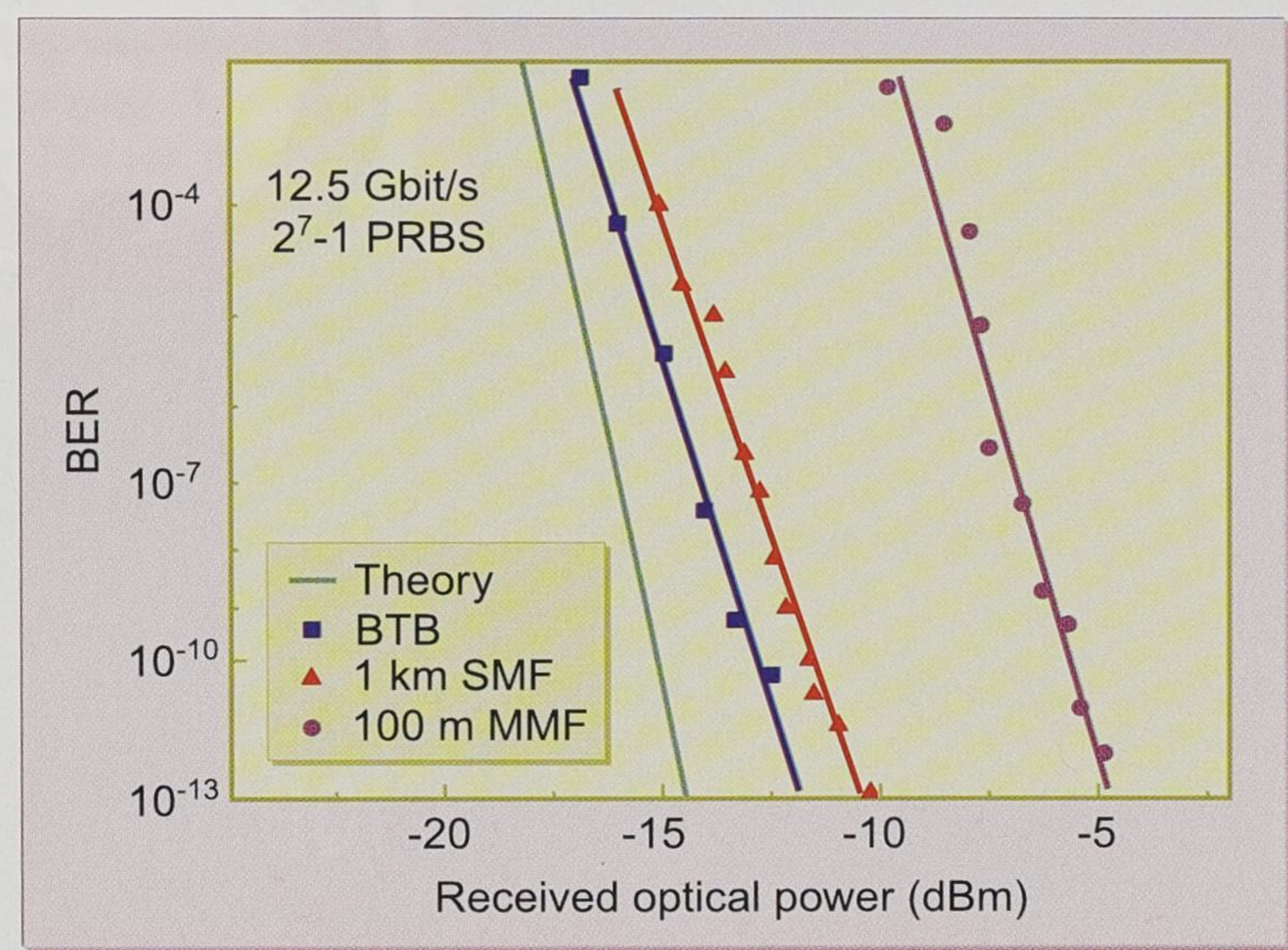
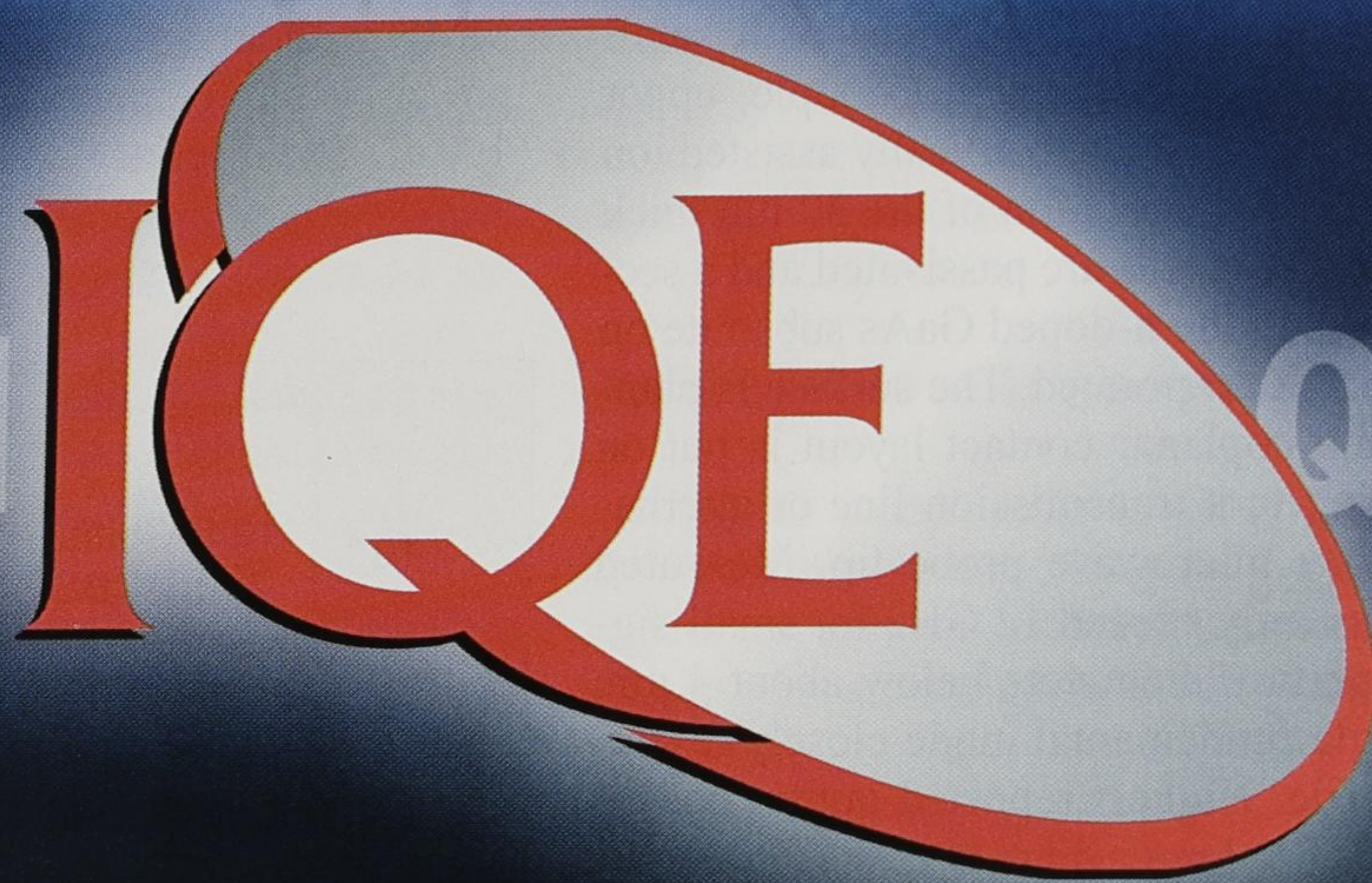


Figure 3. BER characteristics for 12.5 Gbit/s data fiber transmission over 100 m MMF, 1 km single-mode fiber (SMF), and BTB testing. The inset shows the eye diagram recorded for a BER of 10^{-11} after 100 m MMF transmission [3].



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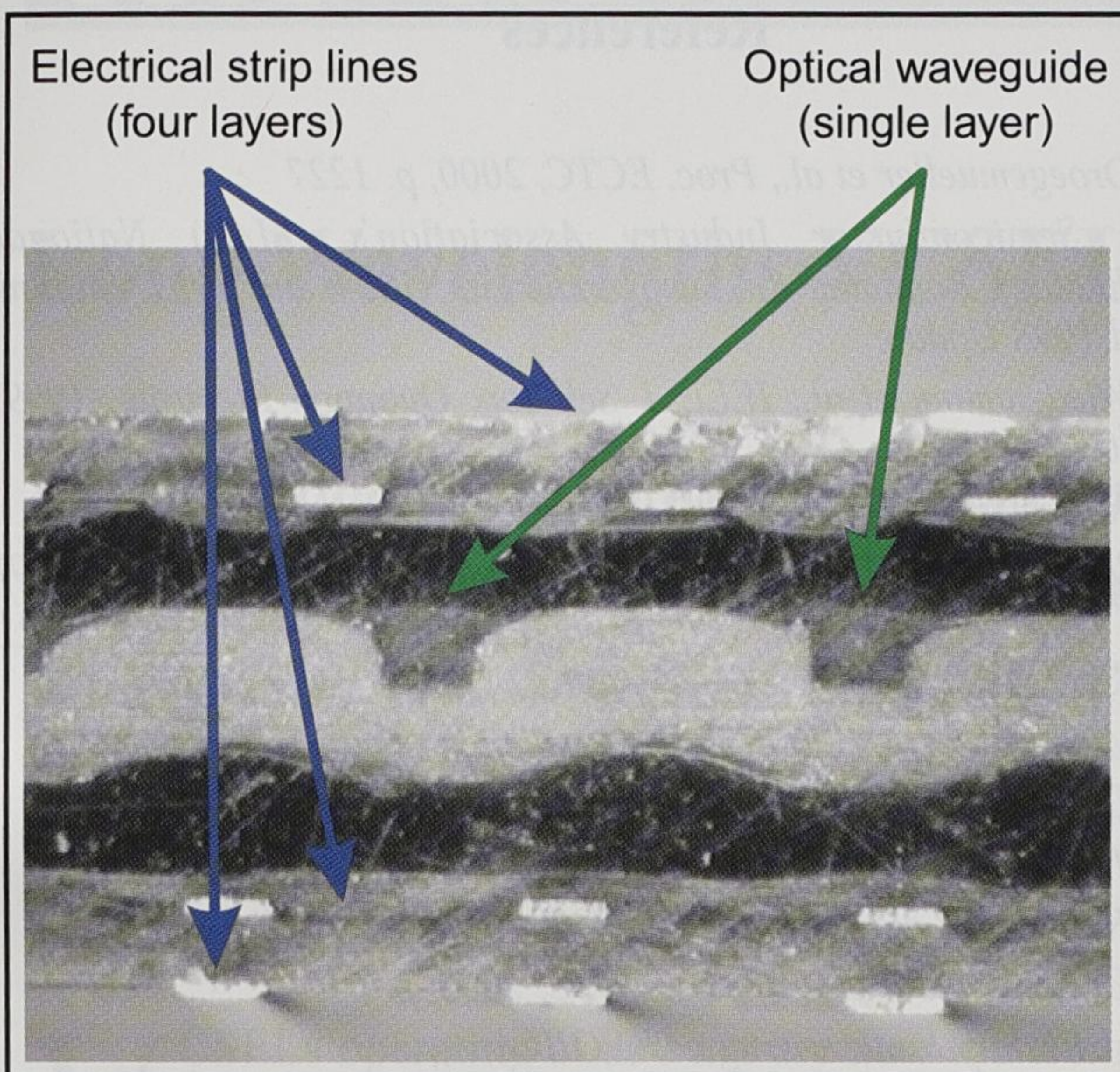


Figure 4. Side view of an optical intraboard waveguide array sandwiched in a four-layer electrical printed circuit board [10]. The waveguide pitch is 500 μm .

the maximum temperature. Under all given conditions, the eye is sufficiently wide open and symmetric.

Since the work toward a 10-GbE standard has started in March 1999, much research effort is focused on providing prototype components capable of operation up to 12.5 Gbit/s data rate [6]. Figure 3 summarizes the results of a transmission experiment performed at 12.5 Gbit/s with a 850 nm single-mode VCSEL [3]. The unacceptably large power penalty for the MMF link is caused by strong intermodal dispersion in the low-bandwidth fiber. Recently, 50 μm core diameter MMFs optimized for the 850 nm spectral region have appeared on the market that have enabled 10 Gbit/s operation over a distance up to 2.8 km with less than 4 dB power penalty at a BER of 10^{-13} [7, 8].

Future Systems Employing Parallel Optical Interconnects

As outlined in the introduction, VCSELs are ideally suited transmitters for realizing optical interconnects within computer systems. On the highest level, optical backplanes can provide an attractive means to connect different printed

circuit boards (PCBs) [9]. However, even within a board, the distribution of high-speed electrical signals is getting more and more challenging. For intraboard communications, work is in progress to integrate a layer of polymer waveguides into a conventional multilayer PCB, thus obtaining a hybrid electrical-optical board shown in Figure 4. In [10] we report on first experiments showing 3 Gbit/s data transmission over prototype board samples. In the target scenario, optoelectronic components are placed and soldered onto the hybrid PCB together with conventional

electrical and electronic components. Waveguide coupling is done through integrated 45° mirrors. Envisaged attenuation coefficients of about 0.1 dB/cm will result in affordable power budgets even for 19-inch long boards.

To explore the future applicability of direct optical interconnection on a CMOS chip-to-chip level, we are serving as partners in a joint European research project named Optically Interconnected Integrated Circuits (OIIC) [11, 12] by fabricating two-dimensional VCSEL arrays containing 4×8 elements arranged in a 250 μm pitch [13]. Except for a full p-contact and an anti-reflection coating on the bottom of the substrate, the same design as in Figure 1 is applied in these 980 nm wavelength bottom-emitting devices based on In-GaAs QWs. Flip-chip soldering is used to hybridly integrate the optoelectronic chip epitaxial side down with silicon CMOS.

Figure 5 shows the output characteristics of all 32 devices in an optimized array. The average threshold current and voltage are 0.6 mA and 1.7 V, respectively. An optical output power of 1 mW is delivered for only 2 mA current. Peak conversion efficiency from electrical to optical power exceeds 35%.



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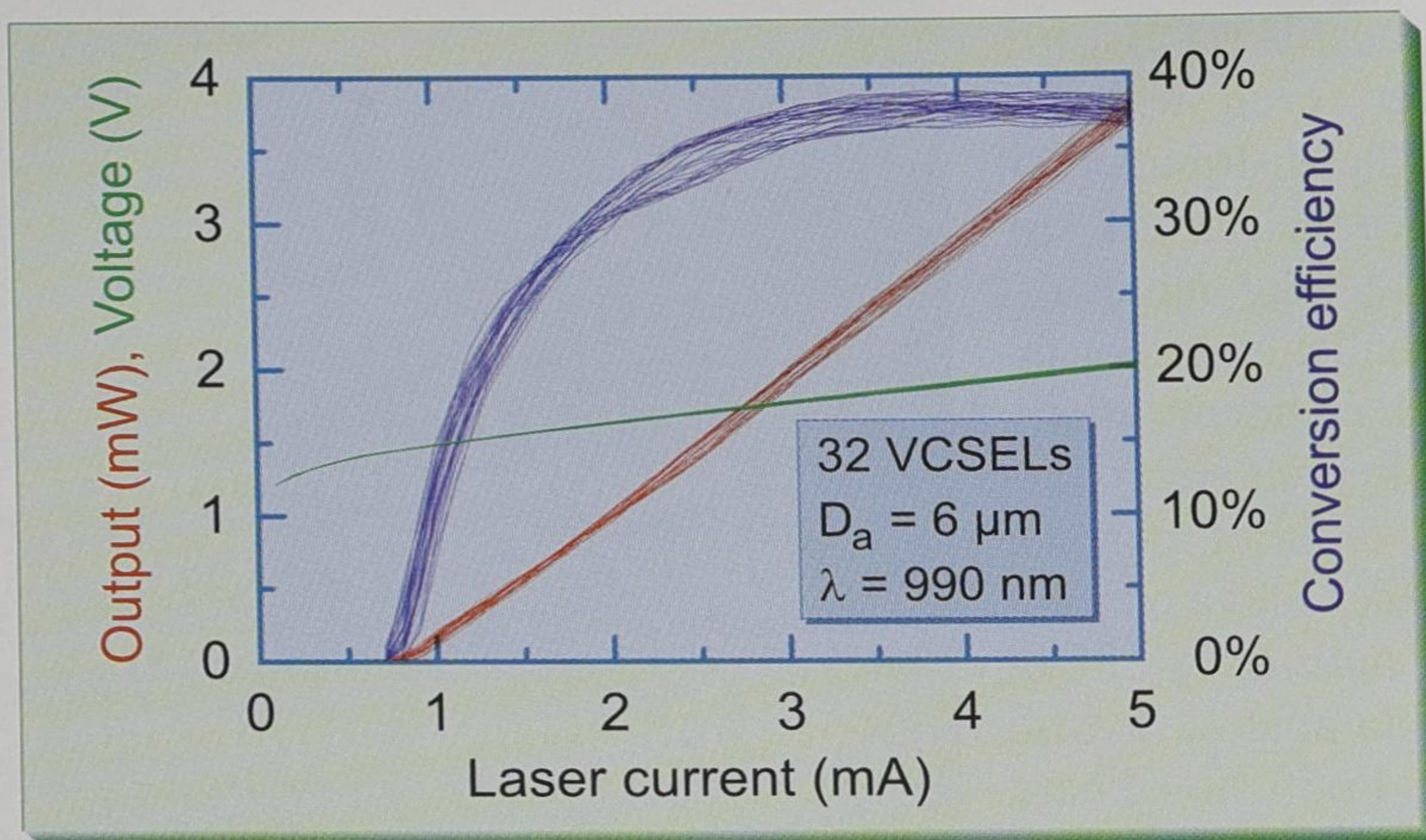


Figure 5. Operation characteristics of a 4×8 oxide-confined InGaAs VCSEL array with $6 \mu\text{m}$ diameter active elements.

With an individual active diameter of $6 \mu\text{m}$, the VCSELs emit in several transverse modes at about 990 nm wavelength.

Different demonstrator systems are realized within the OIIC project. As an example, Figure 6 shows the photograph of an optoelectronic field programmable array chip [14] on a carrier tile, onto which each two VCSEL and InP-based pin photodetector arrays have been hybridized. Neighboring chips on a PCB are interconnected through $120 \mu\text{m}$ core diameter step-index plastic optical fiber bundles [15] that are passively aligned to the CMOS chip. System tests will be conducted within the course of this year and valuable insight is expected on the interplay of the different active and passive optoelectronic components as well as the compatibility with the silicon environment. For sure, many new directions for further research will be identified.

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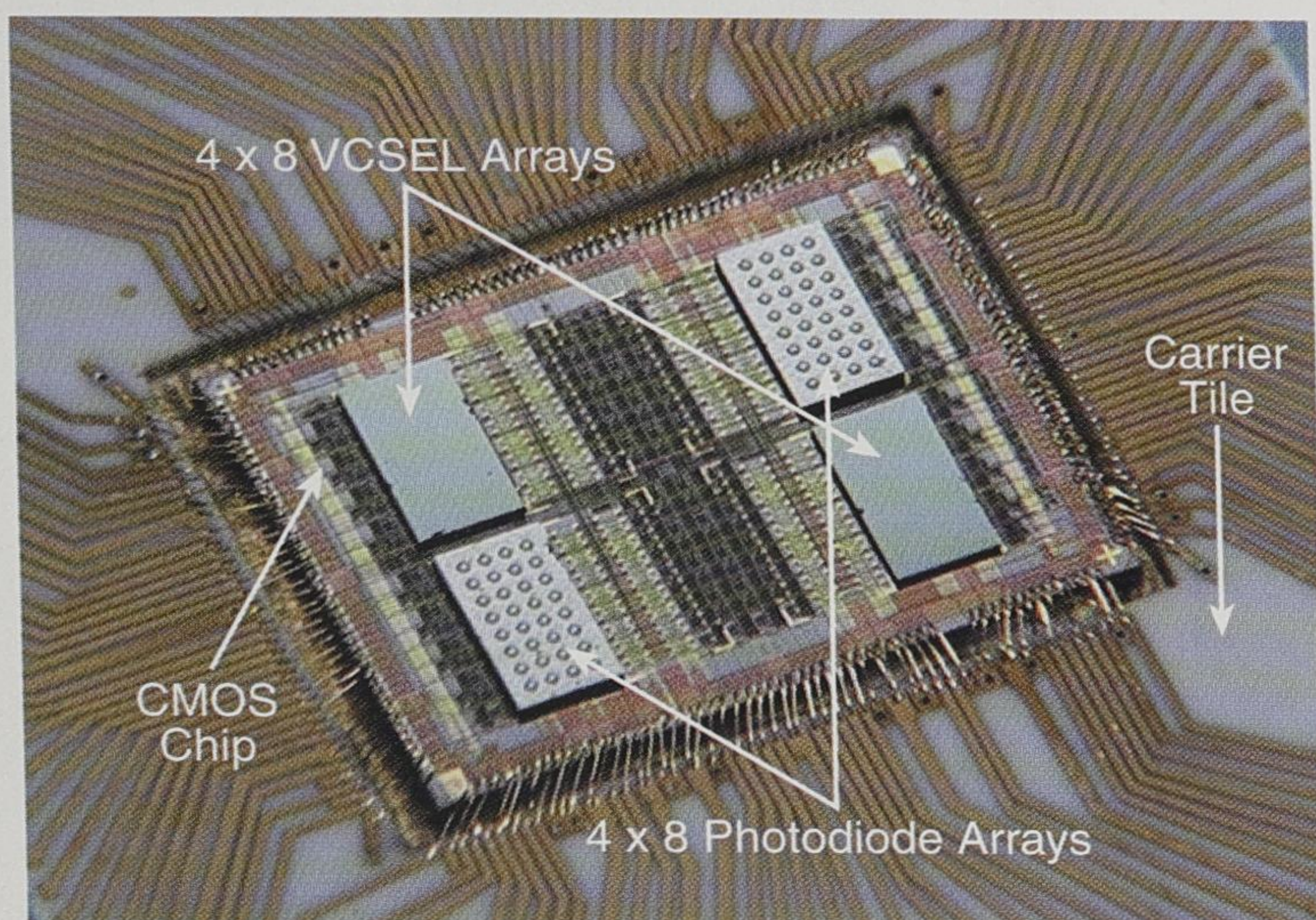


Figure 6. VCSEL and photodetector arrays flip-chip mounted onto a CMOS chip as part of an interconnect system demonstrator within the European OIIC project.

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Long Wavelengths VCSELs Move Closer to Reality

VCSELs operating at wavelengths compatible with single-mode fiber could significantly reduce the cost of installing fiber-optic links. Two recent announcements have improved the prospects of low cost, high reliability commercial VCSELs operating at 1.3- and 1.55- μm .

TIM WHITAKER

VCSELs operating at 850 nm are now the technology of choice for gigabit speed data communications networks over relatively short distances of multi-mode fiber. Surface emitters offer advantages such as wafer-scale processing and testing, and circular output beams for improved fiber coupling. These and other features result in lower cost fabrication and packaging compared to edge-emitters: VCSELs have also demonstrated excellent long-term reliability. It has long been thought that the development of single-mode VCSELs operating at 1.3 μm or 1.55 μm will extend

these advantages into longer reach applications using single-mode fiber.

However, achieving monolithic vertical emitter structures at these wavelengths has proved extremely difficult. A suitable active region emitting at the target wavelength must be lattice-matched to DBR mirrors exhibiting high reflectivity and low thermal and electrical resistance. Until now, finding the right combination of materials and successfully growing the epitaxial layers has proved extremely difficult, and the leading 1.3- and 1.55- μm solutions have used wafer fusion.

Bandwidth9 Demos Single-Epitaxy Top-Emitting 1.6 μm VCSEL

Bandwidth9, a small company based in Fremont, CA, has developed a conventional VCSEL structure, fabricated using a one-step epitaxial growth, capable of emitting in the 1.55- μm transmission window. At the recent CLEO conference, specific devices operating at 1.6 μm were discussed. These devices emitted a single transverse mode with a fixed polarization, and demonstrated CW output power of 0.45 mW at 25°C, as well as error-free transmission at 2.5 Gb/s through 50 km of single-mode fiber.

The top-emitting device structure (see Figure 1) is grown on InP, and is composed of a lattice-matched n-InGaAlAs/InAlAs bottom DBR mirror and an InGaAs QW active region. A key feature of the device is the inclusion of a metamorphic p-GaAs/AlGaAs top DBR mirror, which provides high reflectivity and allows direct current injection. Details of the strain-relief buffer layer that enabled growth of the metamorphic top DBR were not revealed.

To date, the most successful VCSELs at 1.55 μm have used wafer fusion. A monolithic 1.55 μm VCSEL has been demonstrated by Alcatel; this device has a complex structure incorporating a p-n tunnel junction and is bottom-emitting, which is not as compatible with high volume manufacturing [see CS 5(3), p. 26].

The device structure developed by Bandwidth9 is grown in a single epitaxy run, and is processed using conventional

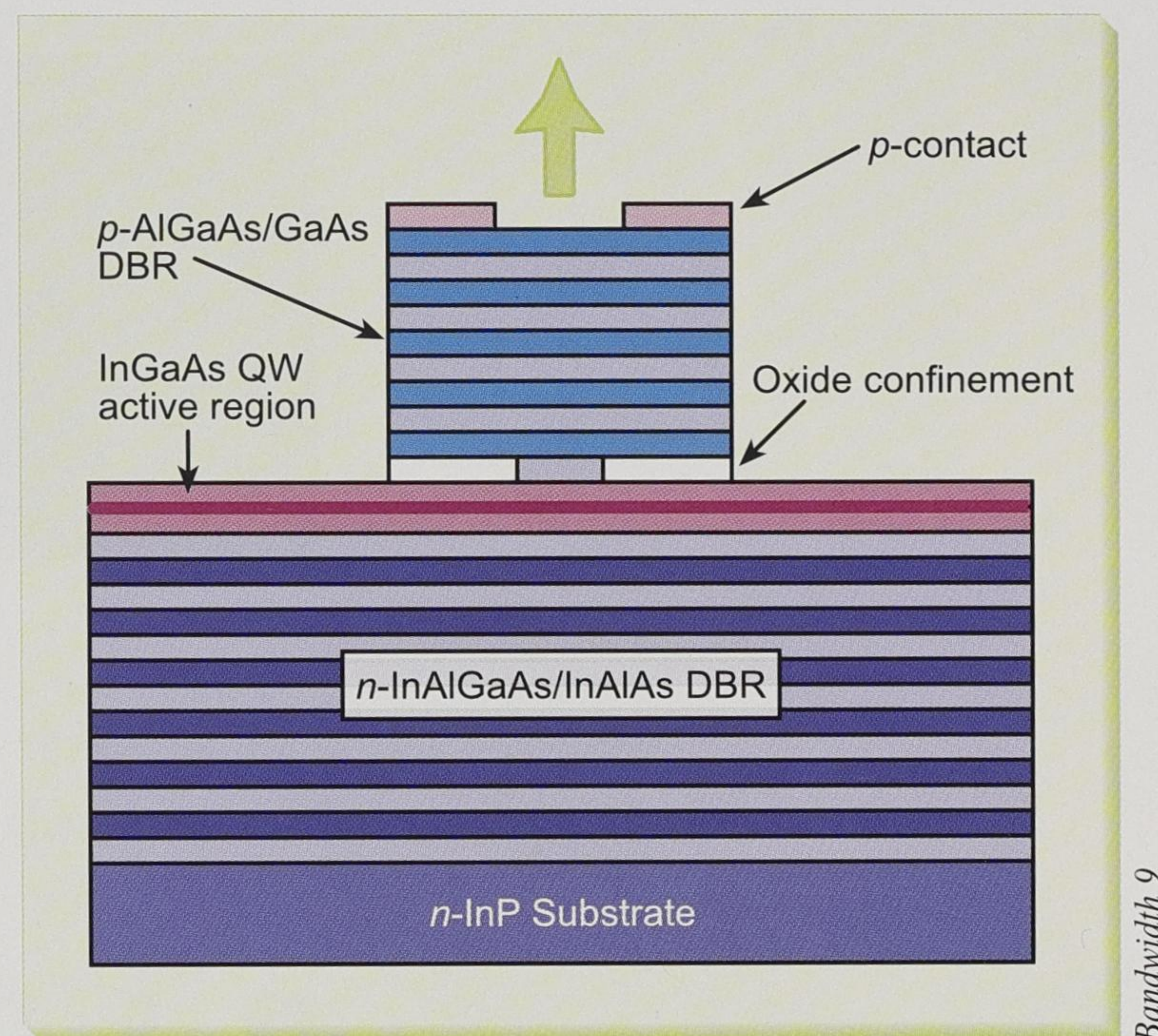


Figure 1. Schematic showing the structure of Bandwidth9's single-epitaxy, top-emitting 1.6 μm VCSEL.

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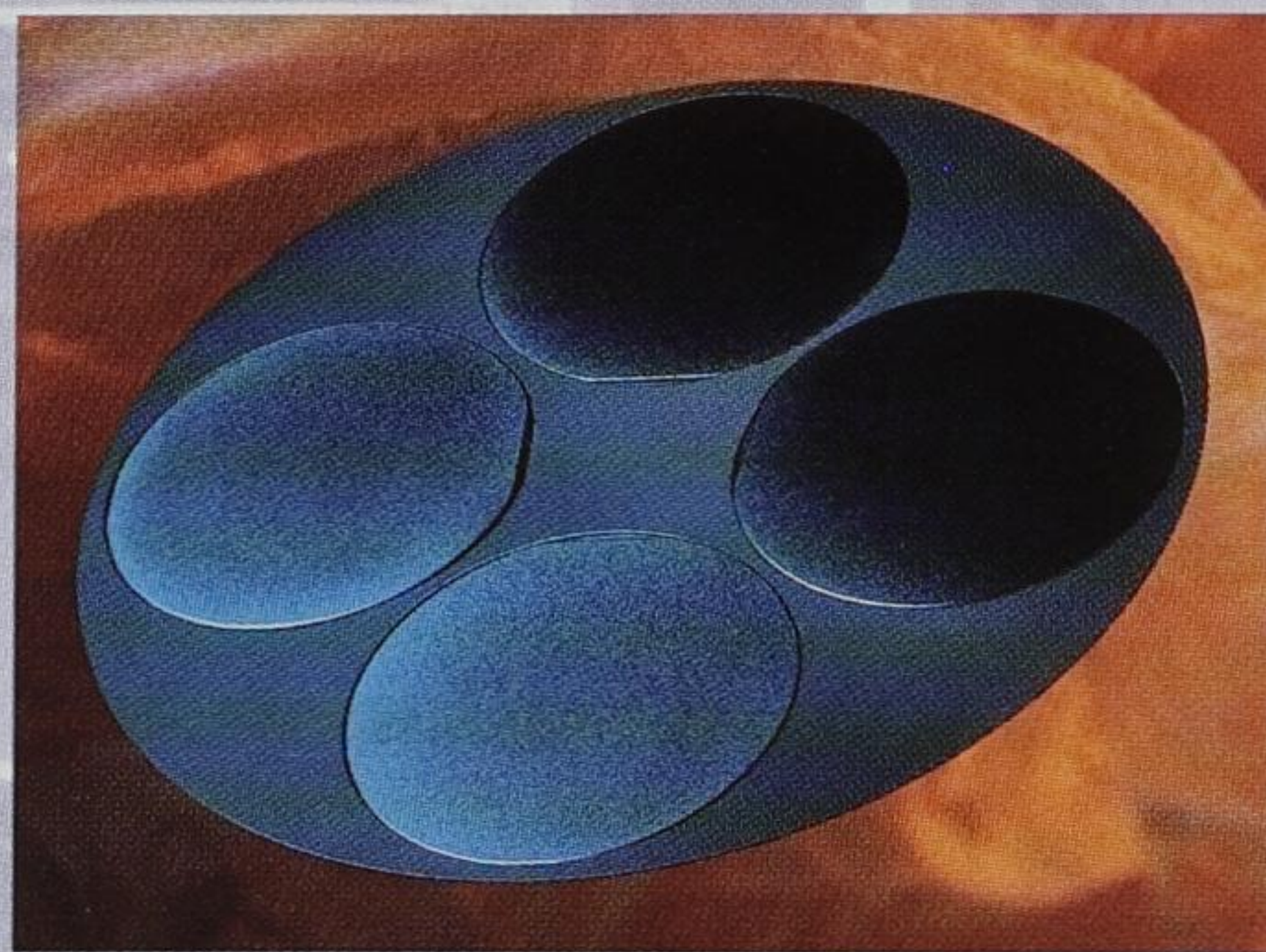
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techniques employed for VCSELs in a wafer-scale compatible fashion. Selective oxidation was used to provide electrical and optical confinement, and the finished devices were tested p-side up under temperature control. CW operation was demonstrated up to 55°C. The maximum output power of 0.45 mW was achieved for a device with a 9- μ m aperture and a threshold voltage of 1.7 V. The minimum threshold current was 0.87 mA for a 3- μ m device.

According to Connie Chang-Hasnain, founder and CTO of Bandwidth9, the company intends to exploit the commercial

advantages of this technology. "This is the first top-emitting, long wavelength VCSEL produced using a mass-manufacturable process," she says. "We are making great progress towards delivering prototypes." Bandwidth9 has fully integrated manufacturing capabilities, from epitaxy to packaging. The 2-year old company has about 50 employees and is backed by venture capital funding. "In addition to the long wavelength VCSELs, we are working on tunable lasers and other photonic components and sub-systems for the DWDM market," adds Chang-Hasnain.

Cielo and Sandia Demonstrate First Electrically-Pumped 1.3 μ m VCSEL

Cielo Communications and Sandia National Laboratories recently reached a milestone for VCSEL technology when they jointly demonstrated the industry's first electrically pumped long-wavelength VCSEL operating in the 1.3 μ m transmission window. The monolithic device exhibited single-mode and continuous wave operation at 1294 nm with an output power of 60 mW. Although improvements will need to be made to the output power, the result could have a strong impact on the cost of delivering high-bandwidth optical interconnects.

Significantly, the VCSEL's layer structure is grown by a single MBE growth process, and does not involve the use of wafer fusion techniques. The new VCSEL is a monolithic GaAs-based structure with GaAs/AlGaAs DBR mirrors and an active region containing 2 quantum wells made from the quaternary InGaAsN alloy, which is lattice-matched to GaAs at low N compositions.

"In the past it has proved extremely difficult to grow a 1.3 μ m active region in a GaAs-based system and match it with mirrors that reflect at that wavelength," explains Bob Mayer, Cielo's

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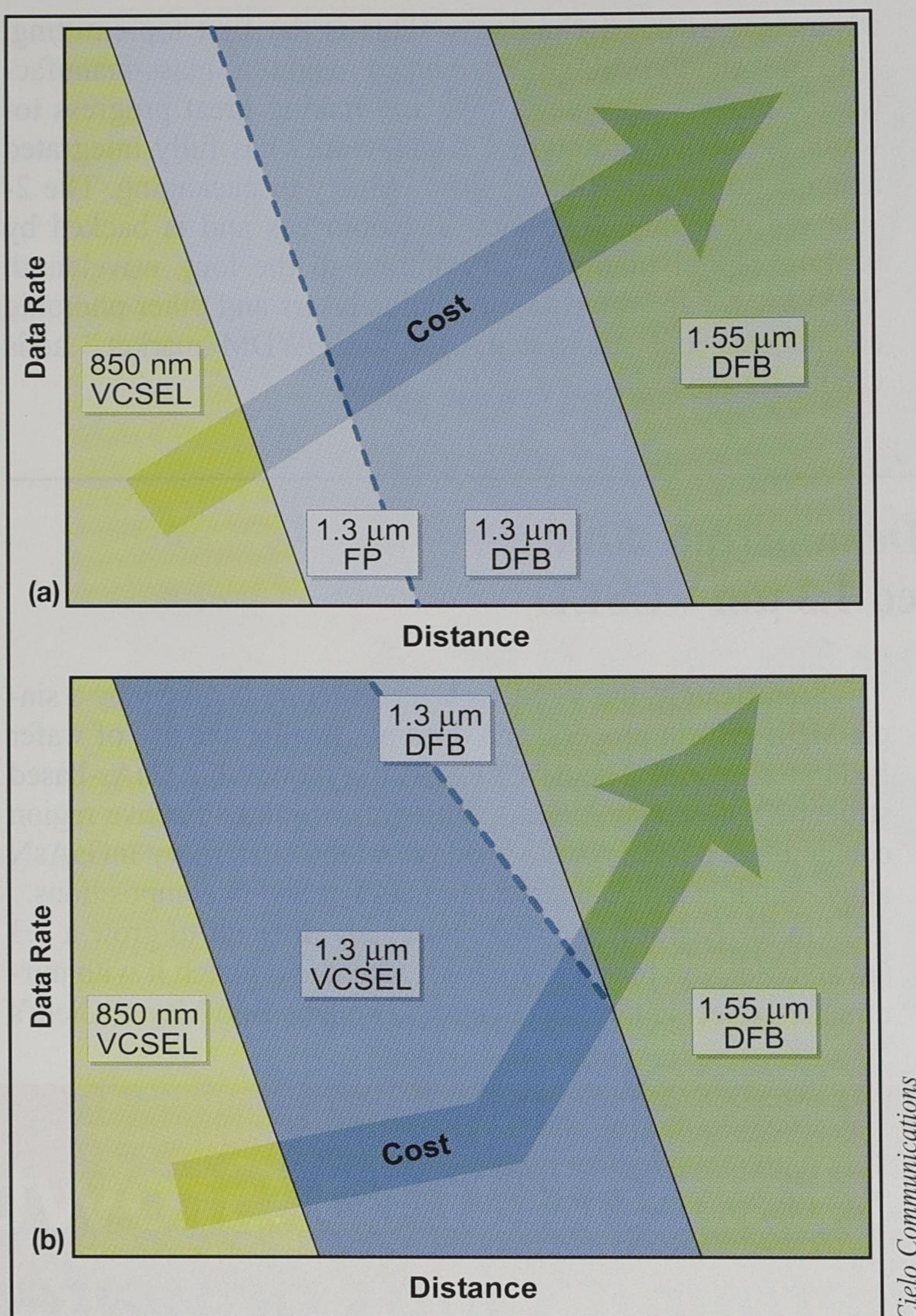


Figure 2. (a) 850 nm VCSELs are the technology of choice for short range, lower speed applications. Moving towards higher data rates and/or longer distances requires different technologies which become progressively more expensive. (b) 1300 nm VCSEL technology will introduce a kink in the cost curve, and this technology will replace many Fabry-Perot and DFB lasers.

VP of Marketing. "Due to these materials issues, other groups have resorted to wafer fusion, which is a very complex process." For example, the 1.3 μm VCSEL developed by Gore consists of an InP-based active region wafer-bonded to two GaAs-based mirrors: the device is optically pumped by a second 980 nm VCSEL.

Other research groups, notably Hitachi, have grown VCSELs with InGaAsN active regions that emit at around 1.2 μm, but have seen a fall-off in efficiency at longer wavelengths. "Our success is a combination of the material used and the way in which we grew the active region, coupled with tuning the structure to maximize performance," explains Bob Mayer.

Sandia and Cielo have been working together under a Cooperative Research And Development Agreement (CRADA) since March 1999, and will continue to work jointly to bring this long-wavelength technology to market within the next 12 months.

VCSELs v. Edge-Emitters

Cielo and Sandia believe that the 1300 nm VCSEL will significantly decrease the cost of delivering high-bandwidth optical interconnects in the telecommunication and Internet infrastructure. "VCSEL technology has historically provided the most cost-effective optical link solution for high bandwidth applications," says Mike Cowley, President and CEO of Cielo Communications. This has been proven in recent years by the rapid adoption of VCSELs over edge-emitting lasers in the data communications market at 850 nm.

"Key performance, cost and reliability advantages typically associated with VCSEL technology will now be afforded to SONET-based telecommunications applications," adds David Kisker, VP of VCSEL technology development at Cielo. "These include an improved beam profile allowing simplified alignment and greater control of the optical beam, and the ability to test in wafer form."

Current telecom and datacom systems operating at 1.3 μm use edge-emitting Fabry-Perot (FP) or distributed feedback (DFB) lasers that must be completely fabricated prior to operational testing, while VCSELs are fabricated and tested in wafer form. VCSELs also dissipate less power; Cielo states that the 1.3 μm VCSEL draws about 33% of the current of a typical FP laser, and 25% of the current of a typical DFB laser. A further advantage of VCSELs is that they can be grown in arrays to maximize density and bandwidth performance.

The fact that this device can be fabricated using the same techniques employed in the high volume manufacture of 850 nm VCSELs appears to offer a major advantage over processes that use wafer fusion and optical pumping. "In addition, the direct electrical modulation of this device provides instant improvements in speed and reliability over optically pumped approaches," says Peter Esherick, manager of compound semiconductor materials and processes for Sandia. Also, Cielo's single VCSEL structure allows for easier dissipation of heat when compared to the optically-pumped multi-VCSEL structures.

Although reliability testing is still underway, the use of a standard VCSEL structure in this case suggests that the devices should meet the relevant reliability specifications. "Hitachi has shown that 1.3 μm edge-emitters with an InGaAsN active layer are reliable," says Bob Mayer. "Our GaAs/AlGaAs mirrors have proven reliability in high volume manufacturing, and these facts give us reasonable confidence that the reliability of the devices will be good."

VCSELs have inherent cost advantages compared to edge-emitters in terms of both manufacturing and packaging, although 1300 nm FP and DFB lasers have an established volume market. However, as Bob Mayer points out, the competition for the 850 nm VCSEL in the datacom market was the CD laser, which was already running in very high volumes—even so, VCSELs won convincingly in that market.

Technology Choice

The 850 nm VCSEL has become the predominant source for short distance transmission at low data rates—VCSELs are widely used for gigabit speed applications (Gigabit Ethernet, Fiber Chan-

Cielo Communications

nel) at distances up to around 500 m. Recent advances in technology will provide access to increased data rate and distance for multi-mode 850 nm applications [see CS 6(4), p. 66 for details of Cielo's demonstration of 12.5 Gb/s at 300 m].

As shown in Figure 2a, moving towards higher data rates and/or longer distances requires different technologies which become progressively more expensive. For example, more sophisticated 1300 nm DFB lasers are used in applications that require a more refined spectral content than can be provided by less expensive 1300 nm Fabry-Perot lasers. For very long distances, both DFB performance and the low fiber attenuation provided by transmission at 1.55 μm are required.

The Cielo/Sandia team believes that the new 1300 nm VCSEL will have a significant impact on the choice of technology for intermediate speed/distance applications, as shown in Figure 2b. "The 1300 nm VCSEL is a replacement for all 1.3 μm Fabry-Perot lasers and the majority of

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Intermediate Reach (12–15 km)	1.3 μm FP	1.3 μm FP	1.3 μm DFB	1.3 μm DFB
Long Reach 1 (<40 km)	1.3 μm FP	1.3 μm DFB	1.3 μm DFB	1.3 μm DFB
Long Reach 2 (<80 km)	1.55 μm DFB	1.55 μm DFB	1.55 μm DFB	1.55 μm DFB

Figure 3. Current laser sources for SONET applications. The Cielo/Sandia team believes that the 1300 nm VCSEL will become the technology of choice in the areas highlighted in deep blue; the VCSEL will replace all 1.3 μm Fabry-Perot lasers and the majority of DFB devices at this wavelength. DFB lasers at 1.3- and 1.55- μm will continue to be required for high data rates and longer transmission distances.

DFB devices," states Bob Mayer. "Some applications at high speed and or distance will continue to require DFBs until an improved VCSEL structure is developed."

Figure 3 summarizes the dominant technology today in use today for SONET

applications. Cielo believes that the new 1.3 μm VCSEL technology shows promise to replace the incumbent technologies in many of these markets, although longer reach applications at high data rates will still require DFB lasers.

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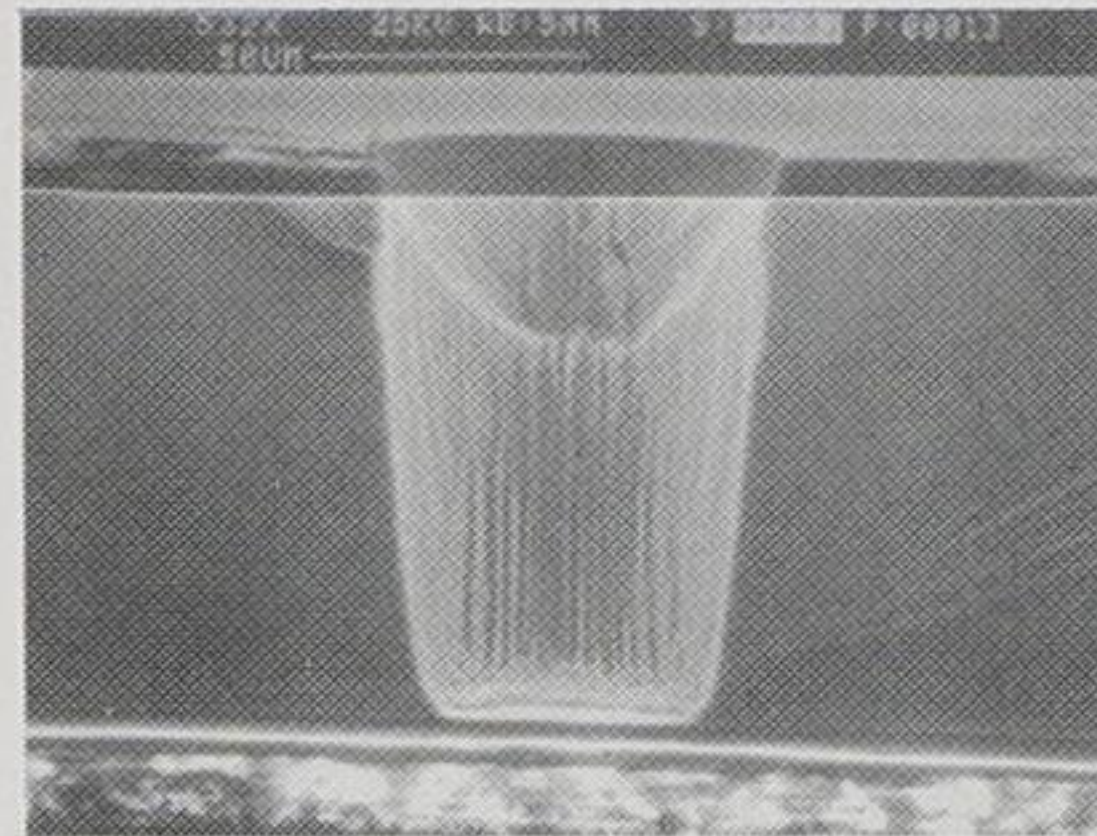
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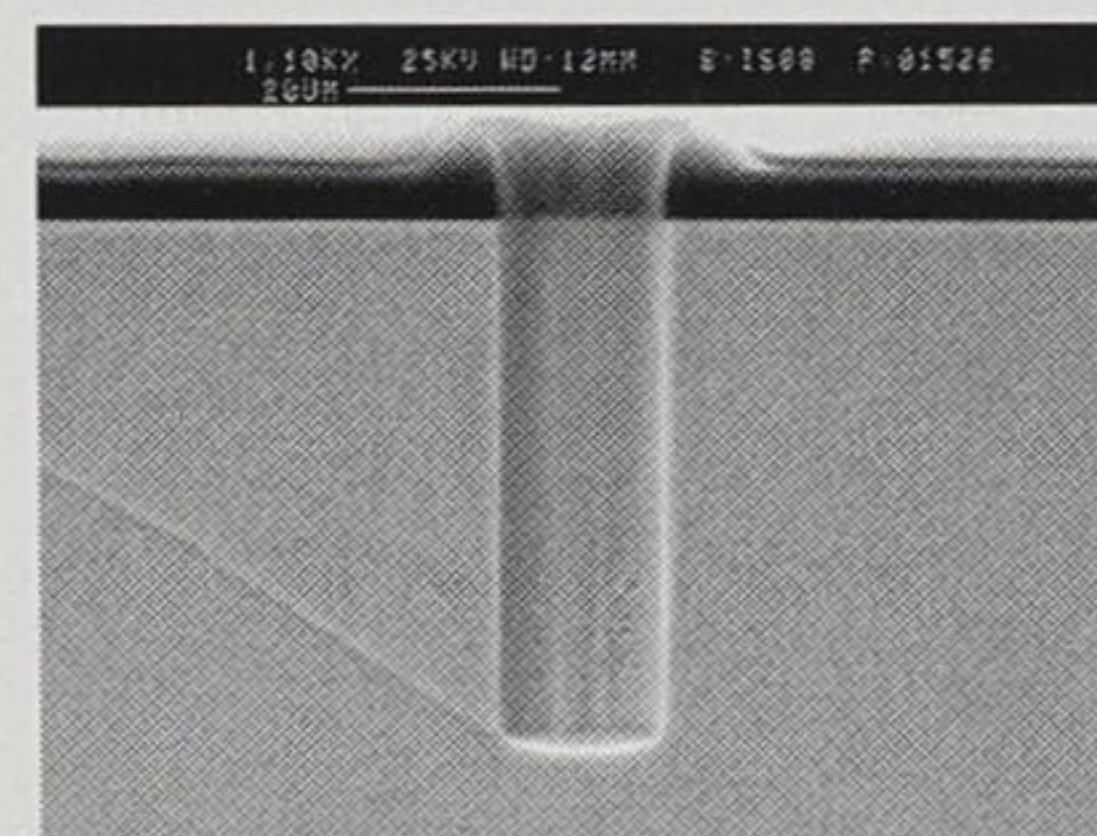
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InGaAsN: Extending GaAs-based Lasers to Fiber Optic Wavelengths

H. RIECHERT*, A. YU. EGOROV†, B. BORCHERT and S. ILLEK

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Today's standard wavelength for data communication lasers in optical fiber systems are 850 nm and 1.3 μm . For 850 nm, there is a clear trend towards vertical cavity surface emitting lasers (VCSELs) because they allow easy and cost-effective coupling of the optical signal into the fiber. The short wavelength standard has evolved primarily to match the capabilities of the well-established InGaAs/AlGaAs material system.

On the other hand, several technical aspects would greatly favor 1.3 μm as the operating wavelengths of such systems. First, of course, the dispersion minimum of the standard single-mode fiber at this wavelength would allow maximum transmission rates and much longer transmission distances due to the much lower absorption losses as compared to 850 nm. Besides this, a 1.3 μm laser requires roughly only two thirds the drive voltage of a comparable 850 nm laser. Finally, the issue of eye-safety may well be decisive, since at 1.3 μm the human eye tolerates about ten times the optical power that would be dangerous at 850 nm.

No wonder, therefore, that a 1.3 μm VCSEL ranks high on the list of today's desired devices, but chances to realize such a laser from InGaAsP/InP, the well-established material system for 1.3 μm emission, are slim. The difference in refractive indices in this system is only about 0.3 (GaAs/AlAs gives 0.6) such that an excessive number of DBR periods would be needed for high reflectivity mirrors. More importantly, the thermal conductivity of quaternary materials is next to zero compared to binaries. Serious thermal problems would result for such devices, all the more so, since the high-temperature characteristics of InGaAsP lasers leave a lot to be desired.

The GaAs system obviously holds all the advantages, with only one decisive point missing—an easy possibility to reach light emission at 1.3 μm , since the long-wavelength limit for InGaAs quantum wells is at about 1200 nm. Therefore, several new routes are being investigated to reach this goal. One is the use of InAs/GaAs quantum dots, which indeed allow emission at

1.3 μm . Secondly, despite uncertainties about the band lineups, GaAsSb/GaAs has been studied and this wavelength has also been reached. Both approaches, however, require layers that are under a very high level of compressive strain.

This problem may be avoided by a third approach, which utilizes the alloying of GaAs with low concentrations of GaN. In the early 90's, this had been predicted to lead to a strong "bowing" of the bandgap, i.e. a reduction of the bandgap well below the one of the nearest binary material. Since the lattice constant of cubic GaN is 20% smaller than that of GaAs, in principle all of the compressive strain in InGaAs can be compensated (even though this would not be ideal from the point of view of laser design).

This approach was pioneered by Kondow et al. [1] of Hitachi, who made the first and for a long time the only practicable lasers in this novel material and even demonstrated a VCSEL operating at 1.2 μm . While they could demonstrate the superiority of the high temperature characteristics of InGaAsN lasers, which had been expected as a consequence of the large conduction band

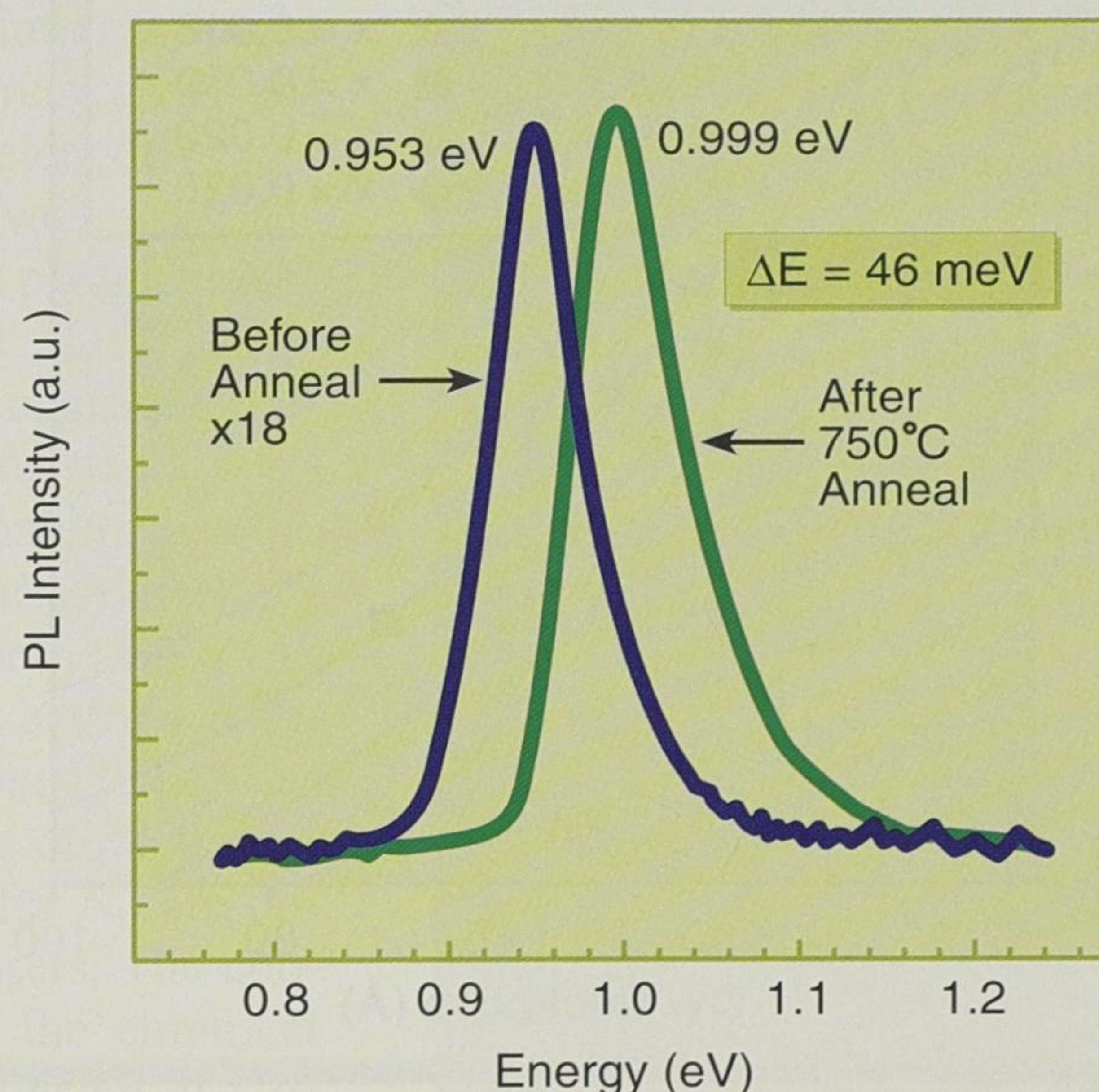


Figure 1. PL spectra of an $\text{In}_{0.35}\text{Ga}_{0.65}\text{As}_{0.982}\text{N}_{0.018}$ MQW structure before (left) and after (right) annealing at 750°C.

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offset, they also showed that the luminescence efficiency of InGaAsN strongly degrades if more than a few percent of N are incorporated. Therefore, their InGaAsN lasers were still inferior to InGaAsP with respect to threshold current and efficiency. At this point the question arose if the problems of material quality of InGaAsN were fundamental or if they could be overcome by careful optimization of material growth and device design.

Material Growth

Like the Hitachi group, we have grown all our structures by solid source MBE on GaAs substrates using an RF-coupled plasma source to generate reactive nitrogen from N_2 (as it is commonly done in the MBE of GaN). We find that growth can proceed much like that of InGaAs, under the usual As-stable conditions. A peculiarity of GaAsN growth is that it requires temperatures below 520°C to incorporate all reactive N. Under these conditions, N completely displaces As on the group V sublattice and therefore the N-content of the layer is only determined by the N-flux. Fortunately, when adding N to InGaAs this remains unchanged and we find no major mutual influence between the incorporation of N and In, quite unlike in the MOCVD growth of this material, where this problem complicates the growth process.

The experiments on growing InGaAsN heterostructures show that one of the more significant growth factors is the growth temperature [2]. The brightest and narrowest PL spectra are obtained for growth at temperatures about 70°C to 90°C lower than the optimum for InGaAs. As reported before [3], we find that InGaAsN heterostructures are very susceptible to post-growth heat treatment. This is illustrated in Figure 1, which

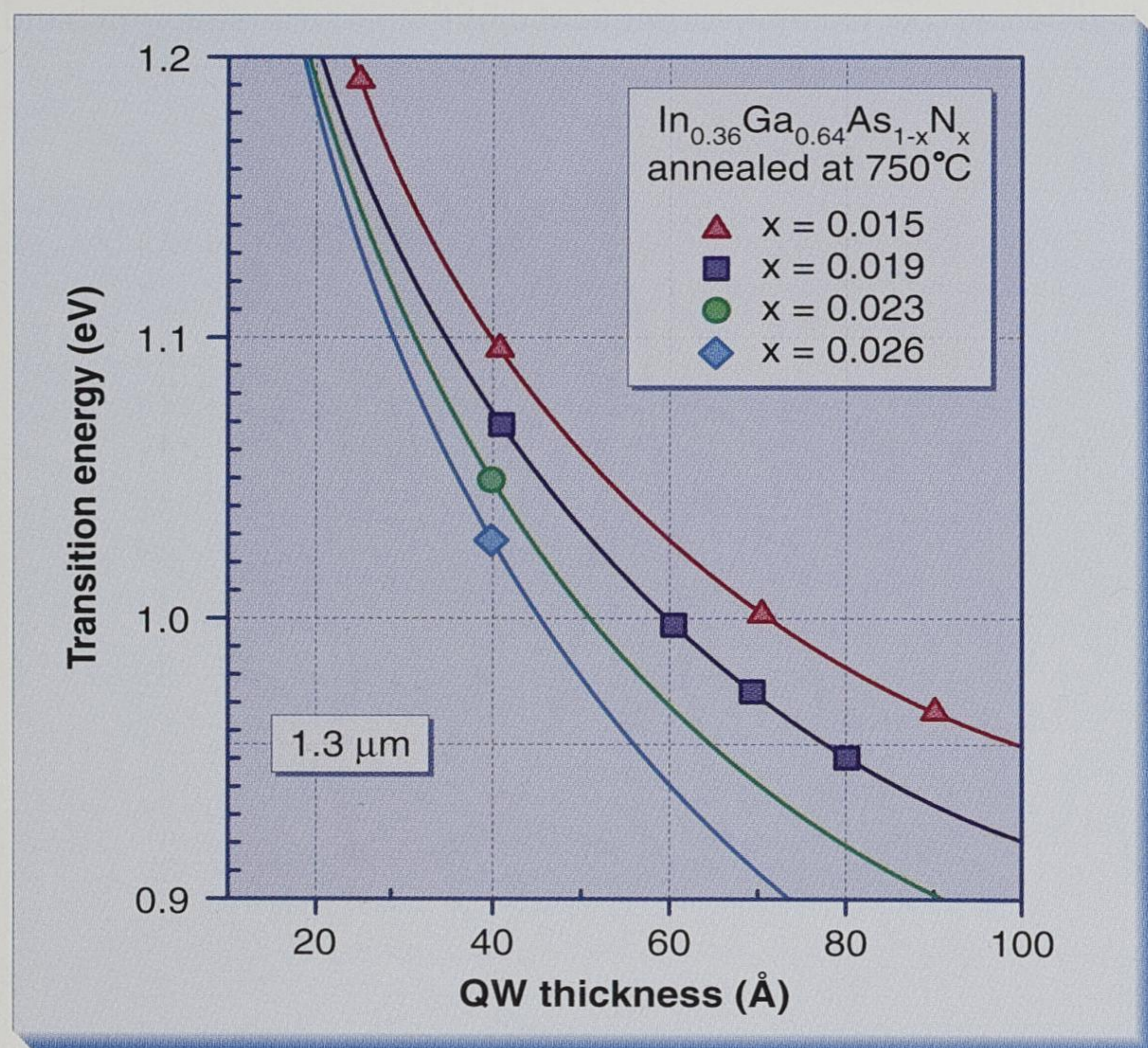
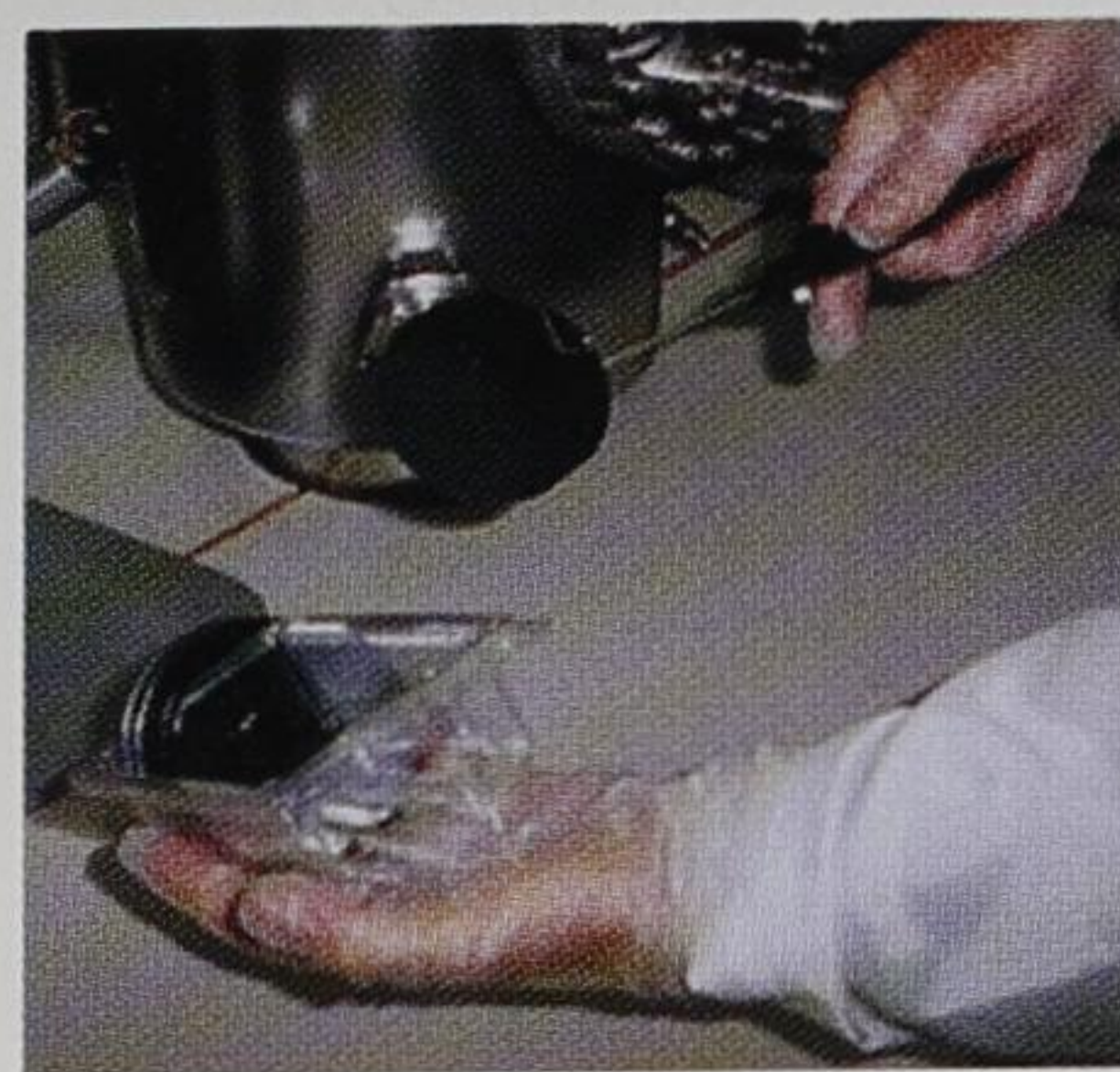


Figure 2. Ground state transition energies (300 K) for InGaAsN/GaAs QWs. Experimental data (symbols) determined by photoluminescence.

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shows the photoluminescence spectra of a strained InGaAsN MQW before and after annealing at 750°C .

The PL intensity typically increases by a factor of 20 and only by performing such annealing routines do we obtain a luminescence efficiency that is sufficient for high quality laser material. However, during this process, the PL peak shifts by up to 50 meV towards higher energies, i.e. the as-grown material must be designed for correspondingly longer wavelength emission. Interestingly, this strong shift only occurs for strained InGaAsN QWs, whereas GaAsN and InGaAsN lattice-matched to GaAs show a peak shift of less than 15 meV after the same annealing—as do strained N-free InGaAs QWs. We therefore assume that the shift in emission energy upon annealing results from nitrogen-induced out-diffusion of In from the quantum well region.

The ground state transition energies for thermally annealed InGaAsN QWs with varied thickness and N-contents are shown in Figure 2. As illustrated, 7 nm thick InGaAsN/GaAs QWs with In- and N-contents of about 35% and 1.7%, respectively, allow to achieve 300 K luminescence at $1.3\ \mu\text{m}$. It should be noted that the increase of either the N-content or the QW thickness beyond these values leads to a significant reduction of luminescence intensity, such that the realization of devices emitting at still longer wavelengths appears to be difficult. For this reason, we have generally minimized the N-content in the QWs of our laser structures by employing smaller bandgap barriers (i.e. GaAsN or InGaAsN).

An analysis of the PL and PLE of InGaAsN/GaAs QWs of different thicknesses [4] (with compositions as shown in Figure 2) has provided two important results. First, the confinement energy

for electrons in these structures is very high (about 400 meV) due to the fact that the conduction band discontinuity amounts to 80% of the band gap difference. Secondly, there is clear evidence for a strongly increased electron mass compared to InGaAs with the same In-content, as has been predicted in [5]. Both facts promise an excellent high temperature performance of lasers based on InGaAsN/GaAs QWs since they make it very unlikely that electrons are thermally excited out of the conduction band well. However, the reduced confinement in the valence band well may begin to pose a problem, in particular for GaAsN/GaAs QW structures.

Device Applications

The active regions of our laser structures were grown in the temperature range mentioned above and annealed during the growth of the upper cladding layer. The layer sequence was chosen to be similar to those in reference 1. In case of 3QW lasers, three $\text{In}_{0.35}\text{Ga}_{0.65}\text{As}_{0.983}\text{N}_{0.017}$ QWs of 6–7 nm thickness, separated by 20 nm barrier layers, are symmetrically inserted into a 300 nm thick, undoped GaAs cavity. Lowest laser thresholds were obtained by using quaternary InGaAsN barriers with the same N-content, which were lattice-matched to GaAs. The p- and n-type cladding layers consist of 1.5 μm thick $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$, doped with Be and Si to 4×10^{17} and $5 \times 10^{17} \text{ cm}^{-3}$, respectively. The 0.6 μm thick p-type GaAs contact layer is doped to $1\text{--}5 \times 10^{19} \text{ cm}^{-3}$ in the top 200 nm. Broad area lasers were fabricated by metallization and subsequent wet-chemical etching of the p-contact layer.

Broad Area Lasers

For the assessment of material quality, broad area lasers (fabricated by the shallow mesa stripe technology, width 100 μm) were characterized. The emission wavelength of all lasers referred to here is around 1.29 μm . The threshold current density of 3QW lasers is found to decrease from 1 kA/cm^2 to less than 0.7 kA/cm^2 for cavity lengths increasing from 400 μm to 1.2 mm. The lowest threshold for $L=800 \mu\text{m}$ is 650 A/cm^2 . At this length, the single quantum-well (SQW)

laser has a threshold current density of about 500 A/cm^2 , which decreases to 405, 335 and 270 A/cm^2 for cavity lengths of 1000, 2000 and 3200 μm , respectively. These values are much lower than previously reported in the literature and indicate that we have significantly improved the material quality of InGaAsN compared to earlier work.

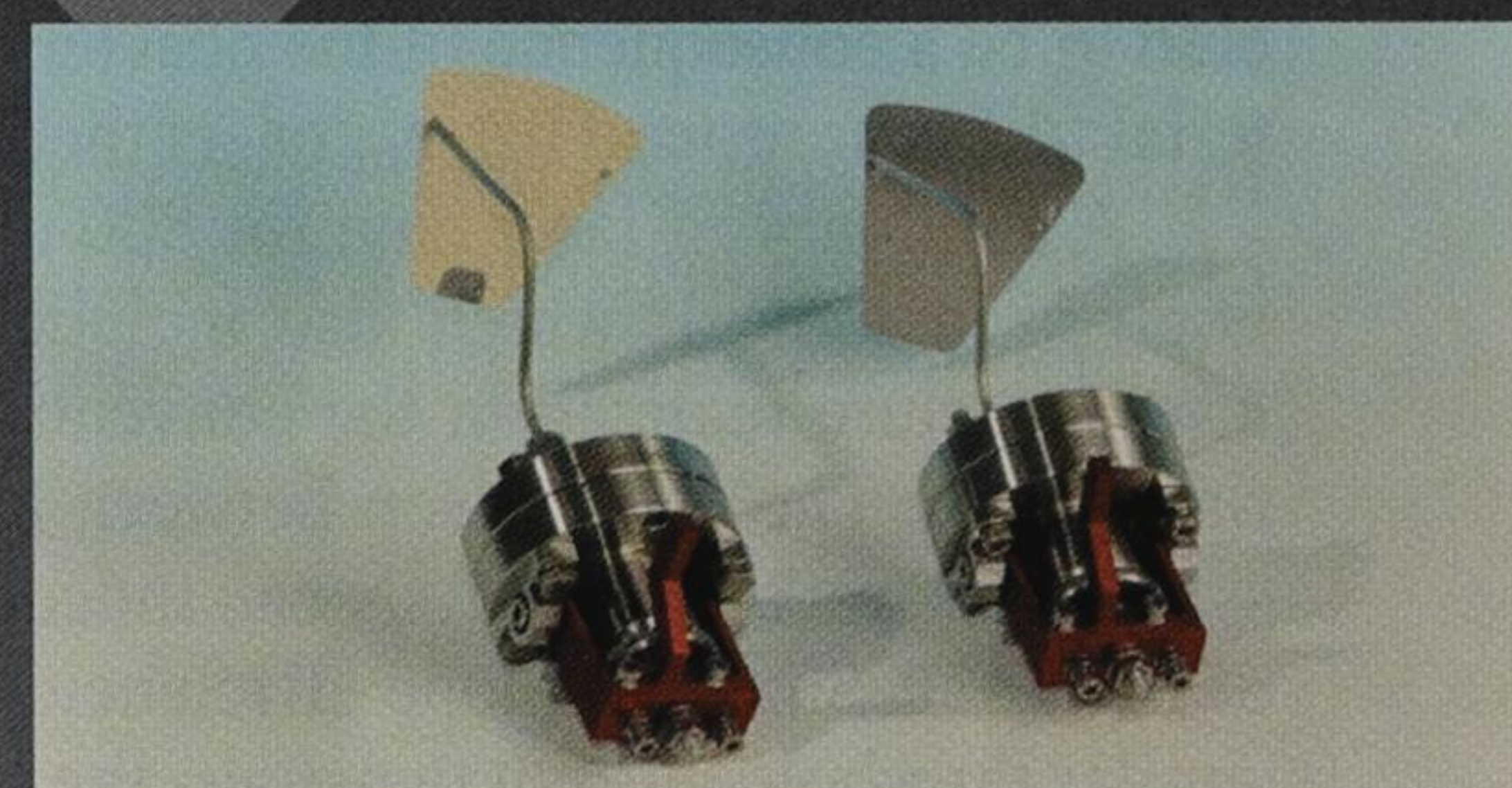
Using heatsinking at 10°C, cw operation could be demonstrated for these lasers with record output powers. In earlier work, we have obtained 2.4 W from a 3QW laser structure [6], which was processed into a $1300 \times 100 \mu\text{m}^2$ broad area laser. More recently, up to 8W could be achieved with a 2000 μm long SQW laser structure of the same width [7]. It should be mentioned that in the latter case, great care was taken to keep the active region at 10°C, which required significantly lower temperatures of the heatsink. In both cases, the values of optical output power are by far the highest ever reported so far for any wavelength in the GaInNAs material system.

The analysis of laser parameters yields transparency currents of 145 and 540 A/cm^2 , internal losses of 4 and 10 cm^{-1} and internal efficiencies of 93% and 81% for the SQW and the 3QW lasers, respectively. The transparency current densities are roughly three times as high as for 980 nm lasers with InGaAs QWs, a consequence of the higher electron mass and the non-radiative Auger recombination, which may be neglected at shorter wavelengths. The somewhat increased internal losses may be due to the larger free carrier absorption for the longer wavelength.

By using the above values we attempted to extract the gain parameters of the GaInNAs QWs in our 3QW lasers, using a model including Auger recombination [8]. In this procedure we have assumed in a first approximation that the radiative and non-radiative (Auger) recombination coefficients for the GaInNAs QWs are roughly the same as for 1.3 μm InGaAsP QWs (which remains to be verified in future work). Values of 2800 cm^{-1} for g_0 and $2.4 \times 10^{18} \text{ cm}^{-3}$ for N_{tr} are obtained for our InGaAsN lasers. The constants g_0 and N_{tr} refer to the empirical gain-carrier-density relationship $g = g_0 \ln(N/N_{tr})$, which is commonly used to describe the gain saturation in QWs. Both values are significantly higher than those

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Active Region	Structure	Growth method	J_{th} (kA/cm ²)	λ (nm)	Slope efficiency (W/A)	T_0 (K)
InGaAsN	1 QW (6.8 nm)	MBE	0.5	1285	0.2	60
InGaAsN	2 QWs (6.5 nm)	MBE	0.63	1295	0.25	70–80
InGaAsN	3 QWs (6.2 nm)	MBE	0.65	1290	0.23	75
InGaAsP (reference)	5 QWs (6 nm)	MOCVD	0.5	1300	0.22	60

Table 1. Summary of broad-area laser data for InGaAsN-based and InGaAsP-based QW lasers.

for 1.3 μm InGaAsP QWs, where the corresponding values for g_0 and N_{tr} are found to be 1545 cm^{-1} and $1.45 \times 10^{18} \text{ cm}^{-3}$, respectively. The higher values for g_0 and N_{tr} in GaInNAs are considered to be a consequence of the heavier electron mass in this material [4,5] (m_e around $0.1m_0$, m_0 is the free electron mass).

A summary of laser data for 800 μm long broad area lasers is given in Table 1, which also includes a broad area reference laser structure realized in the conventional InGaAsP/InP material system. The comparison between lasers in the two material systems shows that InGaAsN can indeed match the performance of InGaAsP. Since the slope efficiencies are roughly the same at similar threshold current densities, the optical output powers are also comparable. However, due to the higher material gain, the InGaAsN-based lasers require fewer quantum wells for a given optical power and they exhibit a higher characteristic temperature T_0 due to the much stronger electron confinement.

Ridge Waveguide Lasers

Narrow-stripe ridge waveguide lasers were processed using an Ar-ion dry-etching technique for the ridge formation. Stripe widths of 3.5 μm were realized and were passivated with RF-sputtered SiN_x . After conventional p- and n-contact formation,

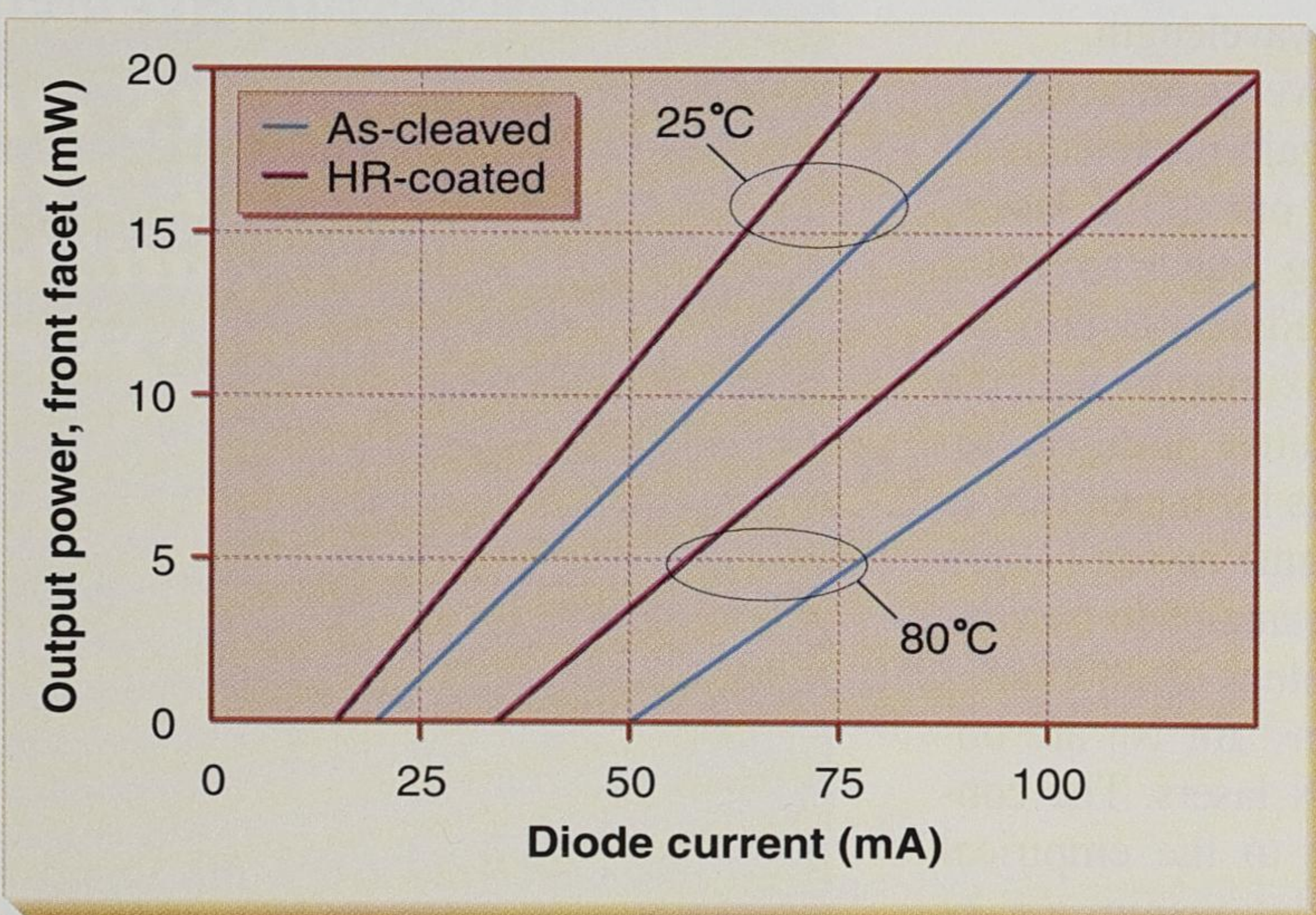


Figure 3. Pulsed light-current curve for as-cleaved and high-reflection (HR) coated 1.3 μm InGaAsN ridge waveguide lasers with a cavity length of 350 μm .

the chips were mounted epi-side up on copper heatsinks for detailed characterization.

The pulsed light-current characteristics of 350- μm -long ridge waveguide laser diodes at room temperature are shown in Figure 3. As above, the emission wavelength is around 1290 nm at room temperature, the active region consists of 2 InGaAsN QWs. Lasers with as-cleaved facets show threshold currents as low as 21 mA with efficiencies of 0.25 W/A per

facet. By high-reflection coating of one side (with reflectivity of about 75%), the threshold is lowered to 16 mA and the efficiency increases to 0.35 W/A. Again, these data represent a significant improvement compared to previously published results [9].

It is particularly interesting to examine the laser characteristics at elevated temperatures since InGaAsN QWs are expected to yield clear improvements in this respect. As can be seen in Figure 3, the threshold current increases to about 50 mA at 80°C but even at 100°C lasing operation could be maintained. The best high temperature performance we have achieved so far is shown in Figure 4, which shows light vs. current for a 2QW ridge waveguide structure, which in this case is 4 μm wide and 700 μm long. This laser could be operated under cw conditions up to at least 100°C and exhibits a characteristic temperature T_0 of 110 K.

Figure 5 shows the evolution of laser threshold with increased operating temperature for 350 and 700 μm long ridges processed from the same structure. The corresponding values for T_0 are 80–90 K and around 110 K, respectively. These values compare favorably to those of 1.3 μm InGaAsP RWG lasers, where values around 70 K are typical.

To investigate the performance of InGaAsN lasers, we have made the first measurements of differential gain of InGaAsN QW lasers [10]. They yield values similar to InGaAsP lasers ($dg/dN = 5 \pm 1 \times 10^{-16} \text{ cm}^2$), which indicates that they will be sim-

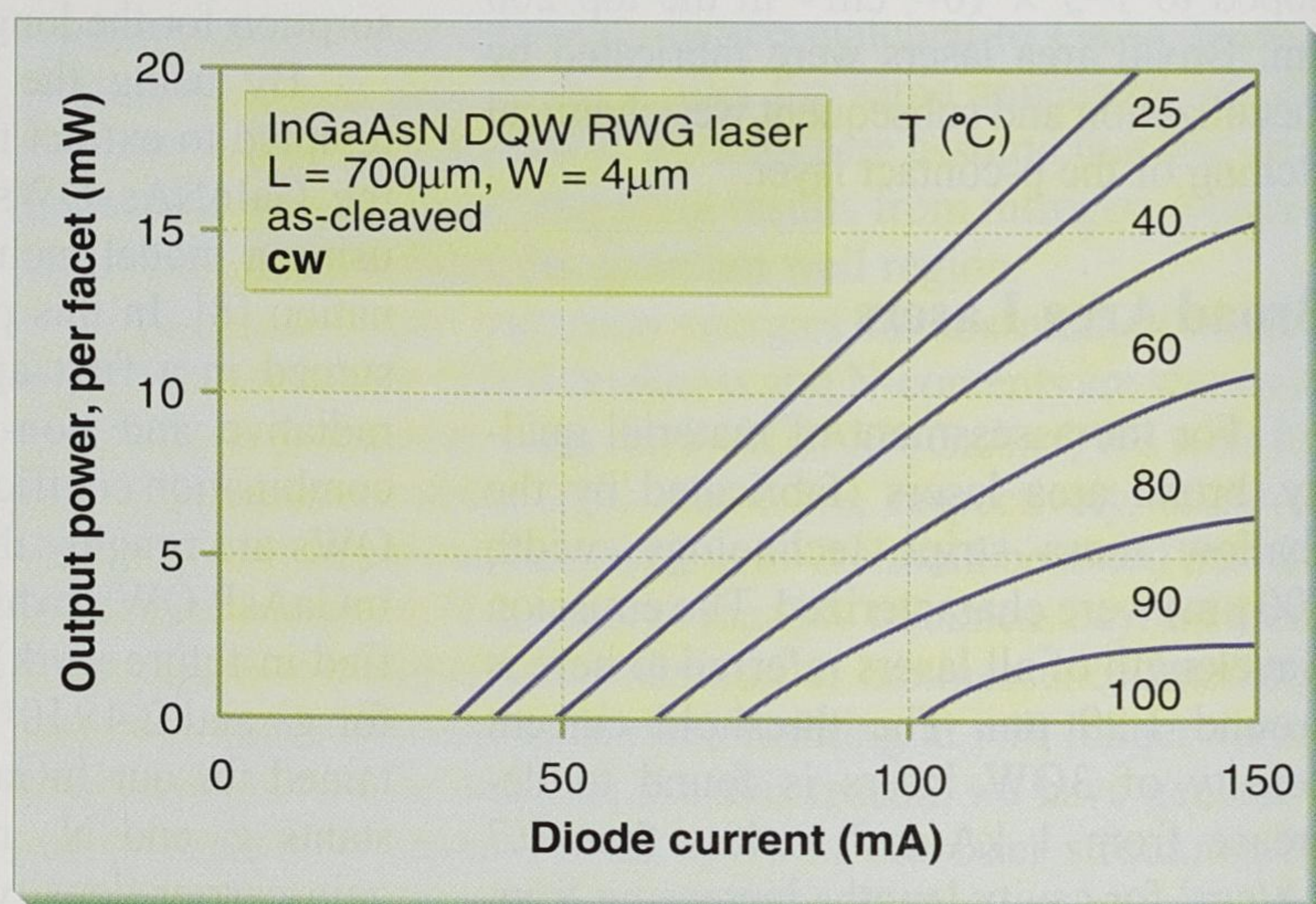


Figure 4. High temperature CW operation of a 700- μm -long, as-cleaved ridge waveguide laser emitting at 1.30 μm . T_0 is measured to be 110 K.

ilarly suitable for use as transmitters in high-speed transmission systems.

Finally, the main question of the practicability, the reliability of such lasers needed to be examined. For this purpose, we have subjected ridge lasers to lifetime tests at accelerated aging conditions to clarify if the new active region material is stable under lasing condition (which was initially doubtful due to the uncommonly strong annealing behaviour of InGaAsN QWs). Although the lasers were driven at 80°C with a cw current of 100 mA (corresponding to a current density of 6 kA/cm²) they showed no noticeable degradation of the threshold current after more than 1000 hours [10].

Narrow Stripe Oxide-confined lasers

Last but not least, we have attempted to make use of the unique processing capabilities for the AlAs/GaAs system, where AlAs can be converted to an insulating oxide layer in a steam atmosphere. Usually this is employed to define current restricting apertures in VCSELs. In our case we have inserted 15 nm thick AlAs layers in the upper and lower AlGaAs cladding layers, with the aim to define the laser stripe by lateral oxidation of a wider ridge. In fact, these oxide layers can serve not only as a restriction of the current flow but also as a laterally waveguiding layer due to their refractive index which is lower than the one of AlGaAs.

Simulations have shown that one single, 15-nm-thick oxide layer is not efficient for proper waveguiding. Our structures therefore contain 2 such layers in each cladding layer. The lateral and vertical structure of a ridge laser realised by this method can be seen in Figure 6. Details about their processing are given in [11]. As above, these lasers received a high-reflective coating on one facet. Because the doping of the AlAs layers is not yet optimized, these lasers do not give the same cw performance as the ones reported above. In pulsed operation, however, they exhibit the lowest threshold reported so far in this material: 300 μ m long devices have a threshold of only 11 mA and a slope efficiency of 0.39 W/A at 25°C. At 80°C, the threshold

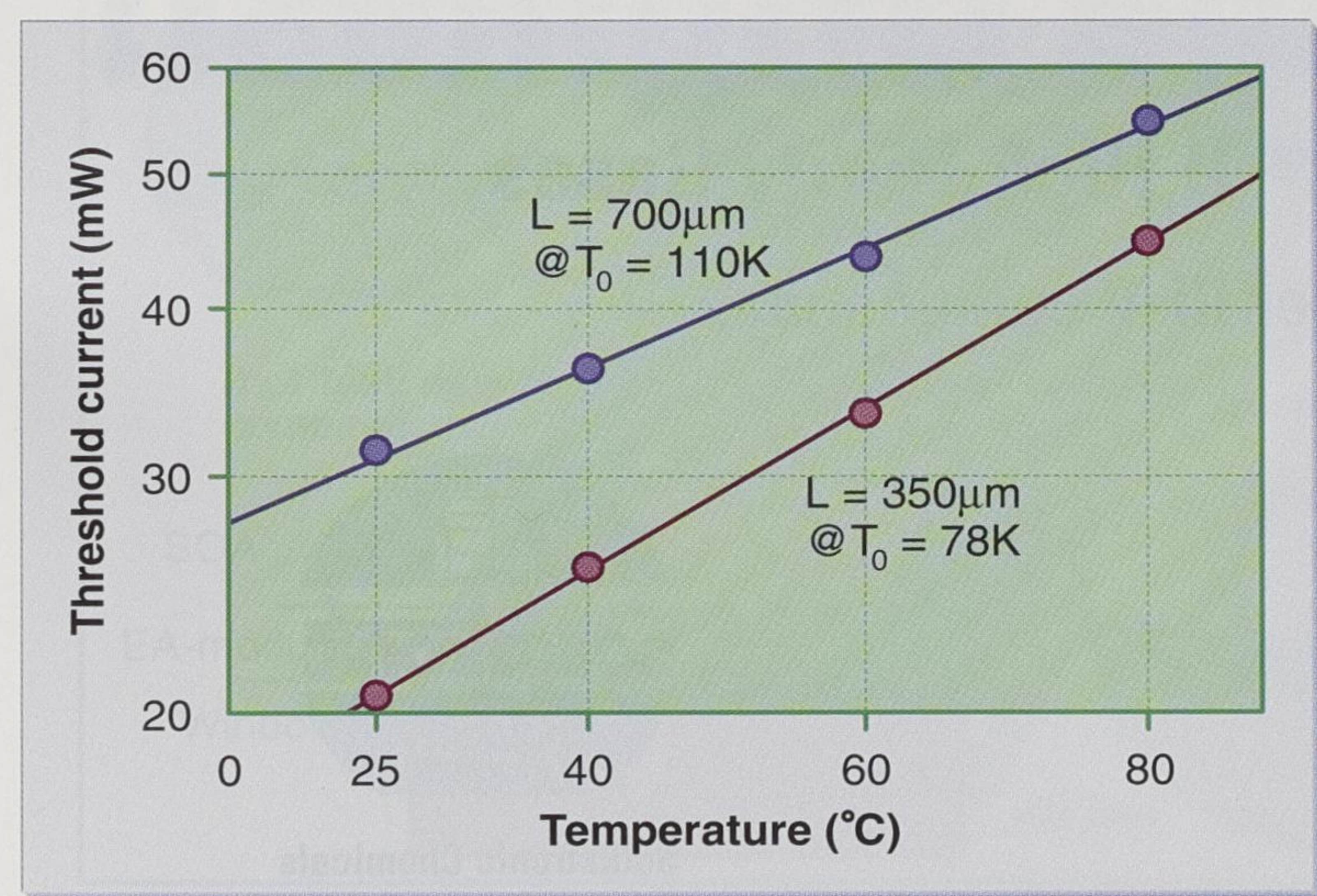


Figure 5. Temperature dependence of threshold current for 350- μ m and 700- μ m long as-cleaved 1.29 μ m InGaAsN ridge waveguide laser.

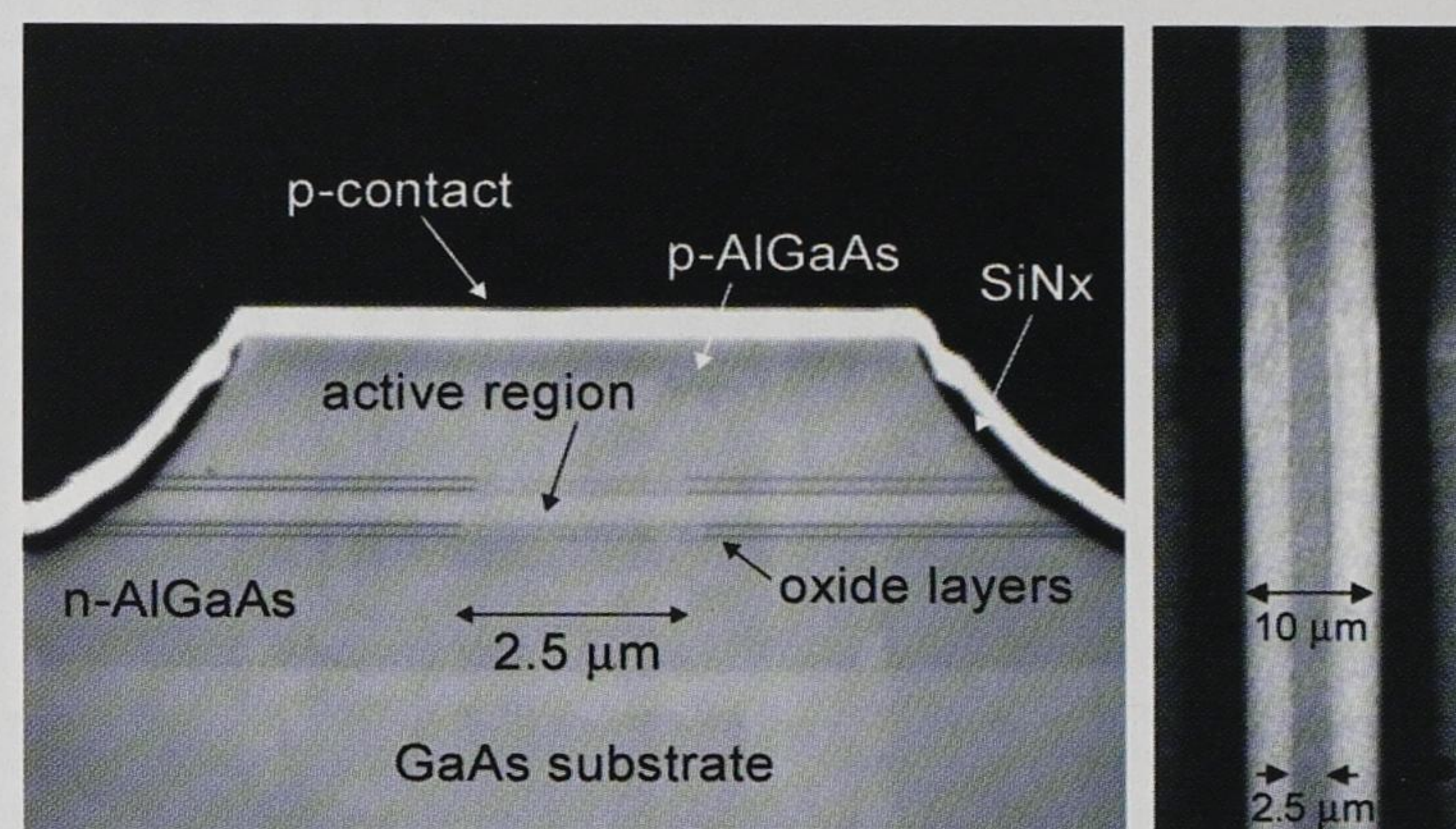


Figure 6. Left: Electron micrograph of the cross section of a completed oxide-confined laser structure. Right: Infrared microscopic top view of the oxidised mesa.

is still as low as 25 mW, corresponding to a T_0 of about 80 K. At a heatsink temperature of 120°C, optical output powers up to 15 mW have been achieved, demonstrating the excellent potential of such lasers.

Conclusion

In summary, we have demonstrated low threshold current density cw operation of MBE-grown InGaAsN lasers at wavelengths of 1.28 μ m to 1.3 μ m. Their performance is comparable to InGaAsP lasers emitting at the same wavelength, but they have the advantage of higher material gain and a significantly enhanced T_0 . The next challenge is now to realize vertical cavity lasers for optical fiber communication systems.

Acknowledgement

We gratefully acknowledge the collaboration of D. Bernklau, M. Komanda and M. Schuster. A. Yu. E. is supported by an Alexander-von-Humboldt fellowship. Our work was partly funded by the EU under BriteEuram BRPR-CT98-0721 (OPTIVAN).

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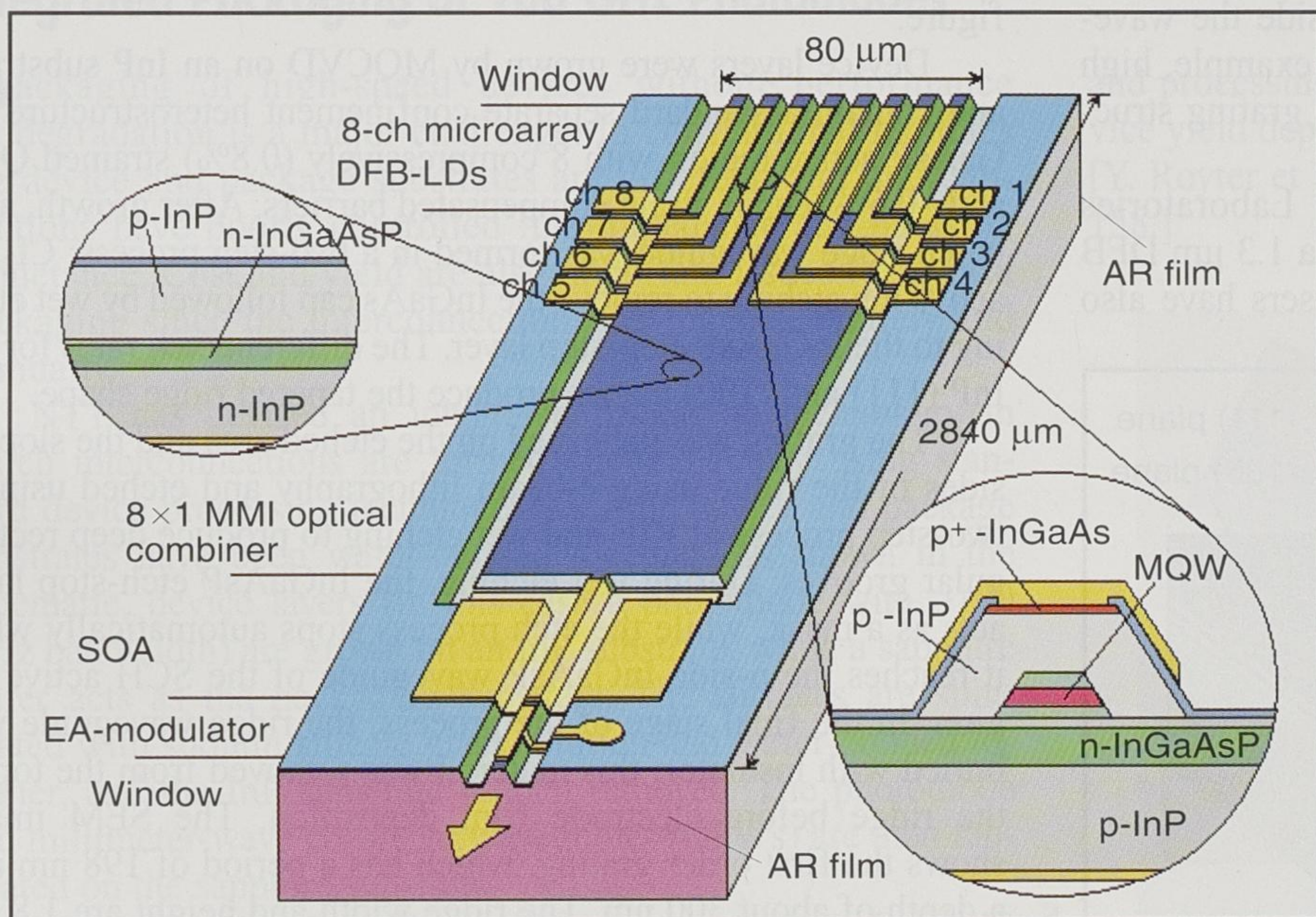
Wavelength-selectable, or tunable, transmitters are in strong demand in DWDM systems as the number of channels increases. The use of such devices can lead to substantial inventory reduction—the same device covers several wavelength channels—as well as providing spares to repair failed channels. A further use will be in reconfigurable networks that rely on optical add-drop multiplexing.

There are several different approaches to realizing wavelength-selectable devices. Here, researchers from NEC's Optoelectronics and High Frequency Device Research Labs have fabricated an integrated array of DFB lasers, which provide stable and highly reliable single-mode operation. In contrast, multi-section DBR lasers can mode hop when operating conditions (temperature, injection current) change.

The device consists of an eight-stripe microarray of DFB lasers coupled into a monolithically integrated 8×1 multimode interference (MMI) optical combiner. The light is also coupled

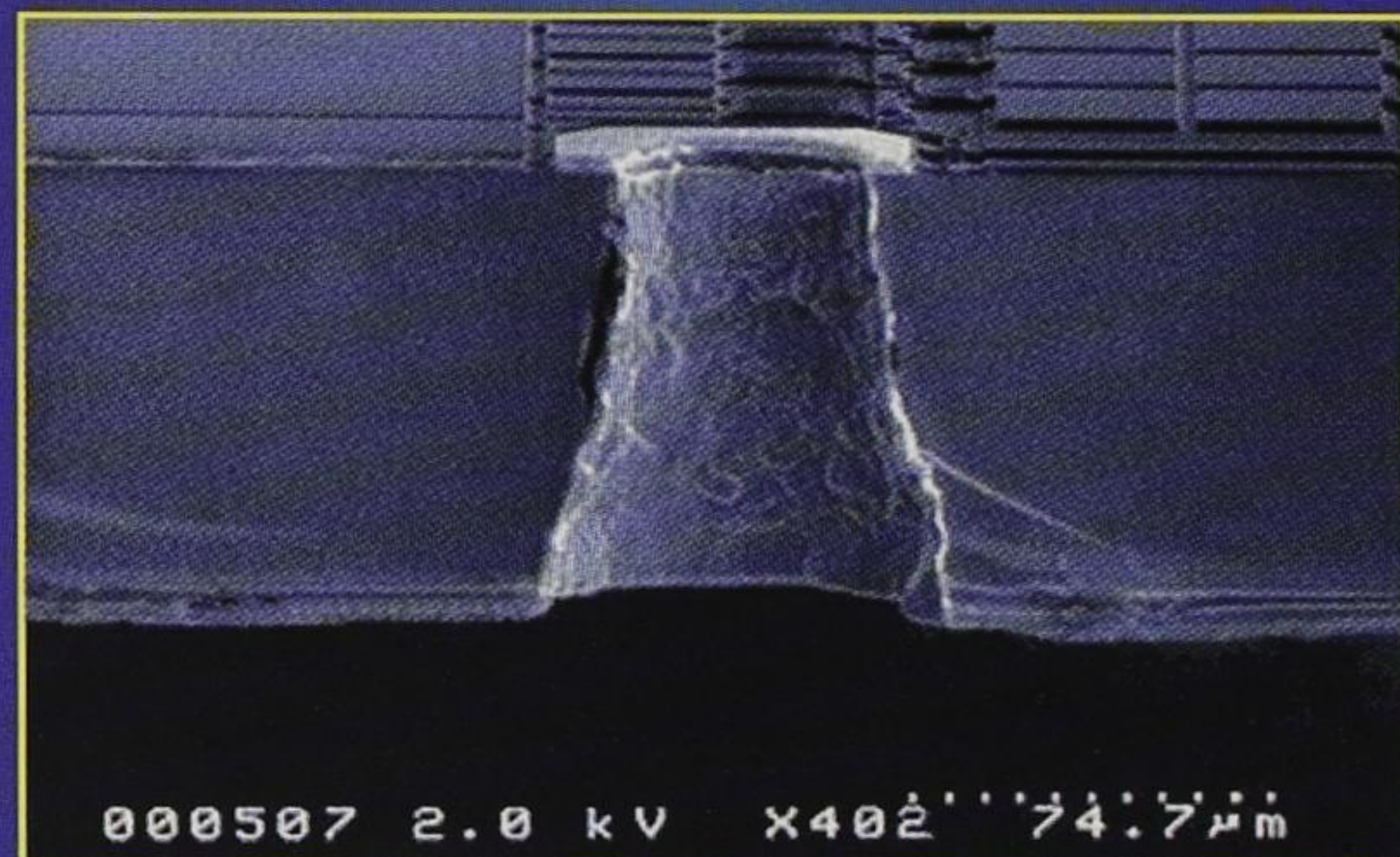
through a semiconductor optical amplifier (SOA) and an electro-absorption (EA) modulator. The total chip size was $400 \mu\text{m} \times 2.84 \text{ mm}$. A wavelength range of 15.3 nm was obtained by switching channels and controlling the operating temperature over a 20°C range. Single mode operation with a side-mode suppression ratio of $>40 \text{ dB}$ was obtained, with an output power of 7 mW , and 2.5 Gb/s modulation was demonstrated for each channel.

The device was fabricated using a three-step MOVPE process. After eight different pitch gratings were defined in the laser section, using e-beam lithography and wet etching, an InGaAsP waveguide was grown over the entire surface. In the second MOVPE step, InGaAsP/InGaAsP MQW stripes were grown in the laser, SOA and modulator sections using the microarray selective epitaxy (MASE) technique. In the laser section, an asymmetric mask was used to adjust the gain peak wavelength of each stripe to the designed lasing wavelength.



Schematic structure of NEC's wavelength-selectable eight-stripe microarray DFB lasers with integrated multimode-interference (MMI) combiner, semiconductor optical amplifier (SOA) and electroabsorption (EA) modulator.

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The third step was to grow a p-InP cladding layer and InGaAs contact layer.

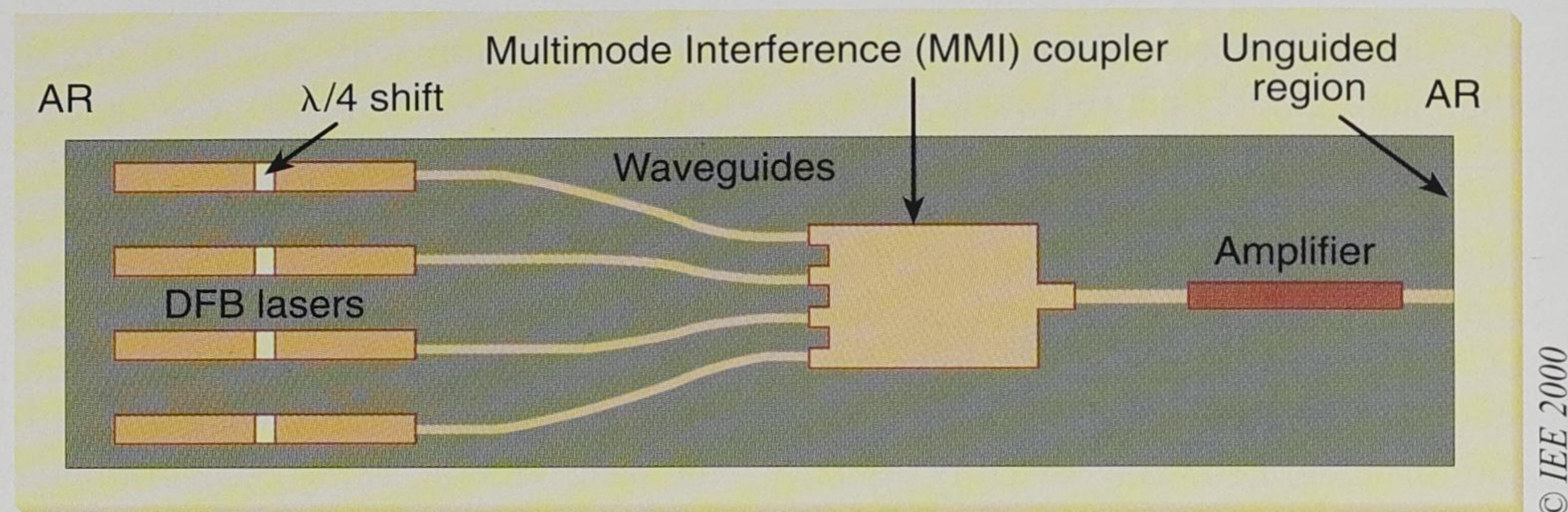
More recently, the same group has simultaneously fabricated three such wavelength-selectable devices on the same wafer, each with a different wavelength range, providing continuous coverage across a 47 nm window from 1539 nm to 1586 nm. [K. Kudo et al, **NEC**, IEEE Photonics Tech. Lett. 2000, 12(3), p. 242; K. Kudo et al, Elec. Lett. 2000, 36(8), p. 745.]

An alternative approach, developed by SDL and Seoul National University, uses curved waveguides to couple the output from four DFB lasers into an MMI combiner. The device has an amplifier section and an unguided region at the front facet to eliminate feedback related problems, and is designed for use with an external LiNbO₃ modulator.

A passive buried waveguide runs continuously throughout the chip, and the QWs and grating layer are placed above this backbone. The grating layer is etched completely in the amplifier section, and both the QWs and the grating are removed in the passive section; this prevents light reflected at the

facet from coupling back into the device and causing feedback interference. To achieve singlemode operation and a simple manufacturable process, a phase mask was used with a quarter-wave shift in the center of the laser cavity. The lasers were placed only 50 μm apart, and the total chip size was 2.5 mm long by 500 μm wide.

The device can be coarsely tuned by switching lasers (wavelengths are ~ 3 nm apart) and finely tuned by adjusting the temperature within a 30°C range, providing tuning across 12 nm with up to 15 mW of fiber-coupled power. [B. Pezeshki et al, **SDL and Seoul National University**, Elec. Lett. 2000, 36(9), p. 788.]



Four DFB lasers coupled together with an amplifier and an unguided region to reduce facet feedback. The lasers have gratings and QWs above a buried ridge waveguide; the grating layer is removed in the amplifier section, and both QWs and grating layer are removed in the passive sections.

Laterally Coupled DFB Lasers

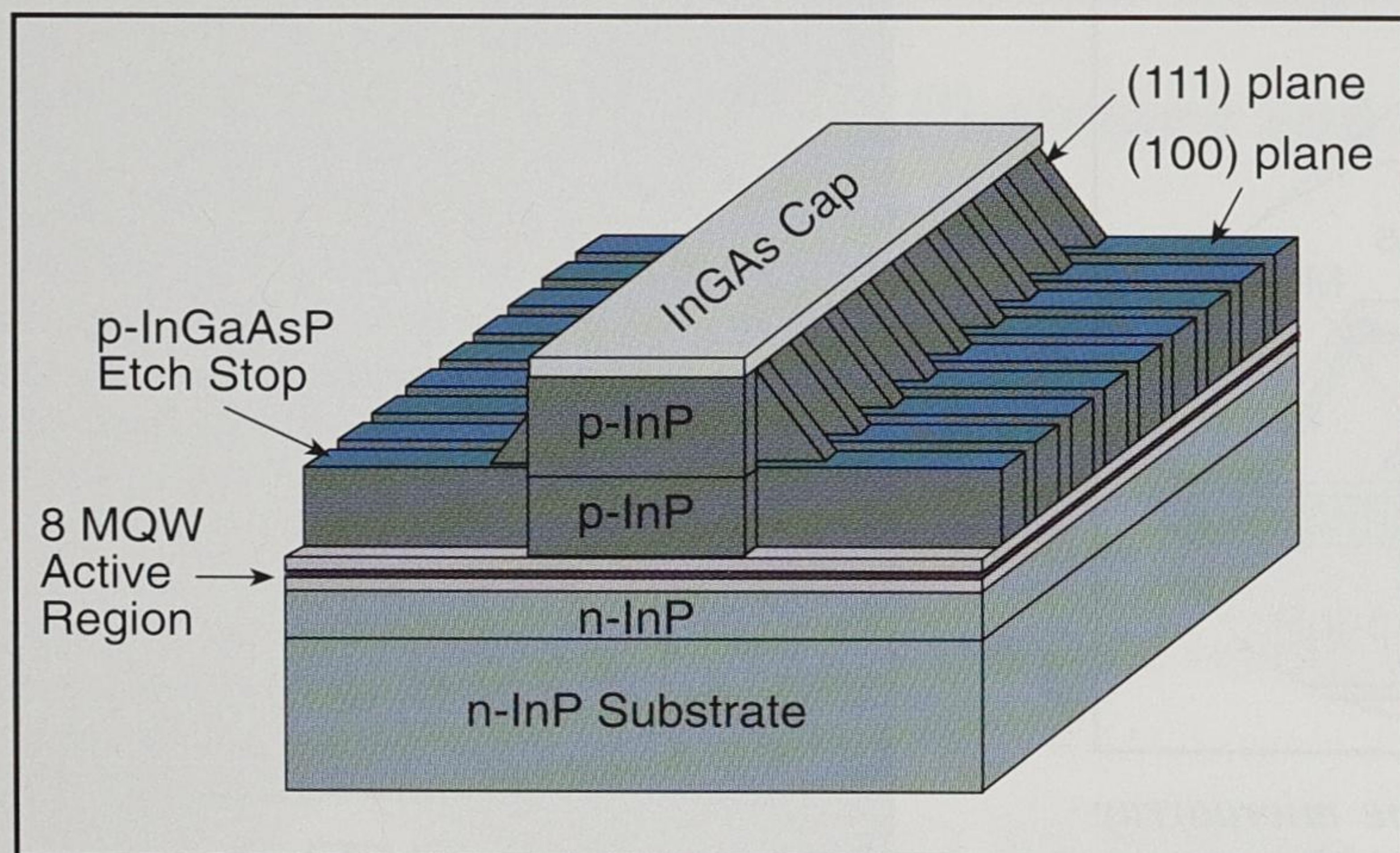
The relatively high cost of DFB lasers poses a problem for practical use, especially for applications such as fiber-to-the-home. Multi-step epitaxial growth is required to fabricate conventional DFB lasers with a grating structure inside the waveguide, and this can result in low device yield. For example, high temperature regrowth on the substrate with a fine grating structure may deform the grating shape.

This work, by Pioneer Corporate R&D Laboratories (Saitama, Japan), describes a method to fabricate a 1.3 μm DFB laser using a single epitaxial growth (1.55 μm lasers have also

been fabricated). The device utilizes lateral coupling into a surface grating structure formed by a two-step etching process after growth is complete. A schematic of the device is shown in the figure.

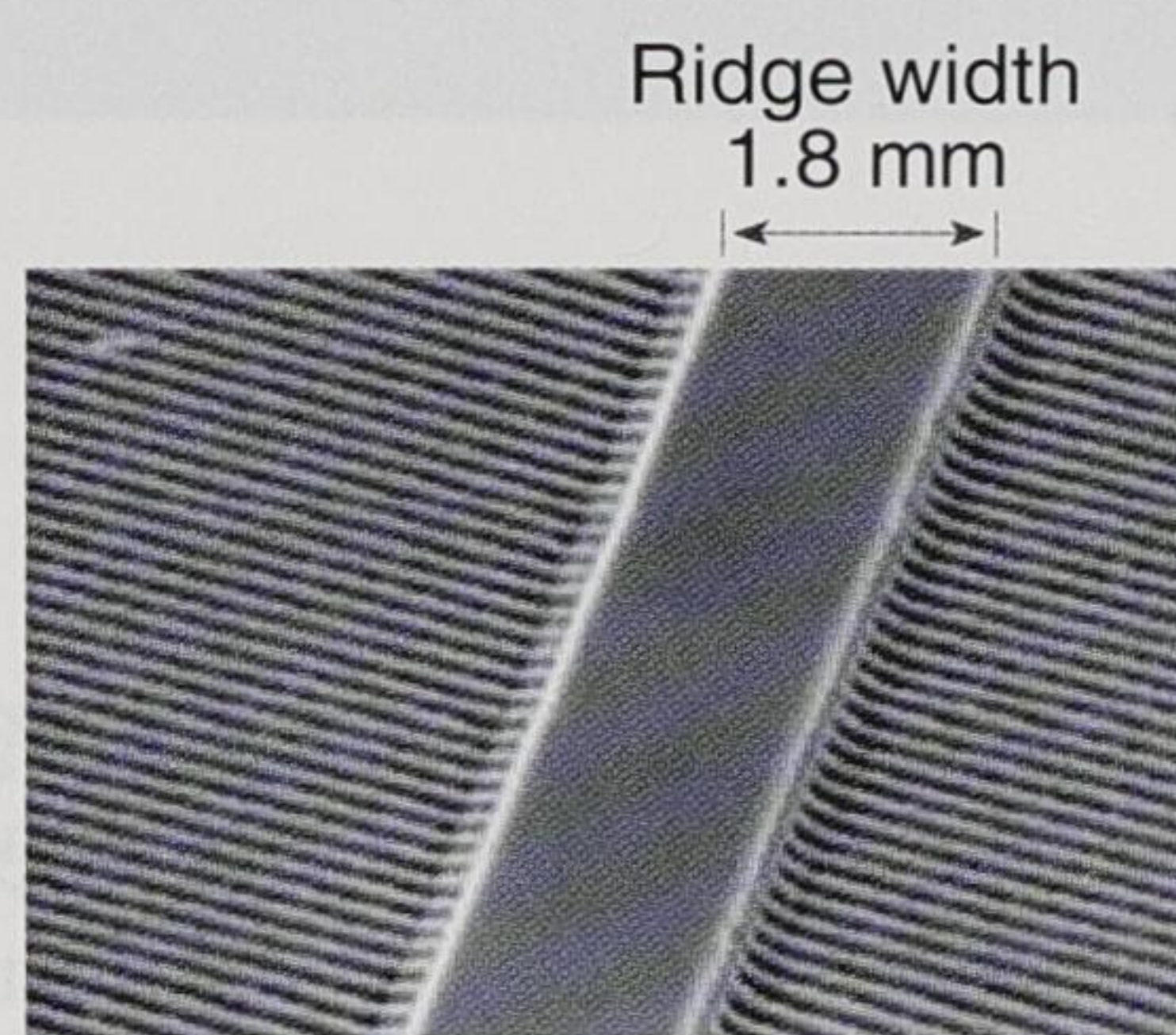
Device layers were grown by MOCVD on an InP substrate, and contain a standard separate confinement heterostructure InGaAsP active region with 8 compressively (0.8%) strained QWs and -0.5% tensile strain compensated barriers. After growth, a tapered ridge waveguide was formed in a two-step process: Cl₂ reactive ion etching to remove the InGaAs cap followed by wet etching to the InGaAsP etch-stop layer. The different etch rates for the InP (111) and (100) planes produce the tapered ridge shape.

The grating was patterned on the etched area and the sloping sides of the ridge using e-beam lithography and etched using a two-step process of RIE and wet etching to produce deep rectangular grooves. During wet etching, the InGaAsP etch-stop layer acts as a mask, while the etch process stops automatically when it reaches the p-side InGaAsP waveguide of the SCH active region. In the final stage of the process, the ridge waveguide was buried with insulator; this material was removed from the top of the ridge before electrode film deposition. The SEM image shows the first order grating, which has a period of 198 nm and a depth of about 300 nm. The ridge width and height are 1.8 μm and 0.9 μm respectively. The ridge height and grating depth, two key parameters for this device, are accurately controlled by the etch-stop structure.



Schematic structure of Pioneer's laterally coupled DFB laser.

A laser fabricated in this manner with a cavity length of 380 μm exhibited a threshold current of 17 mA at room temperature. A slope efficiency of 0.25 W/A and a maximum output power of 25 mW were shown for devices with Ar-HR coated facets. Also, optical transmission over 1 km of fiber using a preliminary laser module and a Gb/s modulation speed has been demonstrated. The Pioneer researchers believe that this laser offers significant cost reductions over conventional DFB lasers, and expect the device to be used in WDM networks, future optical subscriber systems and other applications. [N. Chen et al, **Pioneer**, Jpn. J. Appl. Phys. 2000, Vol. 39, Part 1 (3B), p. 1508.]



SEM image of Pioneer's laser with a deep grating structure.

1 W Fiber-Coupled Power at 1.45 μm

High power pump lasers in the 1.45–1.48 μm wavelength region are required for fiber amplifiers—both EDFAs and Raman amplifiers—that provide gain at 1.55 μm . Single narrow stripe diode lasers in this wavelength region are limited to around 250 mW of fiber-coupled power. This paper reports a flared laser structure that delivers a record 1 W of output power at 1.45 μm into single-mode fiber. The devices utilize an active region with three InGaAsP QWs grown on InP by MOCVD. The device structure has

a narrow stripe single-mode ridge waveguide section and a laterally tapered unguided amplifying section. The single-mode output of the ridge section is amplified in the tapered section while it is diverging in the lateral section. The peak power obtained was 1.08 W while the peak fiber coupling efficiency was 60%. With a front facet fiber grating, 900 mW of power was coupled into the fiber. [A. Mathur et al, **SDL**, Elec. Lett. 2000, 36(5), p. 410.]

Quantum Cascade Lasers

Pulsed operation of quantum cascade lasers at a heat sink temperature of 425 K (152°C) achieved a peak output power of ~20 mW at a wavelength of ~8.4 μm . The device was a “three-well vertical transition active region” with InGaAs/AlInAs MQWs grown lattice-matched to InP by MBE. The waveguide core consisted of 75 stages of active regions and injectors. High temperature operation is required under certain environmental conditions, including combustion diagnostics in the vicinity of flames or engines, and for accelerated lifetime testing. [C. Gmachl et al, **Lucent Technologies (Bell Labs)**, Elec. Lett. 2000, 36(8), p. 723.]

As the wavelength of a QC laser increases, large waveguide losses and reduced radiative efficiency result in threshold currents that are too high to sustain CW lasing. This paper reports on a new active region design concept employing inter-miniband transitions in the conduction band of “chirped” superlattices of varying period and duty cycle. One such laser exhibited CW operation at ~11 μm up to a temperature of 85 K with an output power of ~8 mW. The maximum power was 75 mW at 25 K. [A. Tredicucci et al, **Lucent Technologies (Bell Labs)**, Elec. Lett. 2000, 36(10), p. 876.]

Optoelectronic Devices

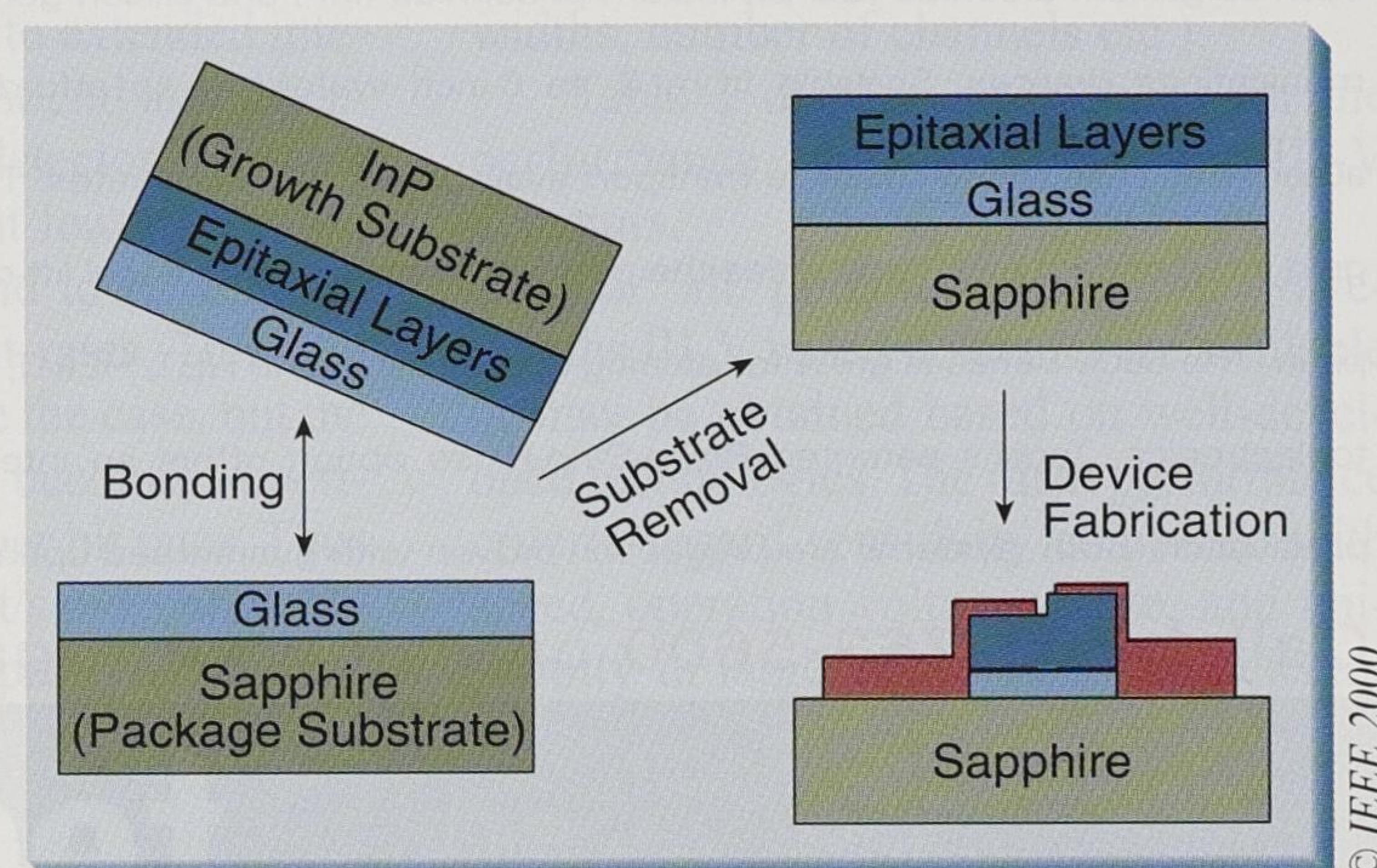
Integrated Packaging of 100 GHz Photodiodes

Packaging of high-speed devices without performance degradation is a major challenge. In conventional modules the device and package substrates are different, and interconnections have poorly controlled line impedance and parasitic inductance. Cost and yield are also important issues for hybrid packaging since the interconnections are made separately and manually.

NTT has devised an integrated packaging technology in which interconnections are formed simultaneously using standard device processing techniques after the device and package substrates have been wafer-bonded together. As shown in the schematic, device layers (in this case a photodiode with >100 GHz bandwidth) are grown on an InP substrate, while a sapphire wafer acts as the packaging substrate. The surfaces are spin-coated with sodium silicate glass solution and wafer-bonded together, and the InP substrate is then removed. The photodiode and millimeter-wave co-planar waveguides (CPWs) are then fabricated on the sapphire substrate.

The performance of uni-travelling-carrier photodiodes (3 dB bandwidth of 102 GHz) was similar to that of conventional devices, and the CPWs exhibited low dispersion. Wafer bonding

and processing was carried out using 2-inch wafers, and the device yield depended directly on the quality of the wafer bonding. [Y. Royter et al, **NTT**, IEEE Electron Dev. Lett. 2000, 21(4), p. 158.]



Schematic illustration of NTT's integrated packaging technology.

High Power Lasers

Highlights From CLEO

(Submitted by Dan Botez, University of Wisconsin-Madison)

In an invited talk at the recent CLEO conference, A. Salokatve of **Coherent Semiconductor Group** reported Al-free active-region (ALFA) diode lasers with superior reliability to their Al-containing counterparts. Results included long-term reliability in excess of 2000 hours at 60 W CW output power from 1-cm-long bars emitting at 0.81 μm . This by far surpasses the best results reported from bars having Al-containing active regions. Another impressive result was the achievement of over 1000 hours lifetime at elevated tem-

perature (75°C) of laser bars with an output power of 50 W quasi-CW. This is the first report of elevated-temperature, high-power (>40 W) reliability from diode-laser bars. The main application is for pumping Nd-YAG solid-state lasers.

In a post-deadline paper at CLEO, J. Skidmore of **Lawrence Livermore National Laboratory** reported on a Si monolithic micro-channel-cooled diode array employing an architecture that provides low thermal resistance, accurate bar placement, ef-

fective active cooling via micro-channels, and effective beam collimation employing microlenses lodged in Si V-grooves. The maximum power level was 1.46 kW, corresponding to an excitation of 1.5 kW/cm². Excitation is one measure of brightness, and this is the highest value of excitation ever reported from a stacked diode array. The wallplug efficiency was 50% at 1 kW and the microlenses provided a very narrow 6.4 mrad (FWHM) beam in the fast-axis direction. The laser contained an Al-free active region (ALFA) emitting at 0.81 μm .

1 W CW Operation of a 730 nm Al-Free Laser

High power (~1 W) lasers operating in the 700–780 nm range are required for emerging applications such as photodynamic therapy, but have suffered from the poor reliability of devices with conventional AlGaAs active regions. Here, 1 W CW output power is achieved from a laser with a compressively

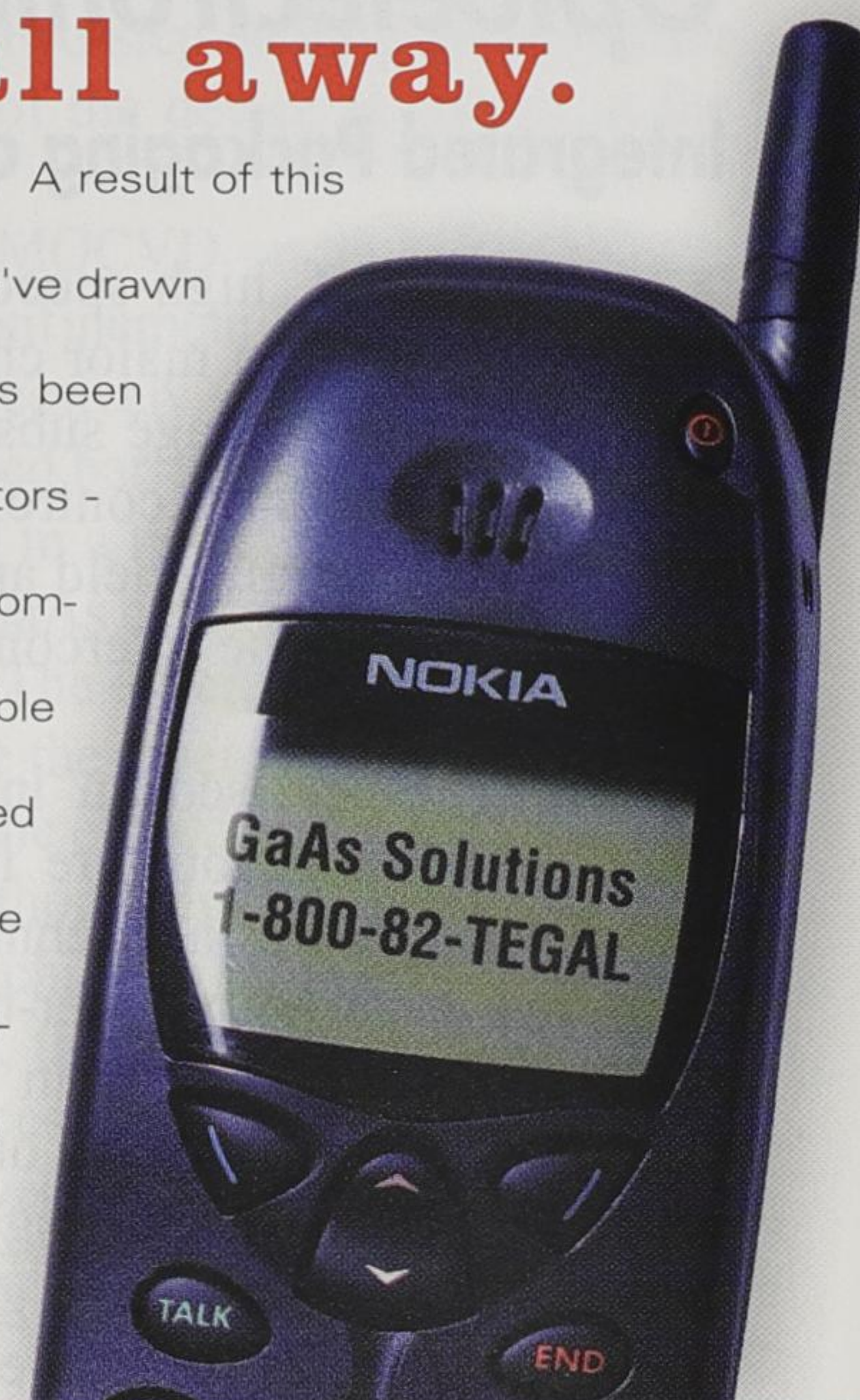
strained InGaAsP active layer and tensile-strained InGaP bounding layers. Broad waveguide devices operating at 1 W CW showed a degradation of 2.5%/kh over 1000 hours at a heatsink temperature of 25°C. [S. Rusli et al, **University of Wisconsin-Madison**, Elec. Lett. 2000, 36(7), p. 630.]

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A Roadmap for Optoelectronic Interconnects for Integrated Circuits, Part II

The future role of III-V optoelectronics as CMOS interconnect solutions is discussed in a white paper¹ published by the Advanced Research Initiative in Microelectronics, a program funded by the European Union. The editors of that work are Alfred Forchel and Pierpaolo Malinverni. Extracts from it are reproduced here by permission.

This is the second and concluding part of this article. The first part can be found in our previous issue, and is also available on our website at www.compoundsemiconductor.net



Detectors and Receivers

For a number of years most of the attention on the various parts of optical links has been successfully focused on the light emitters to reduce size and cost and to increase power efficiency, for example, by reducing threshold current. This has led to a simplification of the laser drivers eliminating the need for light feedback and stringent temperature control.

For the detectors the same development has not occurred yet. This also means that there have been less possibilities to improve the receivers. The optimum receiver is determined by the received amount of light, the required bit error rate (BER) and the type of detector. The optimisation is to make the receiver add a minimum amount of noise to the detector noise while at the same time providing sufficient output swing to drive logic circuits. For minimum noise and high bit-rates bipolar transistors are still the best, if run at rather high currents which implies high power dissipation. The power per channel may actually be higher at the receiver than for the laser driver. This may constitute a serious problem for high density optical interconnects where a pitch in the 10 μm range may become necessary.

One way of reducing receiver power while maintaining the BER would be to increase the received optical power by increasing the emitted power. From a system view this total power optimisation may be worthwhile. However, running lasers at minimum power would increase reliability and eliminate feedback and/or temperature control.

The figure of merit for a field-effect transistor (FET) input is the transconductance divided by the total input capacitance squared, whereas for the bipolar input it is the square root of the transistor beta divided by the total input capacitance. Clearly the reduction of all stray capacitance and transistor associated capacitance while keeping high amplification at given frequencies is of vital importance for receivers. This points to extended integration including the front end amplification essentially with the detector. Whereas FETs are advantageous at lower bit rates, bipolar transistors do tend to have better performance at higher bit rates. This will most likely continue to be the case, but the bit rate where the bipolar becomes superior will move towards higher bit rates. Thus CMOS front end at 1 Gbit/s most probably will in some time be the preferred choice. This would be a possibility to reduce power and size for receivers.

For massively parallel interconnects it could be expected that the uniformity of received light between the channels would be high, provided all channels are optically aligned in parallel. However, uniformity from assembly to assembly may not be as good depending on the alignment tolerances used, where very high alignment requirements would influence cost by a reduction in yield. Thus there may be a strong requirement on dynamic range.

Similarly to other components of optoelectronic interconnects, standardisation of receiver properties is essential for any introduction into applications. This regards e.g. the receiver sensitivity and reliability, supply voltage, the properties of the detectors (wavelengths, bandwidths, number of channels etc.).

Table 1 displays projections for the performance developments of III-V detectors.

For all potential operation wavelengths III-V based detectors are available or may be obtained based on well-developed technologies. The main performance criteria regard sensitivity combined with speed, operation voltage, noise, and uniformity in large arrays etc.. The detector size has to be large enough to allow a sufficiently precise adjustment to the optical path with a limited effort. At the same time the detector area in 2D arrays should obviously be as small as possible to reduce the total interconnect size and to

¹ "Technology Roadmap – Optoelectronic Interconnects for Integrated Circuits" was produced by the Advanced Research Initiative in Microelectronics (MEL-ARI OPTO), which is part of the European Commission's IST Programme for Future and Emerging Technologies.

reduce capacitance. Because there are often a variety of possible detector types with suitable performance, cost of the individual device as well as the yield in larger arrays is also an issue even for exploratory systems.

Large 2D arrays of III-V based detectors are available/under development with very high performance. InGaAs and GaAs detector systems are particularly well developed in terms of large arrays (64×64 channels available in 1996) and regarding sensitivity. Compared to InGaAsP based devices GaAs based detectors require significantly less power.

For systems operating in the wavelength range below $0.9 \mu\text{m}$ GaAs and InP based detectors like GaAs MSMS or InGaAs/InP p-i-n photodiodes as well as Si based photodiodes may be used. Si based photo-detectors have the advantage that they may be monolithically integrated with the receiver chips, whereas III-V-based detectors will most likely require the use of hybrid fabrication techniques like flip-chip bonding. For operation wavelengths beyond $1 \mu\text{m}$ InP based detectors or systems based for example on GaSb or Si/Ge are required.

A clear requirement for optoelectronics to be used is a competitive price level. According to the 1996 OIDA roadmap the price per detector is expected to drop from about USD 1 in 1995 to USD 0.1 in 2010. Different to the present expectation the OIDA focuses on parallel optoelectronic interconnects with several tens of channels only. For the massively parallel optoelectronic interconnects considered here similar or even lower price boundaries are expected.

The spatially modulated light detector (SML detector) is a detector that can be embedded in a standard CMOS technology of any type.

The advantages of the detector integration in standard CMOS are the following: III-V detector arrays don't have to be fabricated, thus avoiding the III-V wafer, fabrication and test cost. Their fabrication yield is extremely high (only the n-well diffusion and some metal strips in the standard CMOS process having very low risk). If, however, much better sensitivities are required, III-V flip chip detectors have to be chosen.

Technology Roadblocks

For monolithic approaches there is a main technology roadblock, namely the realisation of device grade III-V materials for the emitters and detectors on Si substrates. The large lattice mismatch requires special epitaxy techniques to prepare high quality material. At the same time the processing temperatures have to be compatible with the Si IC fabrication, because it is not likely that III-V overgrown substrates are acceptable in IC processes. This, of course, does not apply to hybrid solutions.

For both hybrid and monolithic approaches the technological challenges due to the need to realise large arrays based on high performance elements shouldn't be underestimated. Uniformity requirements, size compatibility, technological compatibility, low power dissipation, functionality as well as IC grade reliability have to be achieved with previously unthinkable precision.

The current IC architectures are based on electronic interconnects and this will continue to be the main interconnection scheme even beyond the next decade. The major problem concerning the implementation of optical interconnects is the economic risk factor in introducing a new technology. This may in fact result in a technology roadblock, as long as electronic solutions to the interconnect bottleneck can be found. Specific proposals for

architecture modifications regarding the optimisation of the IC performance by using optoelectronic interconnects are one of the objectives of the cluster.

A change of IC architectures towards the exploitation of the full capacity of optoelectronic interconnects will most likely occur as an evolutionary process. First long-distance optoelectronic interconnects (board to board etc.), which are currently developed by several IC manufacturers, will be introduced in the next computer generations.

A generally accepted specification of a standard optoelectronic interconnection structure is required for the introduction of these interconnects in future ICs. Properties to be standardized range from geometrical standards (channel footprint in one and two dimensional arrays) to electrical (power, voltage), optical (wavelength, losses), and system performance (bandwidth, latency, coding etc.).

For the commercialisation of optoelectronic interconnects at all levels cost performance is a central issue. There is a particular problem in the development phase: Due to the initially small production volume of optoelectronic interconnects a combination with other volume applications (e.g. optoelectronic interconnects in automotive applications) will be required to allow fabrication and testing at competitive prices. Here again longer distance ($\gg$ chip-chip) optoelectronic interconnects have a special potential due

Year	1999	2002	2007
Optical channels	4k (64x64)	4k (64x64)	16k (128x128)
Wavelength (nm)	750 - 1100	800 - 1100	750 - 1100
Detector diameter (mm)	30	25	20
Detector responsivity (A/W)	0.6	0.6	0.6
Receiver size (mm)	50 $\times$ 120	40 $\times$ 80	30 $\times$ 50
Pitch (receiver + detector) (mm)	150	100	60
Bit rate per channel (Mbit/s)	150	1000	2000
Aggregate bit rate (Gbit/s)	600	4000	32000
Operating voltage (V)	5	2.5	1.2
Power dissipation/ channel (mW)	2.5	1.5	1
Minimum photo current (mA pp)	3.5	5	6
Signal delay (ns)	~ 2	< 1	< 0.5
Cross talk (dB)	-20	-15	-15
Sensitivity uniformity (dB)	± 1	± 1.5	± 1.5
Delay uniformity (%)	± 10	± 10	± 10
CMOS Technology (nm)	0.6	0.25	0.1

Table 1 - Projected performance of GaAs and InGaAs detector/receiver arrays

to the low cost of the optical pathway and the high-performance requirements. On chips or boards improved electric interconnects will be strong competitors for optoelectronics.

Here the cost-performance argument may concentrate the industrial R&D efforts on microelectronic solutions, which would also result in a roadblock for the development and the application of optoelectronic interconnects.

Similar to other micro- and optoelectronic modules packaging and testing determine predominantly the fabrication cost. Cost reduction requires mass fabrication of geometrically, optically and electrically standardized optoelectronic interconnects. For the optical, optoelectronic and microelectronic components of the interconnects mounting technologies have to be developed which minimize the need for individual alignment and testing. This implies first of all a high reliability of all processes involved in the fabrication including e.g. epitaxy, device fabrication, device placement and bonding, etc. In addition automated test procedures (e.g. bit error rates) for one and two dimensional arrays of optoelectronic interconnects have to be developed.

Conclusions

In this document we have described the potential and the perspectives offered by optoelectronics, particularly in overcoming the interconnect problem in tomorrow's integrated circuits.

Most of the systems envisaged use III-V components, especially on the emitter side (lasers, LEDs, modulators). III-V devices offer great advantages in terms of quantum efficiency, manufacturability, and yield. Further options for emitters based, for example, on Si are still far from providing efficiencies required for applications. On the other hand, hybrid and monolithic integration concepts of III-V on Si require the development of compatible process technologies for these different classes of materials. Therefore developments of both III-V and Si based emitters are followed in the cluster.

Another obstacle to the deployment of these systems is that the microelectronic industry will not change the current manufacturing processes, unless there is clear potential for profitability using optoelectronics.

The task of scientists and managers involved in optoelectronics R&D is a challenging one. They need to prove that optoelectronic interconnect systems for ICs clearly outperform electrical interconnects, and that companies can make money with it. Furthermore psychologically "silicon" will remain a magic word, which will still drive and justify huge investments in the years to come. It is therefore one of the central objectives of the present MEL-ARI activity to directly demonstrate the superior performance of optoelectronic interconnects in system applications.

To overcome, but also to exploit these obstacles there are a number of pos-

sible technological options: in the long-term there are visions of silicon-based light emitters and, at relatively shorter term, of highly integrated Si/GaAs light emission/guiding and detection systems. The future challenges in this area are therefore:

- the integration of light sources, waveguides and detectors, with processes that are compatible with the existing Si manufacturing;
- the integration of optical interconnects in system demonstrators that will solve a major problem (communication bottleneck and latency issue in multiprocessors, massive data flow processing in dedicated machines, fast re-configurable architectures, large ultra-fast commutators, etc...) and provide a significantly better solution or a cheaper cost than electronic solutions.
- the creation of a bridge to the telecommunications world that would offer a "fiber to the IC" interface, allowing IC intelligence to merge with fibre's unlimited capacity.

Downloadable copies of the complete white paper are available from the MEL-ARI OPTO Web Site at <http://www.cordis.lu/esprit/src/melop-rm.htm>.

Printed copies are available from the Office for Official Publications of the European Communities - reference catalog number ISBN 92-828-7762-0. The editors of Compound Semiconductor would like to thank Pierpaolo Malinverni for his help with this article.



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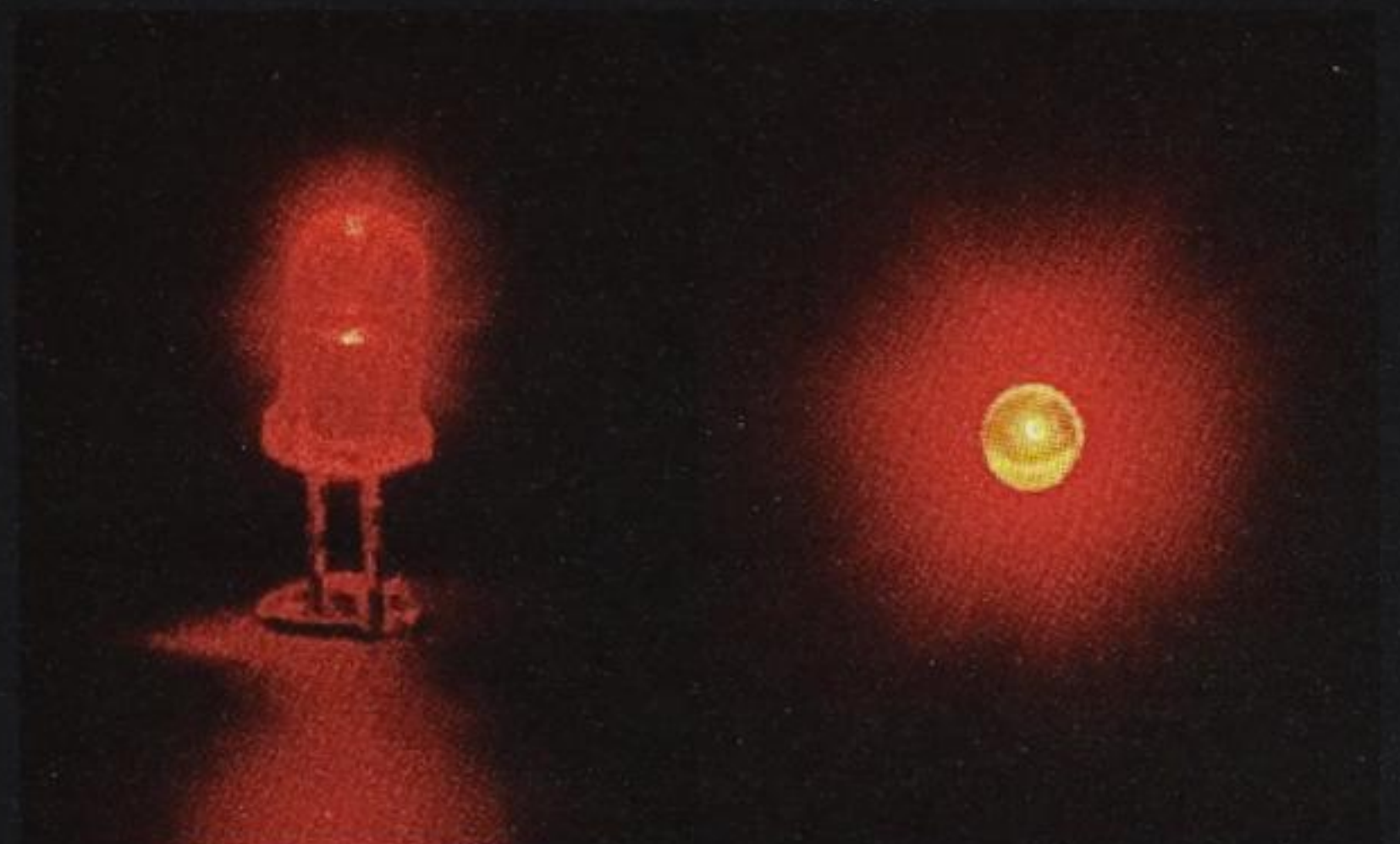
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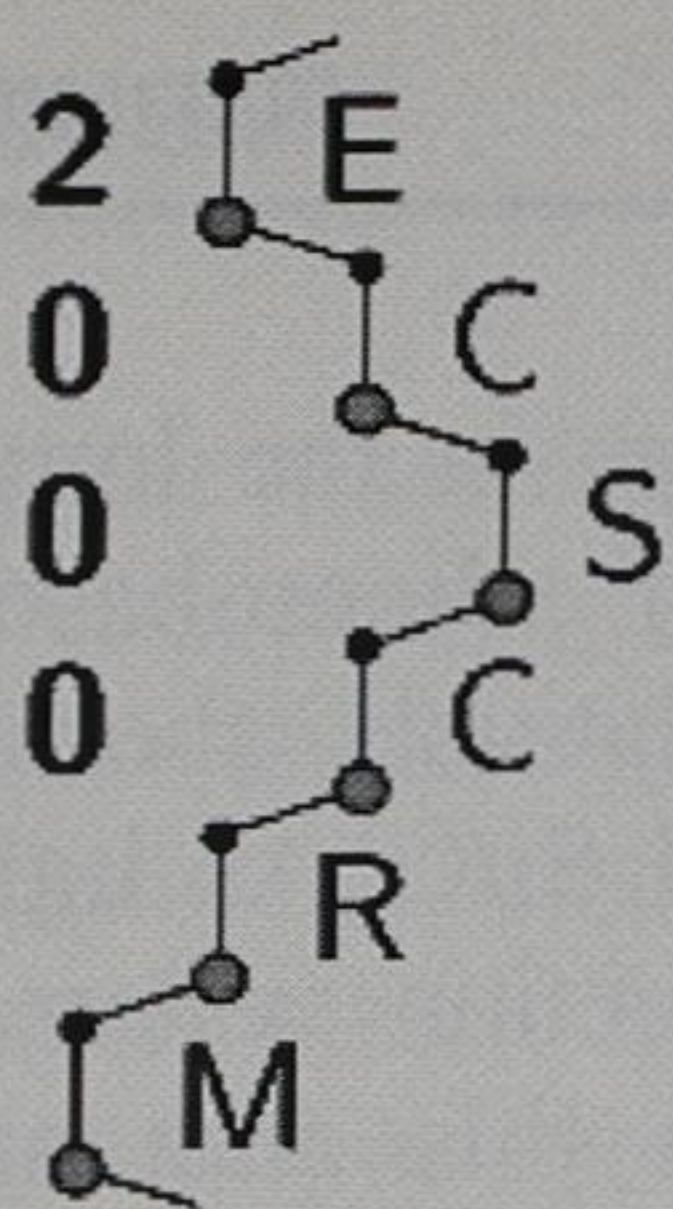
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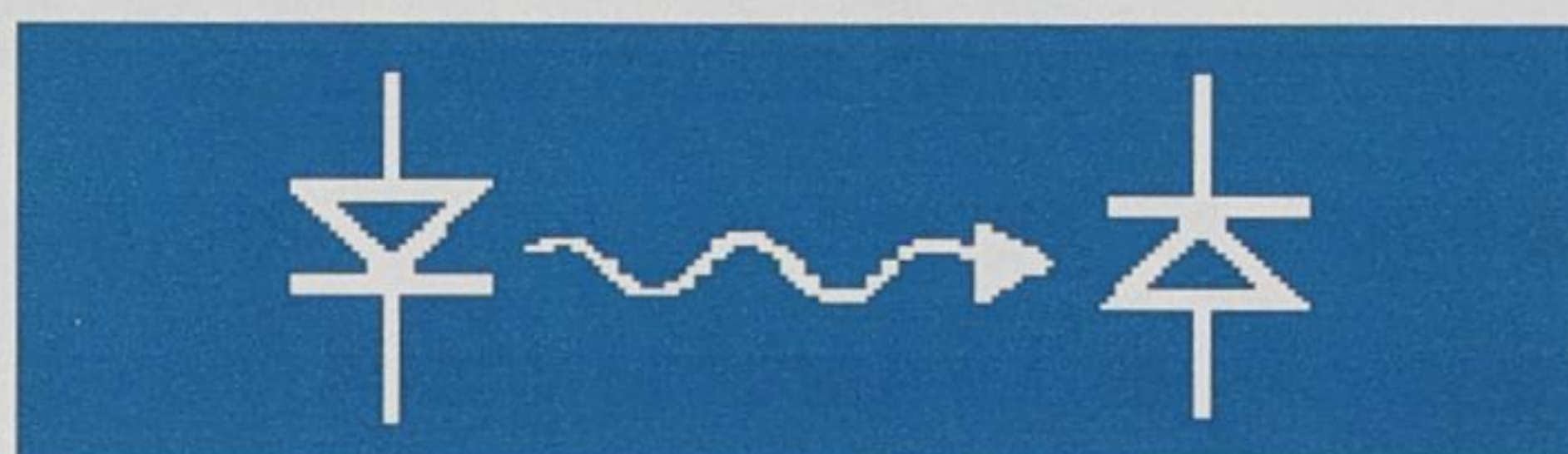
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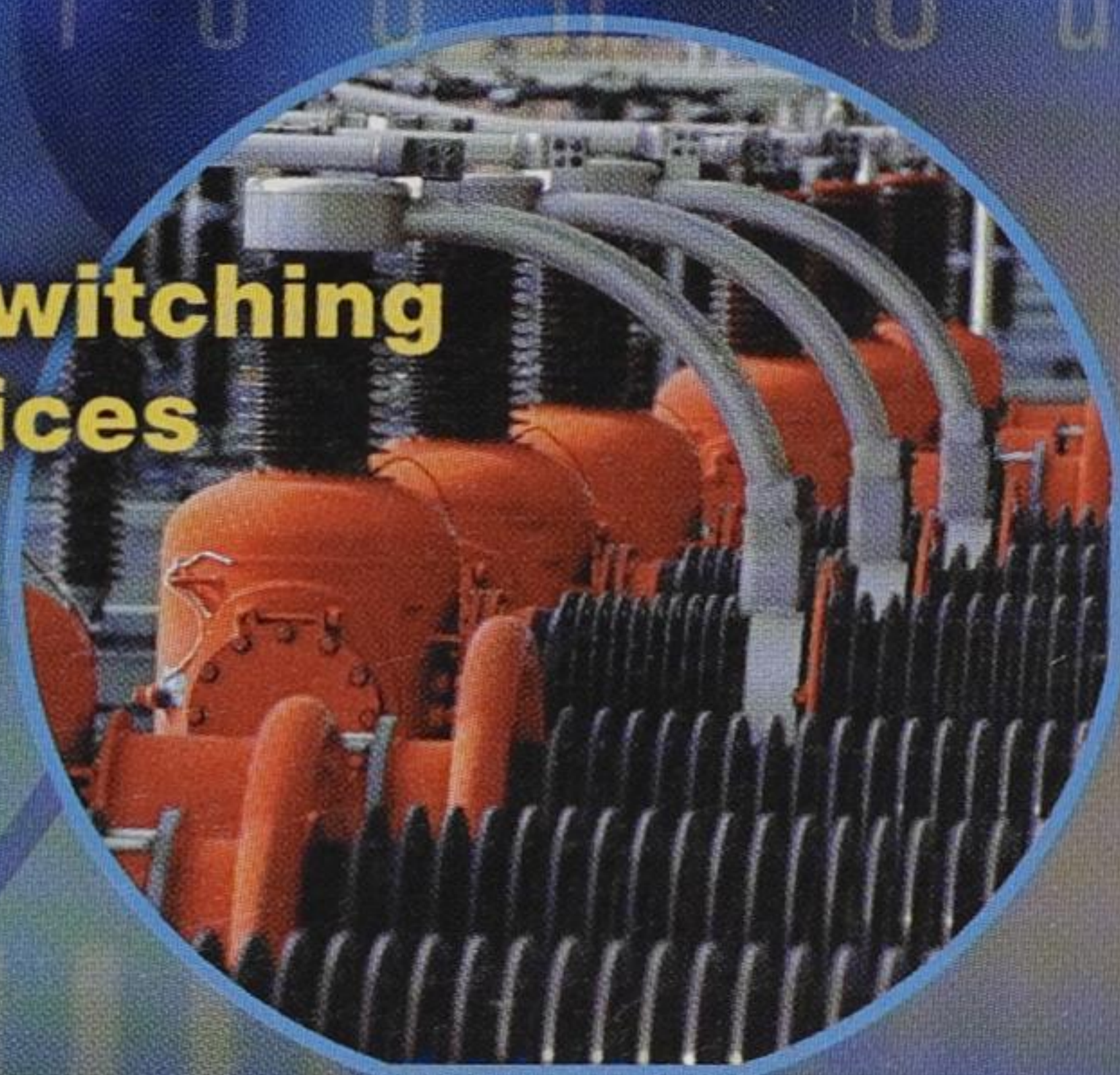
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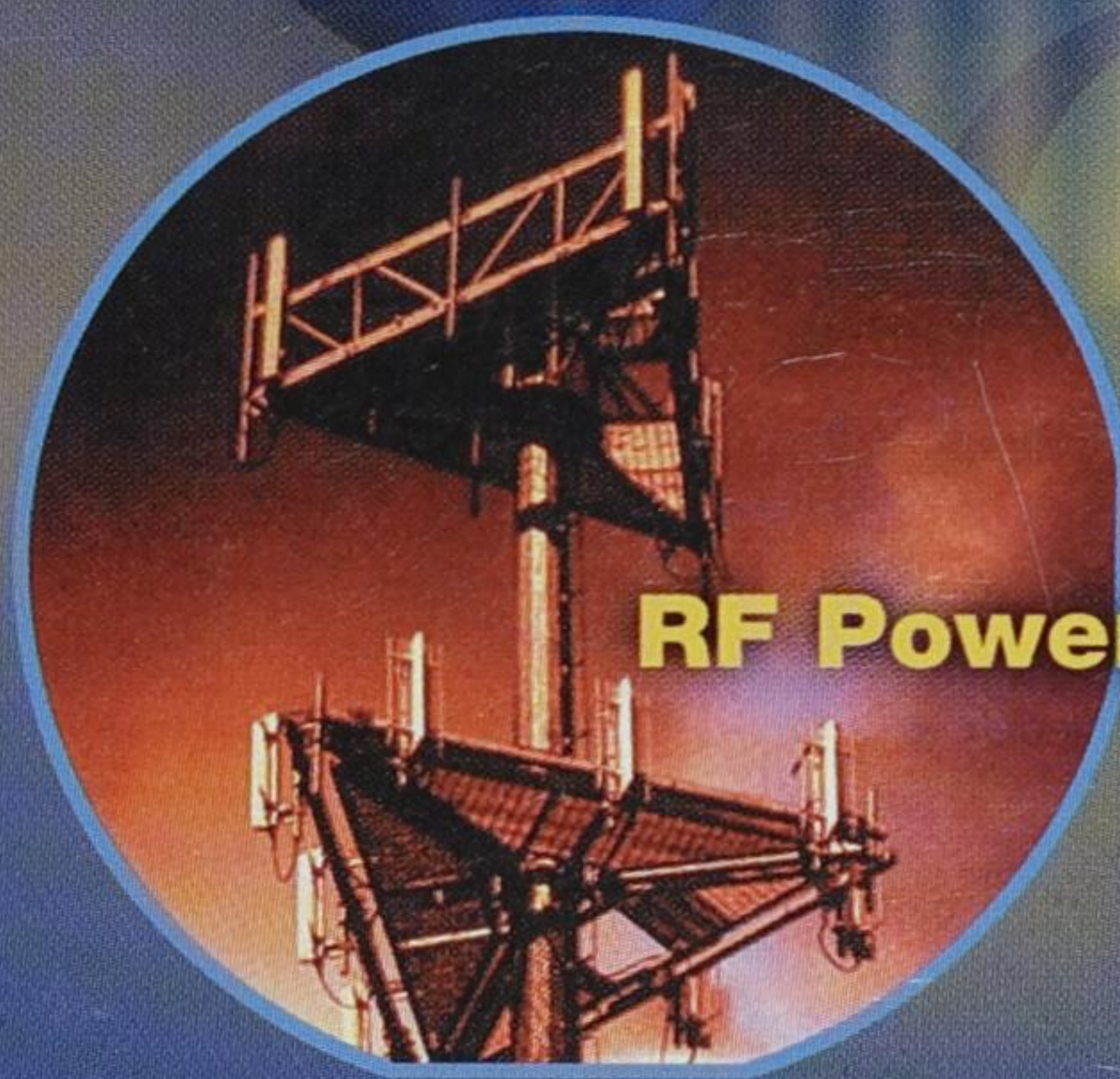
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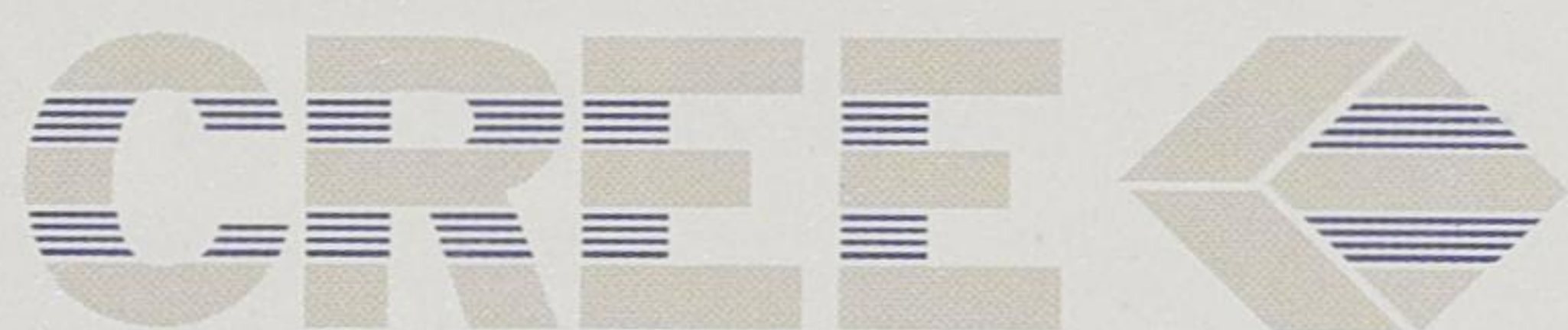
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