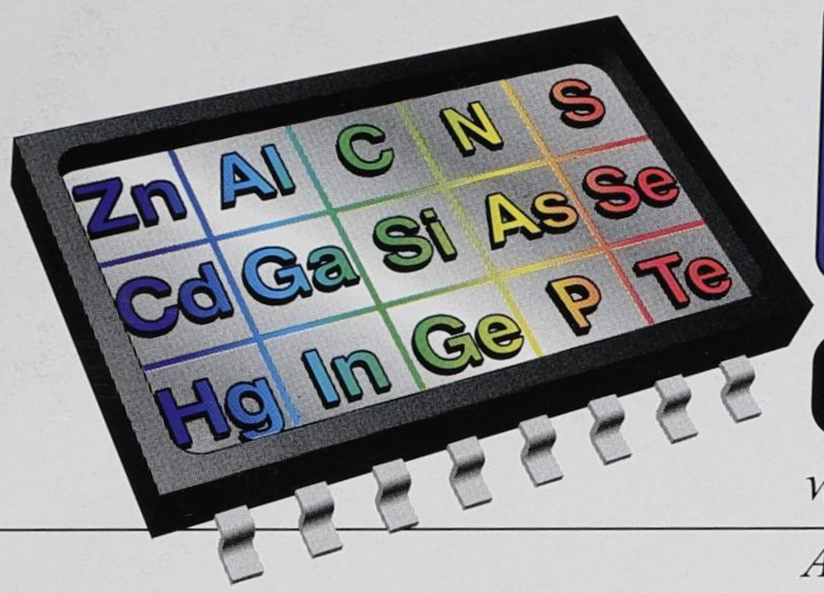


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August 2001 *Volume 7 Number 7*

Fab operation and control

Data, automation and SPC

Fiber glut debate rages
Nakamura book review
Is the wireless slump ending?
LightFair and MIOMD reports



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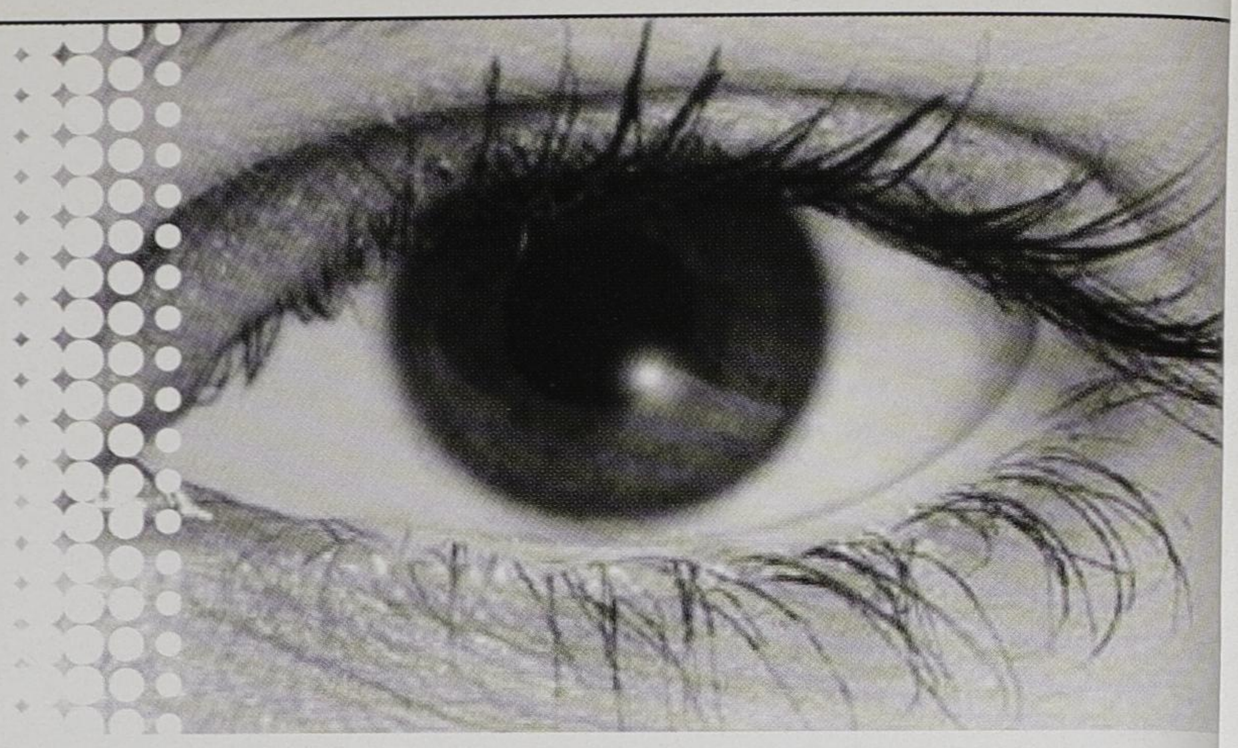
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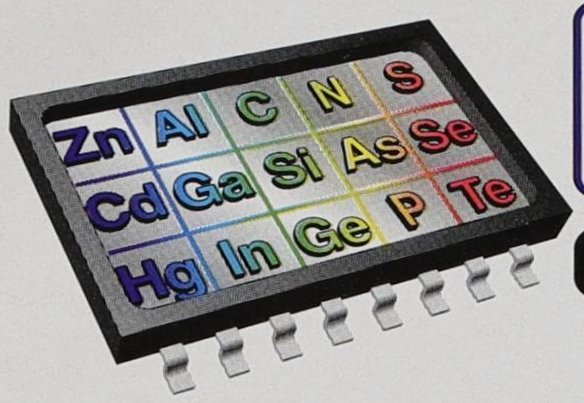
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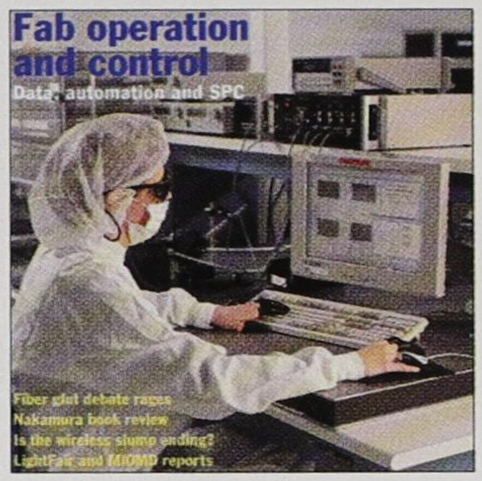
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AUGUST 2001 VOLUME 7 NUMBER 7



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COMPOUND SEMICONDUCTOR

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US mailing information: *Compound Semiconductor* (ISSN 1096-598X) is published 11 times a year for $95 by Institute of Physics Publishing, Dirac House, Temple Back, Bristol BS1 6BE, UK. Periodicals postage paid at Rahway, NJ. POSTMASTER: send address corrections to *Compound Semiconductor*, c/o BTB Mailflight Ltd, 365 Blair Rd, Avenel, NJ 07001. US agent: BTB Mailflight Ltd, 365 Blair Rd, Avenel, NJ 07001.

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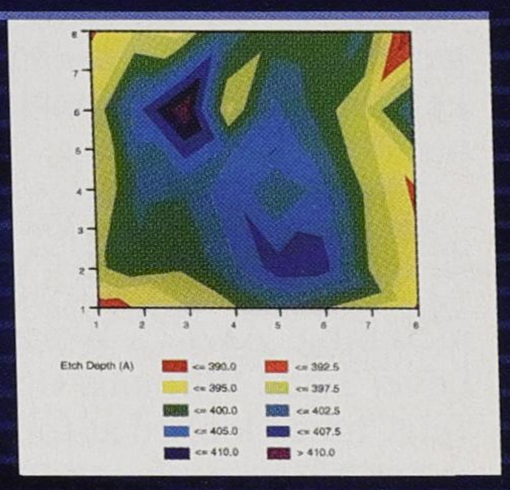


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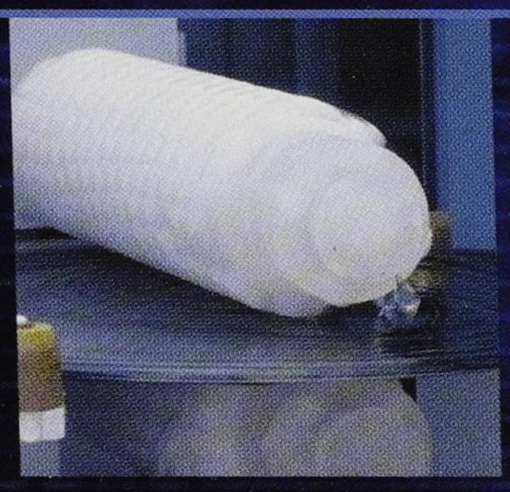




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Debate rages over fiber glut

Good news at last? Elsewhere in this issue we report on preliminary indications that the worst may be over for wireless chip manufacturers (see Portfolio). The fiber-optic sector is also seeing a glimmer of hope, in the form of a new study of fiber capacity utilization in the US released by TeleChoice Inc, a telecommunications consulting firm based in Tulsa, Oklahoma. TeleChoice says that it has developed a new model of fiber usage which indicates that many routes will soon need upgrading, with over 63% of the fiber routes between major US cities at or near full capacity. These findings stand in stark contrast to the general consensus in the financial markets that there is already far too much installed capacity.

The model TeleChoice developed is based on information it collected from 25 different fiber providers in the US, including AT&T, WorldCom, Qwest, Level 3 and Williams Communications. TeleChoice looked at routes between 12 major US cities that are most often used by all 25 companies, comparing the lit fiber capacity to projected peak business and consumer demand for voice and data transmission. On 14 of the 22 routes, current demand equals or exceeds 70% of total supply. According to TeleChoice, 70% utilization is the traditional benchmark that indicates that the carriers need to "light up" more fibers – which means more spending on fiber-optic components and related equipment.

Static on the line

These findings come hard on the heels of several media reports of a "fiber glut" in the US – including an analysis from Merrill Lynch which concludes that less than 3% of US fiber capacity is in use. The image that has been created in the popular press is of an enormous oversupply of capacity that will take years to work off.

Industry executives have been striking back in recent weeks, saying the amount of lit fiber is being over-estimated and that some analysts are mixing lit and dark fiber together inappropriately, thereby misconstruing the economic purpose of "dark fiber". (Since most of the cost in laying a cable comes from digging the trench, and not the cable itself, most companies add in as much fiber as possible when the trench is open, knowing that it may be years or even decades before it will be put into use.) Telecom carriers in particular have been arguing that the size of the "glut" is being overstated.

However, the opposite camp is quick to point to the rapidly declining prices for bandwidth as an indicator that supply and demand are indeed badly out of alignment. For example, Sprint offers long-distance service at two cents a minute, one-eighth what AT&T charged four years ago. *The Wall Street Journal* predicts that wholesale prices for bandwidth are expected to fall another 60% this year. And Qwest estimates that the price of a single fiber line – which many large enterprises lease for their own internal data traffic – has fallen from $5000 per mile in 1997 to $1200 this year.

The TeleChoice thesis

The TeleChoice report is also somewhat controversial, largely because it was funded in part by Williams Communications, one of the major carriers taking part in the study. This fact has led some commentators to suggest that it may be self-serving.

But TeleChoice executives are unfazed. President Christine Heckart, in a recent interview with the *Boston Globe*, said that the TeleChoice model, based on examination of actual traffic routes, rather than treating the entire US fiber infrastructure as one big pipeline, proves that the notion of a systemic glut "is just baloney. There may be a lot of unused capacity in the middle of Nebraska…but not in the high-growth corridors." TeleChoice found only three important routes that it would define as "significantly oversupplied" – New York to Chicago, Denver to Los Angeles and Los Angeles to San Francisco. These three are among the most popular US telecom corridors. But even that does not seem like bad news to TeleChoice. "Over the past several years, virtually every new network project has included creating capacity to overcome traditional shortages on these three routes," says Russ McGuire, chief strategy officer for TeleChoice. "Based on a conservative >>

First CS-MAX show draws large audience

A new conference series for the compound semiconductor industry got off to a successful start when the inaugural Compound Semiconductor Manufacturing Expo (CS-MAX) was held on July 9–11, 2001 at the Hynes Convention Center in Boston, MA. Over 850 people attended the three-day event, which included 95 papers in the Technical Program and over 100 companies in the Exhibit.

CS-MAX, which is organized by the staff of this magazine, is intended to fill the role that Semicon West and similar events play for the silicon industry. "We want to provide an annual showcase for the compound semiconductor industry," said Marie Meyer, chairman of CS-MAX 2001 and managing editor of *Compound Semiconductor*. "While there are already plenty of technical conferences in our industry, most concentrate on a single material system and most follow the traditional academic model and therefore tend to be very 'researchy'. CS-MAX is designed to provide a forum for ideas about improving high-volume manufacturing of all types of compound semiconductor devices."

The larger-than-expected turnout could be seen as a sign that interest in compound semiconductors is continuing to grow, despite the sharp slowdown in the economy. "Cut-backs in travel budgets reduced the number of attendees from some of the most well-established companies in the industry," said Meyer, "but an unexpectedly large number of new start-ups attended. Given what is going on in the markets right now, we were very pleased with the turn-out, and we think it bodes well for future years."

Conversations with many of the exhibitors confirmed the impression that start-ups are responsible for a large percentage of the current capital equipment spending, with bigger companies delaying further expansion of fab capacity until economic conditions improve.

CS-MAX is planned as an annual event from now on. The dates and location for the 2002 show will be announced in September.

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>> projection of applications demand growth, the excess capacity on these routes will be totally consumed within the next three to five years."

Commenting on the Merrill Lynch report, Heckart told the *Globe* "we're not saying these numbers are wrong, we're saying these numbers are completely useless". McGuire concurs, saying "the recent focus on aggregate supply, including lit and unlit fiber, instead of a route-by-route analysis, completely misses the important factors that drive the industry. The fact that over 63% of the key routes initially evaluated are over the new construction/activation threshold really underscores the fact that, from where the service provider sits, there is no nationwide glut of available lit fiber."

And while there is no denying the fact that carriers are having a hard time raising new capital for investment in their networks, McGuire says the supply and demand picture cannot justify that pattern of behavior on Wall Street. "The truth is there isn't a glut on most of the major routes on the long-haul network," McGuire said. "The lack of carrier spending seems to have little to do with how much capacity is in the network. It's more about how they are managing their business."

Corning closes Nashua Lasertron facility before it opens

Corning will make significant cuts to its Photonic Technologies business in response to what the company describes as severely reduced market demand for photonic components and modules. The plan involves closing three plants, including the Corning Lasertron facility in Nashua, New Hampshire, which was scheduled to begin manufacturing active components this summer.

"With the dramatic reduction of infrastructure spending across the telecommunications industry, and our expectation that this market downturn could last 12 to 18 months, we are taking decisive action to lower costs and improve the future profitability of our Photonic Technologies business," said John Loose, Corning's president and CEO.

Nashua facility never finished

Construction work at the Nashua facility began late last year, as part of an expansion of Corning Lasertron's capacity for active components. Funding came from a company-wide $225 million investment that included spending $45 million to double capacity at Lasertron's main facility in Bedford, Massachusetts. The investment was intended to greatly increase the production of 980 nm pump lasers used in EDFAs, as well as DFB and Fabry–Perot source lasers, and receivers.

According to a company spokesperson, the Nashua building remains empty and was never opened; it is now being considered for sale.

Corning will also close its photonic module facilities in Benton Township, PA and Corning NetOptix, a supplier of optical thin-film coatings and components with operations in Natick, MA. These changes will be completed by the end of the year. The company also intends to scale back production at Erwin Park, NY, which makes optical amplifiers, and across the remainder of its photonics operations. This will result in a workforce reduction of 1000. So far this year Corning has eliminated 3500 photonics positions, and with the current round of layoffs expects its total reductions in 2001 to reach 5900 – around 15% of the 40 000 workforce.

"Our Photonic Technologies business has grown at a rate of 75–100% per year for the past three years, and we originally anticipated similar growth again this year," said Loose. "As a result, we added significant capacity and fixed costs to meet expected market demand that has not materialized." Corning now expects sales this year in the range of $600–700 million for this business, with significantly lower sales of optical amplifiers and other photonic components. "The abruptness of this industry downturn is unprecedented," says Loose. "Nevertheless, we have to deal decisively with these new market realities."

Conexant cuts will not affect GaAs production capability

Conexant Systems has announced cost-cutting initiatives intended to bring its operations into line with revenue expectations in the current industry downturn. A major step will be the adoption of a fabless model for next-generation CMOS processes beyond the company's current 0.13 μm capability. Conexant will resize its silicon fab in Newport Beach, California to match expected demand for specialty processes, including SiGe. "This strategic realignment will allow us to avoid the ever-increasing capital requirements of mainstream digital CMOS process development and manufacturing," explained Dwight Decker, chairman and CEO. "Instead, we can increase the allocation of our resources toward the design and marketing of innovative communications semiconductor products."

The good news for GaAs is that the company will continue to operate its wafer manufacturing facility in Newbury Park, California, and invest in new technology. The fab manufactures GaAs HBTs for power amplifiers, RF subsystems and complete systems for CDMA, GSM and TDMA digital cellular handsets.

Last year Conexant announced a plan to split into two separate communications semiconductor companies. The GaAs fab is part of Conexant's personal networking business, which includes products for wireless communications. The other business, Internet infrastructure, is currently operating under the name Mindspeed Technologies. Mindspeed sells GaAs-based fiber-optic components such as laser drivers, clock and data recovery ICs and crosspoint switches, although it does not operate its own GaAs fab.

While the cost reductions were initiated to improve near-term profitability, longer-term prospects seem good. "We are confident in the long-term growth prospects of the communications markets we address with our personal networking and Internet infrastructure businesses," said Decker. "We remain committed to completing the separation of Conexant into two independent, publicly traded companies as soon as business and market conditions are clearly on a recovery path."

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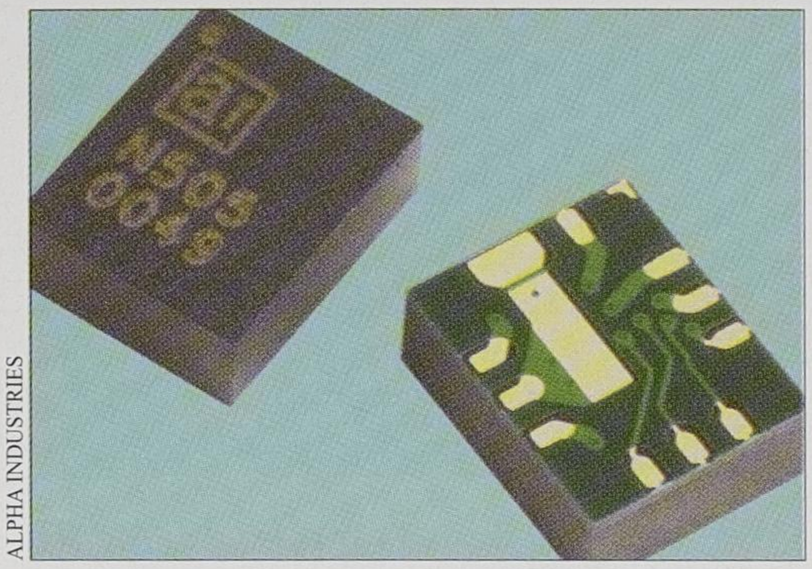
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The Technology of Choice for Compound Semiconductors

Alpha forms switch/filter module alliance

Alpha Industries (Woburn, MA) has formed a strategic alliance with Munich-based SAW filter manufacturer EPCOS to co-develop, manufacture and market switch/filter modules for wireless handsets. EPCOS is a leading European manufacturer of passive components, including LTCC (low-temperature co-fired ceramic) technology – an important integration scheme for passive and active radio-frequency (RF) components.

The agreement underscores Alpha's product roadmap, which is already firmly seated in the company's Alpha Integration Platform approach (see *Compound Semiconductor* December/January 2000/2001, p32). The move also reflects the growing trend among component suppliers to add more value by producing modules with increased functionality. An example is TriQuint's recent merger with Sawtek to acquire SAW filter technology (see *Compound Semiconductor* June 2001, p4).



ALPHA INDUSTRIES

Alpha's switch/filter platform will be integrated into modules with SAW filter and LTCC technology from EPCOS.

"Consistent with our strategy of providing highly integrated RF modules for the mobile phone market, we are partnering with EPCOS to develop technology that dramatically enhances module performance and manufacturability," said David Aldrich, Alpha's president and CEO. "This alliance provides an essential module building-block that secures Alpha's position as the world's leading provider of RF front-end solutions."

Alpha's integration platform addresses manufacturing, packaging and testing issues for multifunction RF modules, and employs the company's InGaP HBT PAs and GaAs switches, SAW filters, passive devices and control logic circuitry. Initial module designs will address dual-band and eventually tri-band GSM handsets, with the first products to be shipped by September 2001.

"Combining switch and filter products into a single, easy-to-use LTCC package offers OEMs shorter design lead times and enhanced functionality. This allows reduced time-to-market for their newest handset models," Aldrich continued.

"Ultimately, we see a competitive advantage in our ability to produce modules that occupy a smaller footprint, provide longer battery life and a better overall RF performance than competing technologies."

Mitsubishi–Kyocera dual-band module streamlines handset designs

Mitsubishi Electric and Kyocera, a Japanese manufacturer of CDMA wireless handsets, have unveiled a dual-band E-GSM/DCS transmit module for mobile phone applications. Available in a $12 \times 10 \times 2.0\,mm^3$ package, the new module includes the antenna switch, PA and coupler components, in addition to an electrostatic discharge protection circuit. The high level of integration makes the design of external impedance-matching circuitry unnecessary.

The module is said to achieve power efficiency improvements at the antenna portion by combining Mitsubishi's high-efficiency GaAs HBT power amplifier with Kyocera's LTCC and low-loss antenna switch module, and by optimizing the coupler and matching circuit design.

The module achieves 43.4% PAE for E-GSM transmission at 33 dBm, and 31.1% at 30 dBm in the DCS band. Mitsubishi has begun product sampling, and expects to enter volume production in February 2002, followed closely by Kyocera.

"This collaboration streamlines the handset design process," said Mitsubishi's Bryon Gutow, marketing manager for microwave and RF products. "Making the external impedance matching circuit design unnecessary allows the designer to focus on activities that drive their products to market faster."

RFMD to open packaging facility in Beijing industrial park

RF Micro Devices (RFMD) will open a packaging facility in China at the Beijing Xingwang Industrial Park, a site established over a year ago by Nokia in conjunction with the Chinese government and local economic development representatives. RFMD is the first supplier to be invited by Nokia to participate in the park, which will support the latter company's business in China and other markets.

RFMD's facility will contain test and tape and reel operations, and will serve as the final stage of assembly for components manufactured at the company's facility in Greensboro, North Carolina.

"The Beijing Xingwang Industrial Park was established to further strengthen our market position in China," said Petri Vainola, Nokia's VP of sourcing and procurement for the Asia-Pacific region. "RFMD is an important supplier, and we look forward to their participation in the park and their contribution to the success of our efforts in the region."

Occupants of the new industrial park will consist of Nokia's preferred suppliers, and RFMD expects its presence to drive further growth in China. In addition to supplying Nokia, the facility's location will enable RFMD to supply other handset manufacturers in China, which last year became the world's second largest mobile phone market behind the US. RFMD will begin construction of its facility in the fall of 2001, and expects the site to be completed within 12 months.

Motorola supplies Beijing CATV company

Motorola's Broadband Communications Sector (Horsham, PA) is to supply Beijing Gehua CATV Network Co Ltd with its Starline RF amplifier, OmniStar optical headend, and SG optical nodes. The agreement will enable Beijing Gehua to upgrade its two-way network and offer video, voice, and high-speed Internet access to around 600 000 users in the region. Motorola's broadband line extender, mini-bridger amplifier and broadband telecommunications amplifiers are based on the company's enhanced-GaAs (or E-GaAs) hybrid technology.

"The superiority of Motorola's products, combined with the expertise of their technical team, helps ensure our success in this project as well as in future ventures," said Gao Fengquian, chairman and GM for Beijing Gehua. "With this robust two-way HFC platform, we will be able to provide high-speed data services with cable modem and interactive multimedia services over digital set-top boxes."

Raytheon supplies PAs to Korean CDMA handset maker

Raytheon's RF Components Division (Andover, MA) has entered into a high-volume production agreement to supply Korean handset manufacturer LG Electronics Co Ltd with its RMPA 1951 GaAs HBT power amplifier. LG Electronics is one of the largest wireless telephone manufacturers in Korea, and has earmarked the TM910 dual-band tri-mode handset for the US CDMA market.

The company's RMPA 1951 is a small outline PA module designed for PCS and WLL applications that incorporates a DC power management capability designed to extend battery life. During peak telephone usage, current consumption is lowered by more than 60% and small signal gain by up to 10 dB, as a result of the amplifier's single reference control voltage. The device achieves a PAE of 35% at an average output power level of +29 dBm.



RAYTHEON RF COMPONENTS

With production slated to begin in October, Raytheon says the agreement marks the first in a series of anticipated production orders with LG Electronics.

In more news, Raytheon has begun sampling its recently announced RTPA 5250 power amplifier/switching module, which targets wireless LAN applications with data rates up to 54 Mbit/s (see *Compound Semiconductor* April 2001, p32). Manufactured with Raytheon's 0.5 μm PHEMT process, the module meets IEEE 802.11(a) and Hiperlan 2 standards, and delivers maximum allowable output power for indoor applications in the 5.15–5.25 GHz band. Production deliveries are expected in the third quarter of the year.

Microsemi ships InGaP HBT amplifiers for WCDMA handsets

Microsemi (Irvine, CA) has shipped its first InGaP HBT power amplifiers for WCDMA handset applications. The company introduced its first GaAs PA product late in 2000. Initial prototype shipments of the new WCDMA PAs are expected to total less than $1 million in the company's FY2001, and volume production is slated for January 2002.

The MWS11PH41 is a flip-chip bonded InGaP HBT IC offered in bare die, with external I/O matching in a 3 × 3 mm^2 chip-scale package. A 6 × 6 mm^2 matched module will be released later this summer. The device is an optimized two-stage design that achieves a PAE of 41% and an idle current of 38 mA; both are key factors affecting battery size and talk time.

IBM claims record for Si-based transistor

IBM has announced modifications to its SiGe process that will allow the manufacture of ICs with speeds of 100 GHz within two years. The company has developed what it claims to be the world's fastest silicon-based transistor, which can reach speeds of 210 GHz while drawing a current of just 1 mA. This represents a 50% reduction in power consumption and 80% performance improvement over existing designs.

The latest design incorporates a thinner base region in the HBT structure, shortening the electrical path and leading to higher operating speed. IBM believes that the new design "gives SiGe a new performance plateau, opening the door to further penetration of SiGe devices into the networking equipment market".

Applied Micro Circuits Corporation (AMCC) is already applying IBM's SiGe process to components for optical networking applications and is looking to the improved process to provide the performance needed for OC-768 (40 Gbit/s) parts, such as transimpedance amplifiers and multiplexers (see *Compound Semiconductor* June 2001, p29).

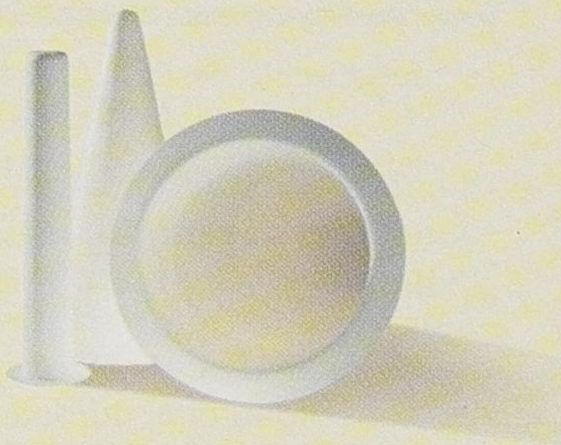
Atmel offers 45 GHz SiGe process

Atmel (San Jose, CA) has unveiled an advanced SiGe BiCMOS process technology developed for telecommunications and high-speed data applications up to 12 GHz. The process offers bipolar speeds of up to 45 GHz, 3.3 V CMOS operation with a 5.0 V I/O option, and a complete digital standard cell library. The AT46000 process is supported by a Cadence design kit and is the first of several processes offered in Atmel's SiGe BiCMOS roadmap.



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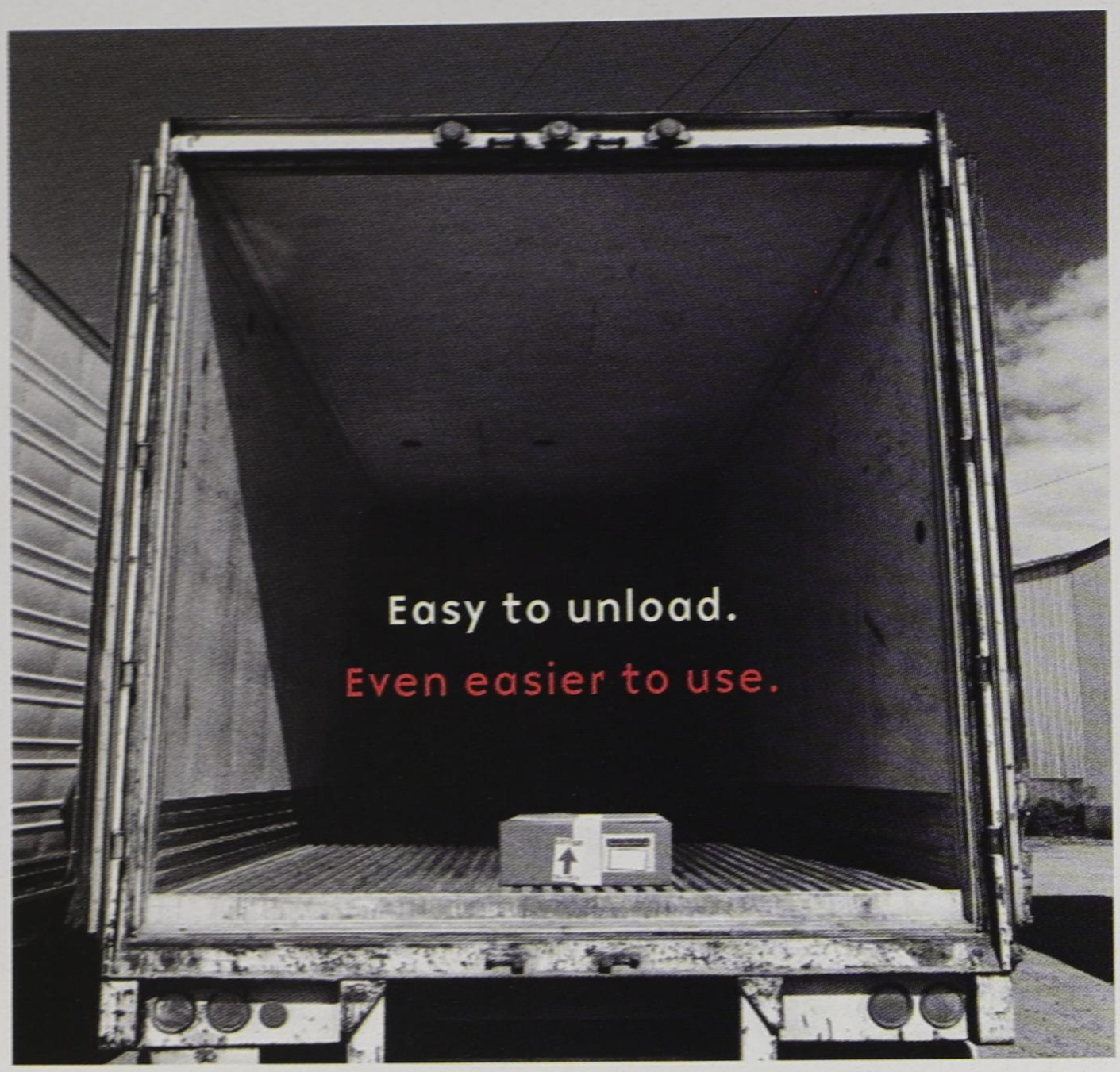
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Memscap establishes active subsidiary

Memscap (Grenoble, France) has established in Finland a subsidiary that will focus on active optical components for metropolitan and access networks. The new company, Memscap Oy, has entered into a licensing and development agreement with Finland's Optoelectronics Research Centre (ORC) to enable Memscap to extend its product line to include source components for the growing plastic optical fiber (POF) market. POF is seen as an inexpensive means of connecting metro and local loops with optical fiber for high-bandwidth data transmission.

Under the agreement, Memscap will license from ORC several products that are immediately suitable for commercialization. These include 650 nm resonant cavity (RC) LEDs and 690 nm VCSELs. Memscap and ORC are also working on a range of edge emitters and VCSELs covering the transmission windows for most fiber types. MEMS-based tunable sources for WDM applications are also in development.

Initially ORC will provide intellectual property and skilled staff for low-volume production of laser components, while Memscap ramps up production capacity over the next 18 months.

"Memscap's RC-LEDs in particular offer advantages for short-haul POF transmission," said Mihail Dumitrescu, director of active optical components at Memscap Oy. "These benefits include operation at the fibers' attenuation minimum, 30% coupling efficiency without any supplementary optics, and eye safety. These RC-LEDs hold the world record in speed for red wavelength spontaneous emitters, achieving error-free transmission rates beyond 622 Mbit/s."

Bandwidth9 adds capacity and collaborates with Corning

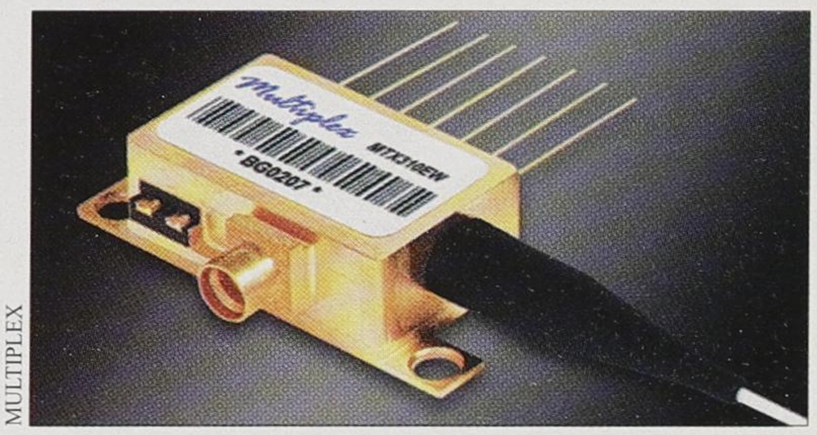
Tunable laser manufacturer Bandwidth9 has acquired a fourth MBE reactor, providing a total production capacity exceeding 100 000 die per month. The company uses a patented MBE process to grow tunable laser structures on 2 inch GaAs wafers, and is able to fabricate lasers and modulators in a single monolithic structure. Bandwidth9 is sampling prototypes of its first product, MetroFlex, an OC-48 transmitter subsystem that is tunable across over 40 wavelengths in the 1550–1600 nm band (see *Compound Semiconductor* June 2001, p49).

"In addition to perfecting our tunable laser technology, Bandwidth9's other key goal is to build a world-class, high-volume manufacturing capacity," said Hatch Graham, chairman and CEO of Bandwidth9. "Our vertically integrated manufacturing capabilities allow us to make and assemble complete optical subsystems in-house, reducing costs and shortening our customers' time to market."

In a further move, Bandwidth9 and Corning have announced a collaboration to explore the combination of Corning's MetroCore optical fiber and Bandwidth9's MetroFlex module. The companies claim that initial test results show that the products maintain excellent optical signal quality over metro application distances. The companies intend to continue advancing the interoperability of their products, making further test results and design information available later this year.

First 1310 nm EML from Multiplex

Multiplex (South Plainfield, NJ) has introduced the first commercially available 10 Gbit/s electro-absorption modulated laser (EML) operating at 1310 nm. EML sources are relatively common at 1550 nm, while 1310 nm systems generally use directly modulated DFB lasers. Multiplex believes that in the future 1310 nm EML transmitters will be used with Raman amplifiers in the S-band, taking advantage of the near-zero dispersion property of fiber near 1310 nm. Amplification using EDFAs is restricted to the C- and L-bands in the 1550 nm window.



MULTIPLEX

Quantum dot laser company wins $6 million in seed funding

Zia Laser Inc, a company formed to develop quantum dot semiconductor lasers for the datacom and telecoms markets, has received $6 million in seed round funding from two venture capital companies, Prism Venture Partners and RWI Group.

Zia Laser is located in Albuquerque, New Mexico, and was founded by faculty members and research scientists at the Center for High Technology Materials at the University of New Mexico. The founders include Luke Lester, Petros Varangis, Timothy Newell, Kevin Malloy, Andreas Stintz, and Allen Gray. The company's interim CEO is Tom Brennan, co-founder and former president of Micro-Optical Devices (MODE), which was acquired by Emcore in 1997.

The company says that it will use the money from this initial funding round to hire key staff, build corporate infrastructure and expand product development. Compared to the current industry standard, quantum dot lasers exhibit increased wavelength tunability and improved electronic properties, thereby offering the potential to provide optical networking subsystems with superior performance at a fraction of the present cost.

Intense Photonics secures first-round funds

Intense Photonics of Glasgow, UK, has received $11 million of first-round funding from venture capitalists 3i and ACT. The financing will help to commercialize Intense's technology for photonic integrated circuits (PICs). The company's proprietary quantum well intermixing (QWI) process allows Intense to address market demands for lower cost and higher performance by increasing levels of monolithic integration and adding functionality to discrete components for hybrid assembly (see *Compound Semiconductor* May 2001, p70).

The QWI technology has already been trialled on a number of device types including lasers, amplifiers, filters, and switches. Intense has announced its first PIC (a 980 nm pump laser), exploiting the integration capability of QWI to manufacture a high-yield chip. "Integration is key to the development of optical communications, and monolithic IC technologies offer a practical platform for delivering it," said Andrew Davison of 3i. "We view Intense Photonics' technology as among those fundamental to the successful evolution of the industry."

The market for optical components used in DWDM systems is forecast to grow to $13.6 billion by 2004 according to RHK. Driving this growth is the increased use of active components and the replacement of multiple discrete components with monolithic multifunction components. Intense Photonics is aiming to capture 20% of its target component sectors within four years.

DuPont facility acquisition

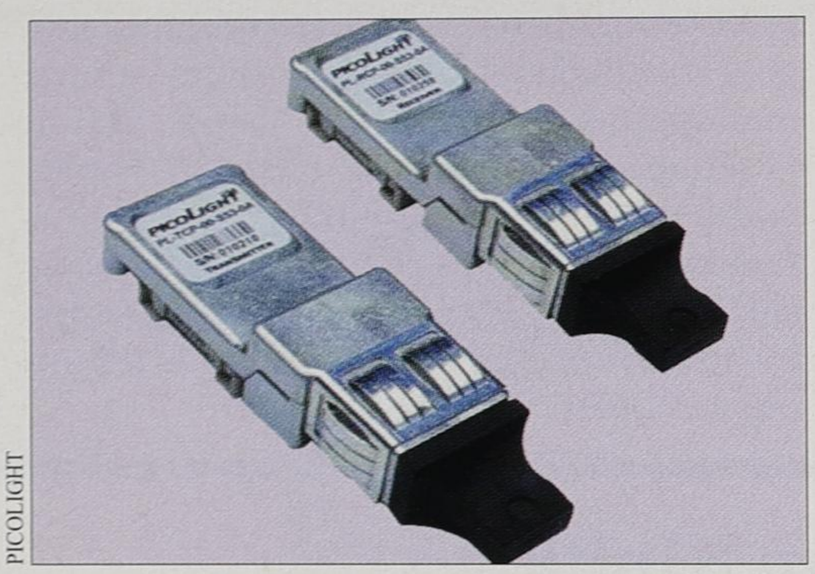
Just a week after its funding announcement, Intense acquired the DuPont photomask facility in Hamilton, Scotland, for an undisclosed sum. The purchase gives Intense the sophisticated manufacturing facilities it needs for the commercialization of its QWI-based devices. The plant, which is only three years old, has 3800 sq. ft of class-one clean room area and a further 13 000 sq. ft of manufacturing and office space. The company will be transferring staff and equipment from its Glasgow laboratories, and expects to have the site operational in September 2001.

"The acquisition not only provides an ideal facility and capability from which to drive growth, but reduces development timescales," said 3i's Chris Hodges.

Picolight ramps production of 30 Gbit/s parallel optical module

Picolight has commenced volume production of a 30 Gbit/s parallel optical interconnect module, which features a snap-on connector for easy integration on back-plane circuit cards of large switches. The VCSEL-based module targets data "bottlenecks" in core routers, switches and cross-connect equipment used in points of presence, central offices, large data centers and MAN hubs.

The module transmits data using an array of 12 parallel oxide-confined 850 nm VCSELs, each operating at data rates of 2.7 Gbit/s, and incorporates a scalable, low-cost ball grid array (BGA) connector that allows the number of ports on a line card to be quickly changed.



PICOLIGHT

Picolight says the device is suitable for very-short-reach links, and features a footprint that is only twice the size of industry-standard 1 Gbit/s small form factor transceivers. The power dissipation is kept to 2 W per transceiver module at the 30 Gbit/s data rate.

Picolight operates a 30 000 sq. ft vertically integrated manufacturing facility in Boulder, Colorado, and is poised to relocate to a second site of similar size in neighboring Louisville. This new facility will house all of Picolight's manufacturing operations, while other functions will remain in Boulder.

Scientists calculate limits of fiber-optic communications

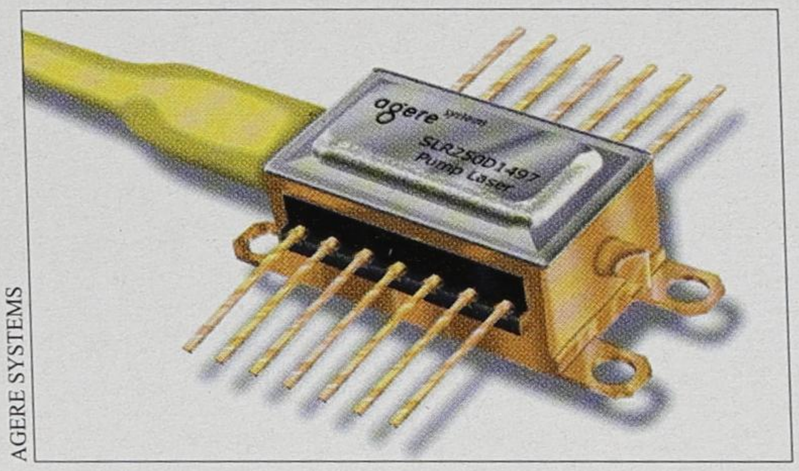
The ability to send multiple wavelengths down a single fiber in DWDM systems has greatly increased the capacity of fiber-optic networks. However, the adoption of DWDM has imposed another set of limitations to capacity. In a letter to *Nature*, Partha Mitra and Jason Stark of Lucent Technologies' Bell Labs (Murray Hill, NJ) estimated the fundamental information capacity of typical optical fibers in DWDM systems (*Nature* 2001 **411** p1027). The capacity of fibers is ultimately limited by the noise introduced by optical amplifiers and the nonlinear response of the fibers. Current optical systems can transmit less than 2 Tbit/s, with laboratory experiments now demonstrating 10 Tbit/s. Mitra and Stark calculate that it is theoretically possible to transmit 100 Tbit/s down a single fiber.

Fiber cores exhibit a nonlinear response to the range of wavelengths used in DWDM systems. Mitra and Stark claim that the information capacity of a fiber in a DWDM system is mostly limited by an effect called cross-phase modulation (CPM), in which each signal in the fiber disturbs neighboring signals. The optical waves in the fiber are intensity-modulated to encode the information in the signal. CPM arises because the modulated intensity perturbs the refractive index at the fiber core, thereby distorting the other signals present.

As the power of an optical signal is increased, the information capacity also increases. This stops at a point where CPM effects begin to rise rapidly, causing a steep drop in capacity. The maximum capacity of the fiber increases with the bandwidth of each signal and the spacing between individual signals. Fiber capacity decreases with the total number of signals and also with the number of amplifiers in the system.

Agere wins 980 nm pump laser contract

TyCom, a leading network provider, has selected Agere's new 980 nm pump lasers for use in its undersea optical amplifiers. Valued at $70 million over the next 12 months, the contract is part of a three-year agreement signed earlier this year. This called for Agere to supply optical components for TyCom's Global Network project, the first phase of which is expected to span 90 000 km and provide capacity in excess of 1 Tbit/s to more than 30 major cities around the world. Agere will supply its new LP200 pump, an uncooled 980 nm Fabry–Perot laser with external fiber Bragg grating wavelength stabilization. The GaAs-based device offers an output of 200 mW to pump an EDFA, and requires a drive current of 350 mA.



AGERE SYSTEMS

New 1480 nm Raman pump

Agere has introduced what it claims to be the industry's first pump laser for Raman amplification in undersea networks. The SLR250 (see above) is an uncooled, high-power Fabry-Perot laser stabilized with an external fiber Bragg grating, which ensures a smaller wavelength shift due to fluctuations in operating temperature. The InP-based laser is available in 1480 nm and other 14xx nm wavelengths, and supports a fiber output power of up to 250 mW. Currently sampling, the new pump is expected to enter production in early 2002.

"Agere's long-term focus on undersea components provides devices with excellent reliability," said spokesperson Stefan Rochus. "Agere has shipped more than 40 000 of its 980 nm pump lasers for submerged applications, and has accumulated more than 132 million hours of service without one failure."

GTRAN ships 40 Gbit/s InP ICs

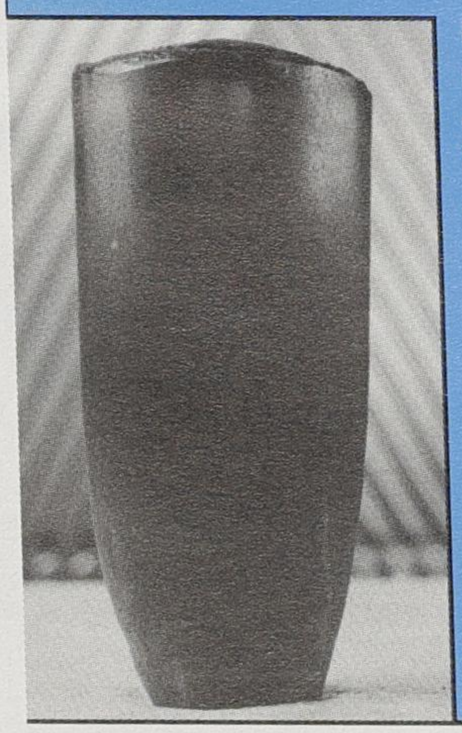
GTRAN (Westlake Village, CA) has begun shipping its first 40 Gbit/s components for SONET applications, including transimpedance amplifiers (TIAs) and limiting amplifiers. The devices are manufactured by foundry companies, including GCS, using GTRAN's recently released InP HBT process, which has achieved f_t and f_{max} values of 150 GHz and 200 GHz, respectively.

GTRAN's TIA achieves a transimpedance of 300 Ω at a bandwidth of 45 GHz, operates with dual positive and negative 3.3 V power supplies and dissipates 150 mW. The company's limiting amplifier offers a bandwidth of 40 GHz, and achieves a differential gain greater than 30 dB with an input sensitivity of 10 mV. The device employs a single –4.2 V supply with a power dissipation of 500 mW. The first units of the limiting amplifier are available as surface-mount ICs in a leaded ceramic package to ensure easy integration.

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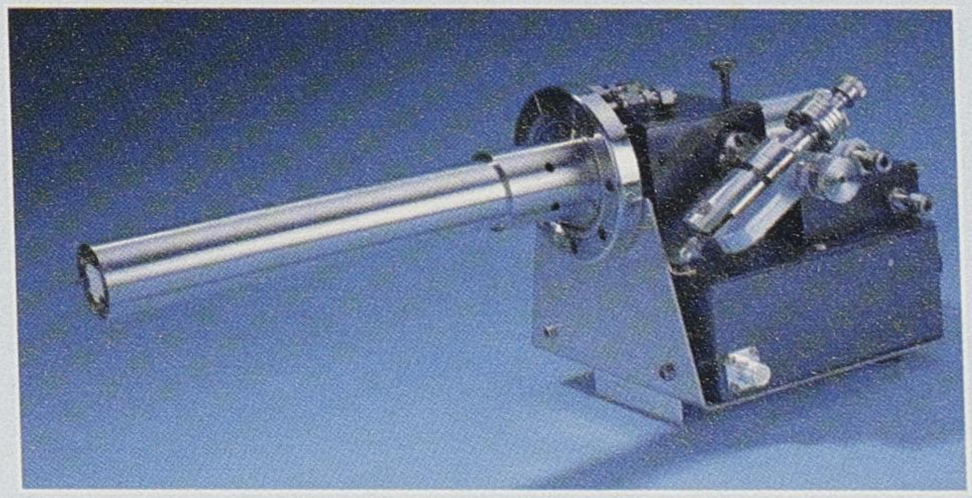


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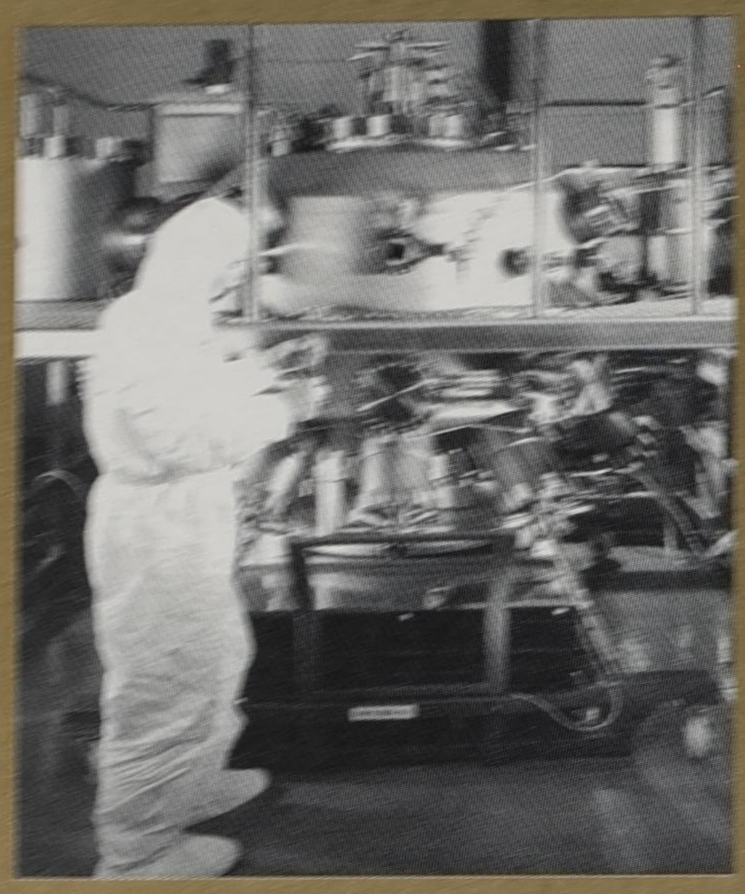
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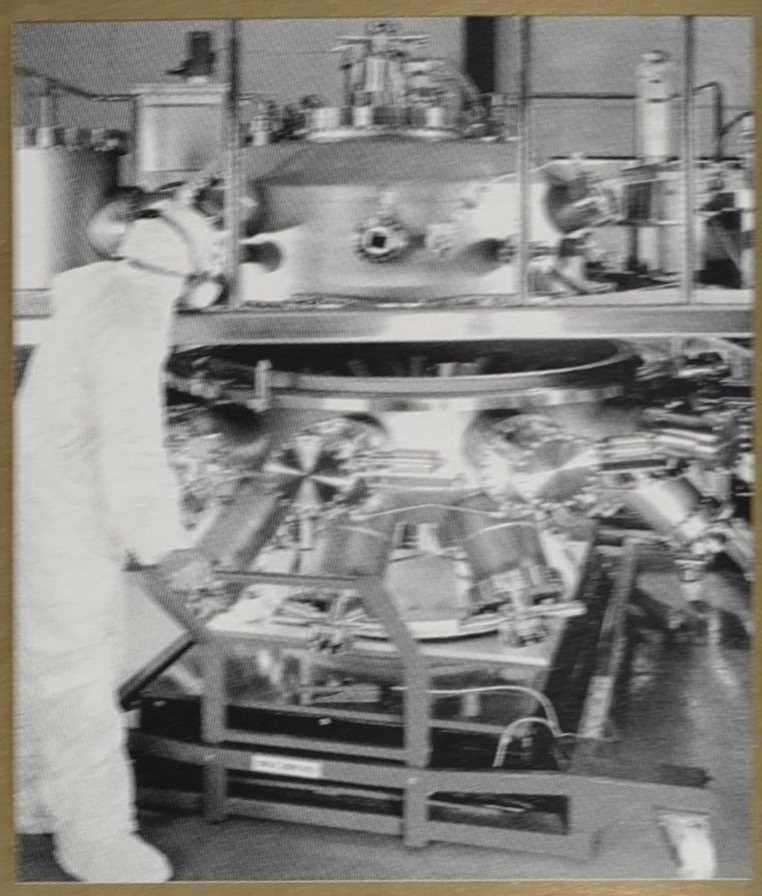
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2 *An hydraulic trolley is rolled underneath and takes the weight of the bottom half of the growth chamber. The four locating bolts are quickly removed.*

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3 *The trolley is lowered at the touch of a button and the entire lower section of the growth chanber is wheeled out for easy cleaning and source loading.*

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Flextronics manufactures for K2 and Gore

Flextronics has received subcontracts to manufacture VCSEL transceivers for W L Gore and external cavity laser modules for K2 Optronics. Based in Singapore, Flextronics Photonics is one of the world's largest non-captive photonic manufacturers, offering design, process development and volume manufacturing of active and passive components.

"Flextronics Photonics has established itself as the leading component contract manufacturer and is committed to providing the manufacturing automation processes that the metro optical networking industry needs to succeed," said Bill Daniher, K2's VP of operations. "Flextronics also provides several of the critical packaging design elements, which benefits our time-to-market and offers a value-added manufacturing partnership."

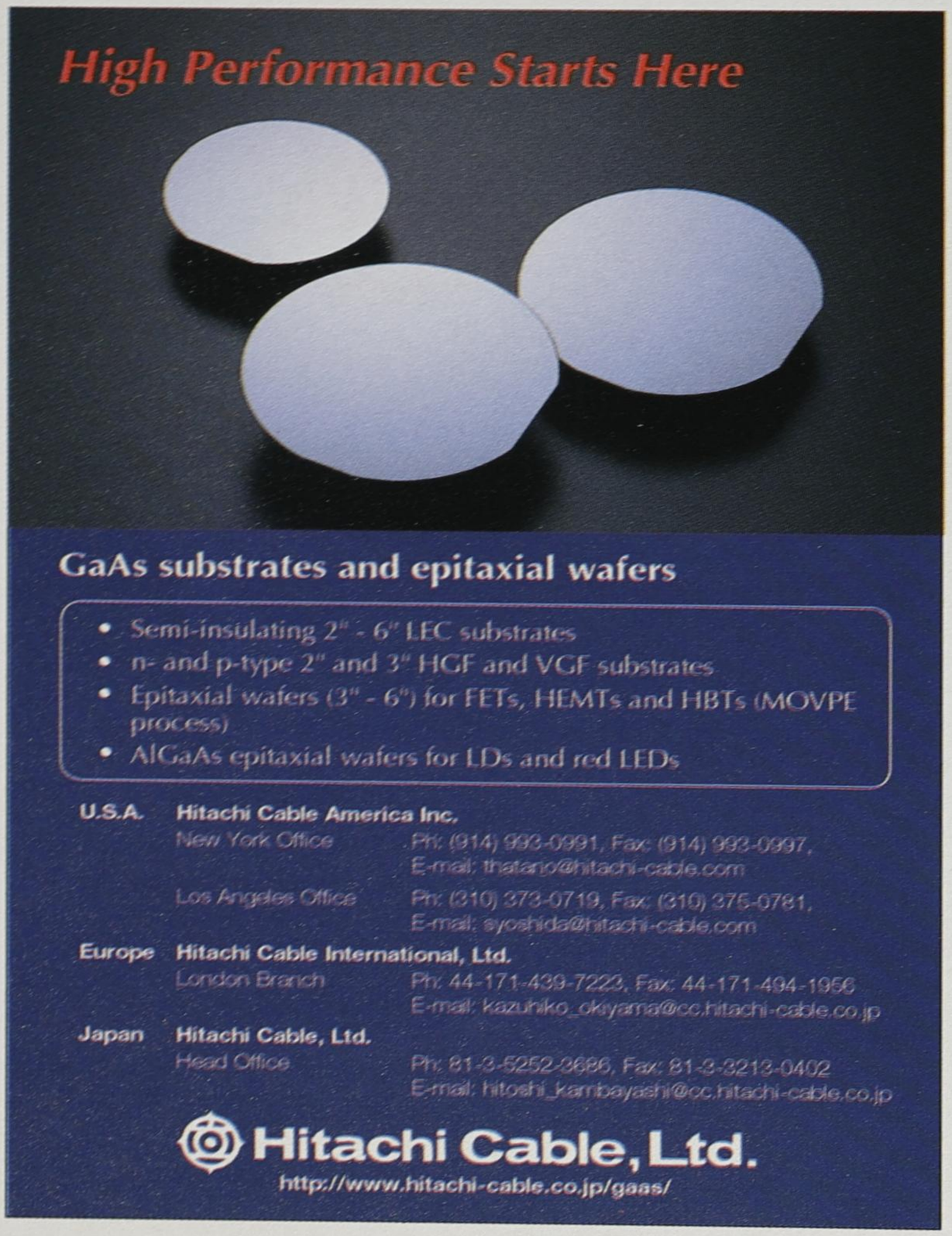
nLIGHTEN goes to higher speeds

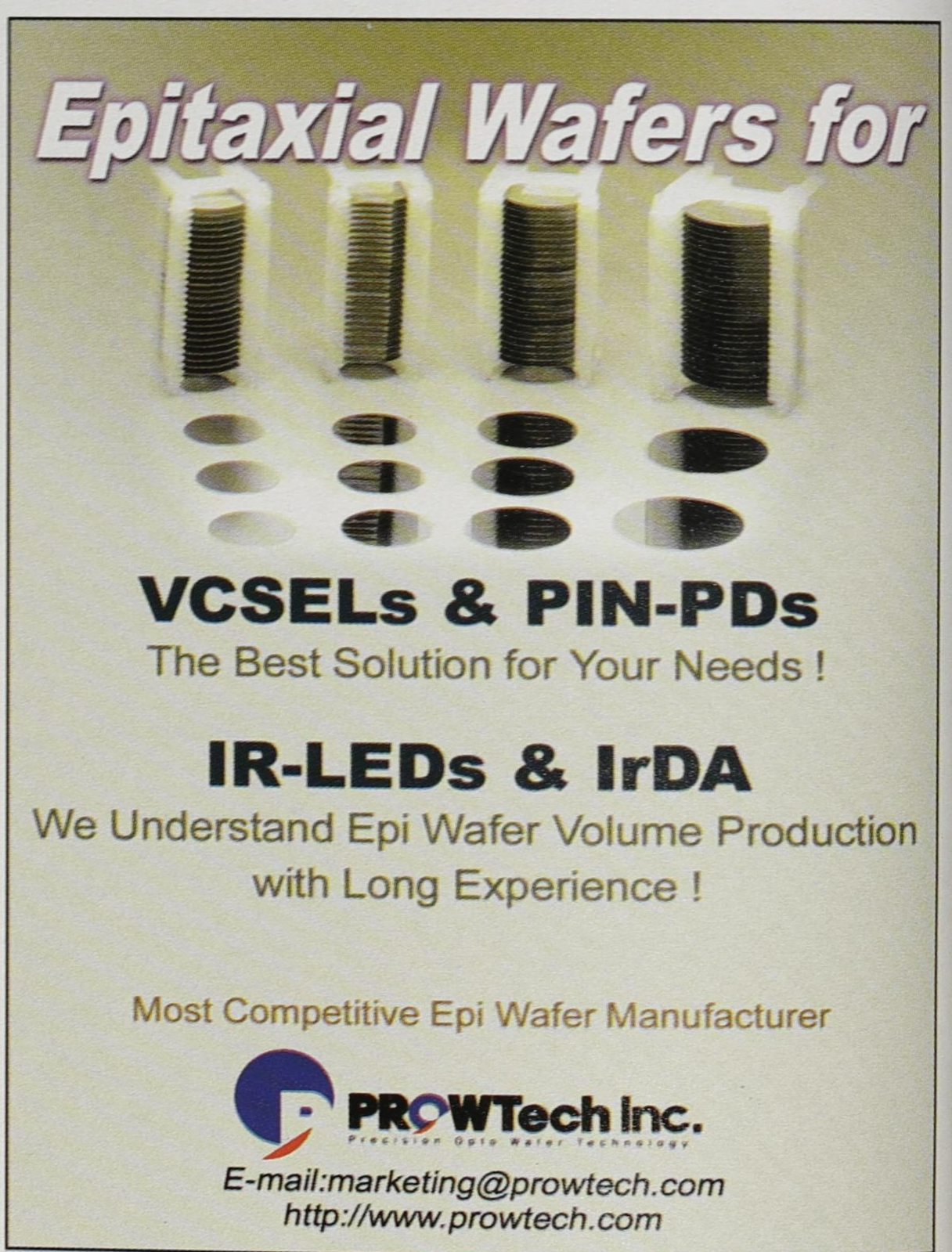
Flextronics will manufacture Gore's nLIGHTEN multichannel optical transceiver module, a VCSEL-based product offering an aggregate bandwidth of 15 Gbit/s (1.25 Gbit/s per channel). Gore says a second generation of nLIGHTEN modules operating at 2.5 Gbit/s per channel will also enter volume production by the end of the year.

Atoga chooses Agility's widely tunable laser

Atoga Systems (Fremont, CA) will employ Agility Communications' high-power, widely tunable laser in its Optical Application Router (OAR) product family of highly scalable optical switching platforms for metro networks. Agility's 3040 device is a sample-grating DBR tunable source capable of 4 mW output power, with the facility to tune across the C-band wavelength range (1530–1565 nm) in less than 10 ms. The InP lasers are manufactured at Agility's wafer fab in Santa Barbara, CA, which can produce 1 million lasers per year.

"Our integrated, intelligent OAR platform takes full advantage of Agility's tunable DWDM lasers to rapidly switch from one wavelength to another, offering carriers enormous benefits in networking efficiency through significant performance advantages, improved network flexibility, and seamless scalability," said Mark Lowry, director of photonics at Atoga. "The use of tunable lasers in the OAR product family provides faster provisioning times, more flexible networks and reduced operating costs."





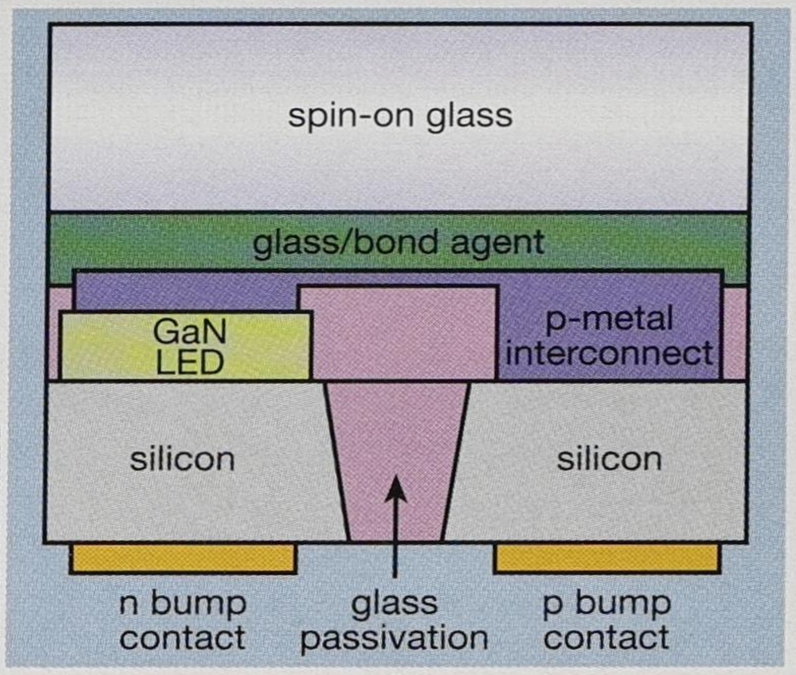
Nitronex funding targets GaN-on-Si LEDs

Nitronex, a developer of GaN devices grown on silicon substrates, has created an optoelectronics division to address applications such as LEDs for solid-state lighting. To fund these initiatives, the company will leverage a recent second round funding injection of $24.5 million from its original investors, who contributed $9.5 million last May. Nitronex intends to use the investment to develop its optoelectronic portfolio, and to expand its existing 10 000 sq. ft facility by a factor of ten. This will primarily support the production of RF devices such as GaN-based HEMTs, which are manufactured on 4 inch Si substrates (see *Compound Semiconductor* March 2001 p17).

Nitronex, based in Raleigh, NC, has developed proprietary MOCVD growth techniques to produce GaN-on-Si layers with relatively low defect densities. This includes its Pendeo epitaxy technique, which reduces the number of dislocations in GaN epilayers by up to four orders of magnitude to around $10^6/cm^2$. In addition, the company has patented a growth process called Sigantic, which it describes as the growth of multiple epitaxial layers to produce GaN-on-Si structures with a final defect density of ~$10^9/cm^2$. Such defect levels can be tolerated in optoelectronic devices such as LEDs.

Blue LEDs on silicon

One of the first initiatives undertaken by the new optoelectronics division was the formation of an alliance with Microsemi (Irvine, CA) to fabricate a line of GaN-based blue and ultraviolet LEDs. The first device, a 470 nm blue LED, will combine



NITRONEX/MICROSEMI

Schematic showing Microsemi's package containing a GaN-on-Si LED fabricated by Nitronex. The emitter has a junction area of 500 × 1000 μm. A spin-on glass coating is applied across the whole 4 inch Si wafer before dicing. A p-metal trace provides a connection to the top of the device, and glass passivation separates the contacts. Bumps on the bottom of the silicon wafer allow flip-chip bonding to a PCB.

Microsemi's chip-scale packaging technology with Nitronex's Sigantic GaN-on-Si structures. These LEDs will sample towards the end of the year.

According to Warren Weeks, VP and general manager of Nitronex's new optoelectronics division, the GaN-on-Si approach alleviates the high cost of SiC substrates and the poor thermal conductivity of sapphire.

"Our GaN-on-Si technology is the ideal platform for creating cost-effective, large junction-area LEDs," said Weeks. "Additionally, vertically conducting device structures are also permissible using ordinary conductive silicon substrates. These same silicon substrates also offer unique processing routes for improving the overall device brightness."

Epoxy-free packaging

The primary aim of the packaging procedure developed by Microsemi is to fabricate low-cost, large junction-area LEDs without the use of epoxy encapsulant. Over time, the epoxy can become degraded by UV emission in the device, causing discoloration and failures.

Microsemi employs a patented spin-on glass approach that produces a hermetic seal over the whole 4 inch substrate prior to chip dicing (see figure). Devices are bump-contacted and diced for subsequent flip-chip attachment, which also eliminates wire bonding.

"Most current blue and ultraviolet LEDs are limited in die size as a result of the available wafer size, material non-uniformity and the cost of SiC and sapphire substrates," said Weeks. "Using the Sigantic platform technology, Nitronex and Microsemi can provide larger LEDs that are packaged at the wafer level. This will bypass LED packagers and provide same-size devices that are up to twice the brightness of competing products."

Weeks added that Nitronex has a capacity for 100 × 4-inch GaN-on-Si wafers per month for LEDs, which produces the same number of die as approximately 400 × 2-inch wafers. While this may suffice for its current LED requirements, Nitronex will consider outsourcing some LED production at a later stage.

Uniroyal ramps capacity at high-brightness LED facility

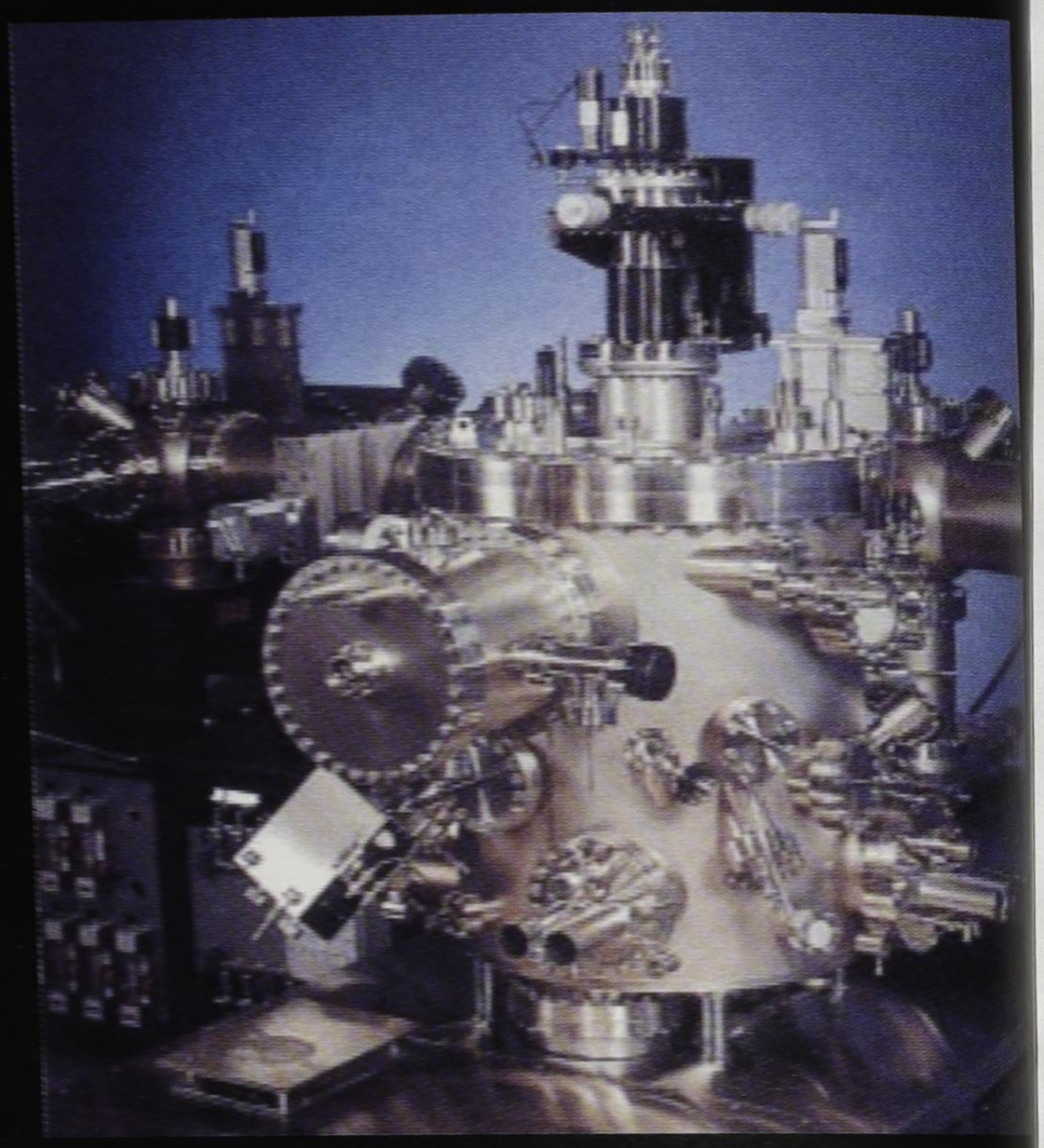
High-brightness LED manufacturer Uniroyal Optoelectronics has completed the expansion of its epitaxial growth facility in Tampa, Florida. Last November, construction began on the remaining 33 000 sq. ft of the 77 000 sq. ft plant, including space for an R&D section that is now also nearing completion.

As part of the expansion, Uniroyal has bought three new MOCVD reactors for the manufacture of blue and green HB-LEDs. Two of these systems are currently being installed, while one is in the final phase of materials testing. The company says that one reactor is designated for R&D, while the other two will be used for manufacturing. Uniroyal now has six MOCVD reactors at this facility.

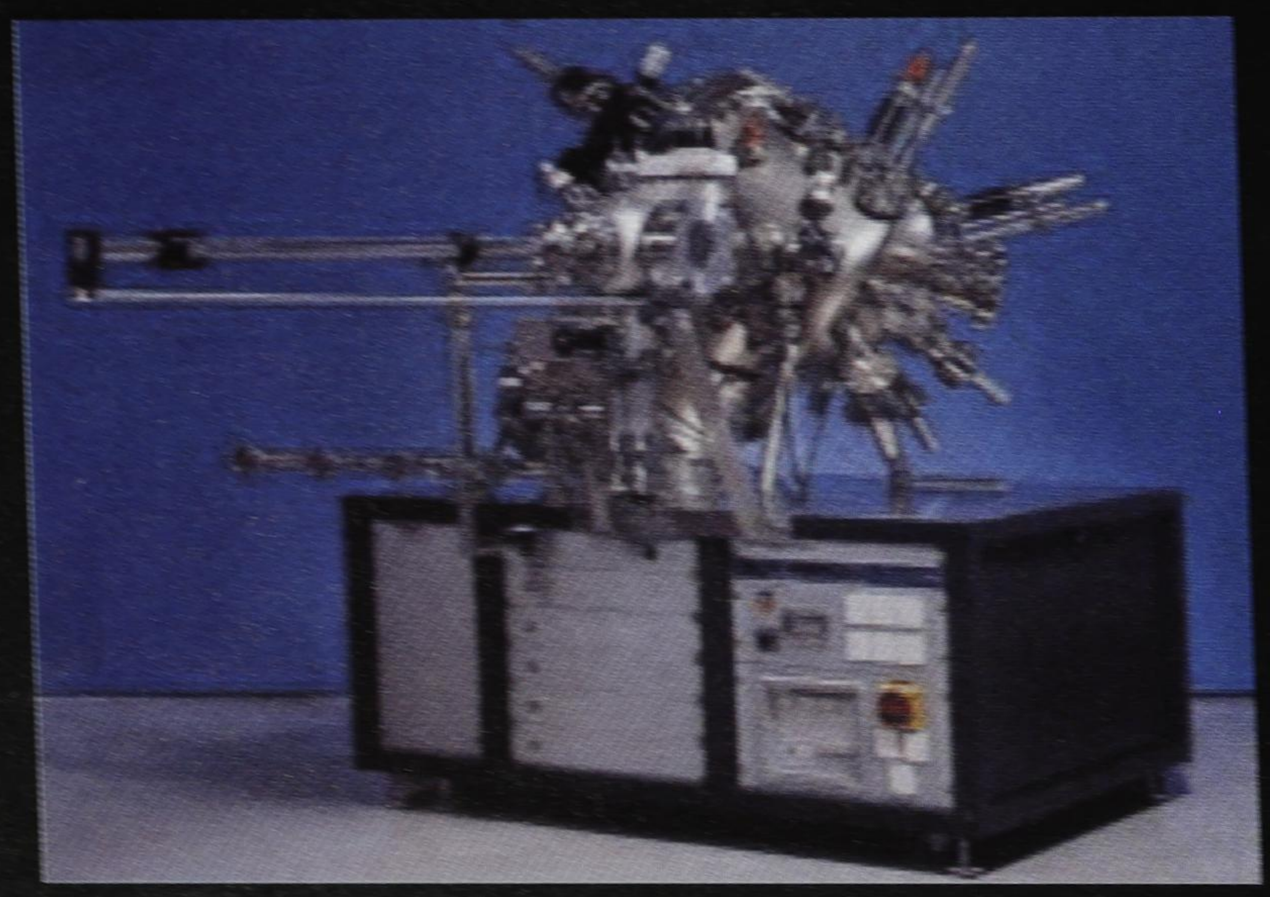
"This expansion puts all the necessary components in place to facilitate the addition of MOCVD reactors as we move forward with our plan for increased capacity," said Robert Soran, president and COO of parent company Uniroyal Technology Corporation. "The exceptional brightness levels achieved by our current products have been achieved in less than two years since our facility began production. The addition of the R&D facility allows our LED scientists to further accelerate product improvements and new product development."

MBE TECHNOLOGY

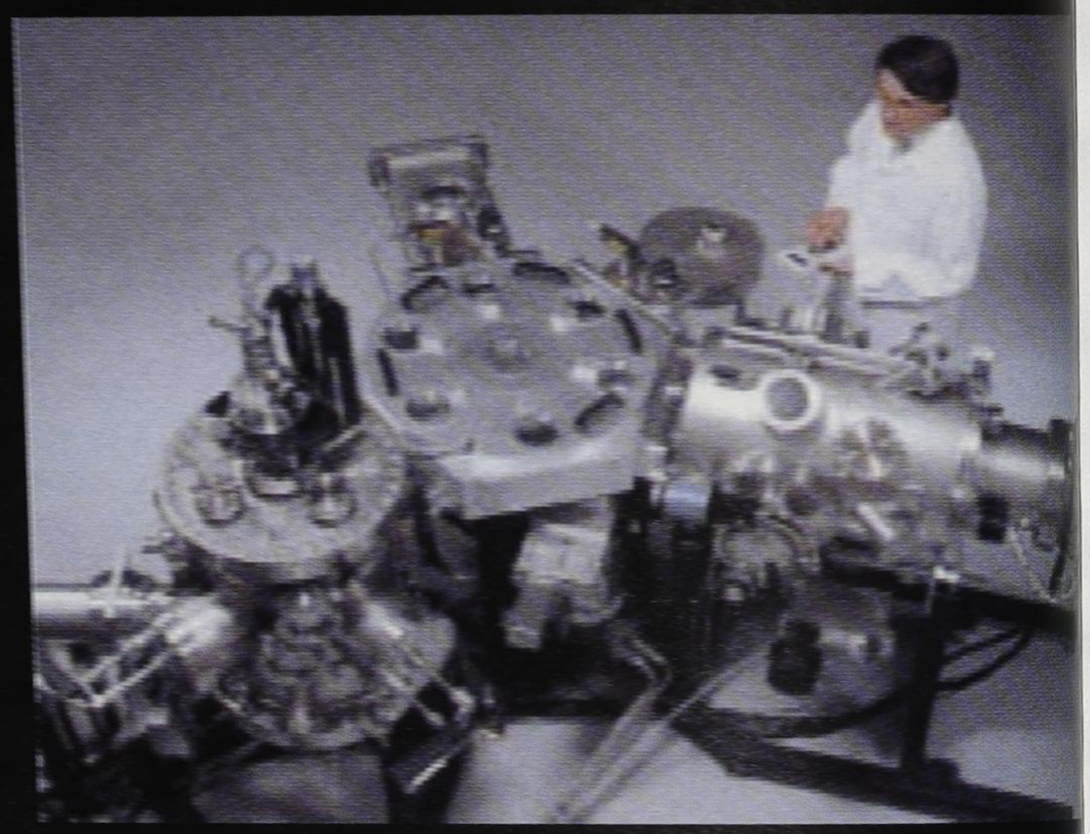
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Nichia loses patent case, Rohm sues again

Recent events in Japan have further added to the legal tangles concerning nitride-based blue LEDs. In a ruling on June 13, the Tokyo District Court accepted a claim from Toyoda Gosei that a patent held by Nichia was invalid. This marked the first occasion on which a court has struck down one of the hundred or so blue-LED patents held by Nichia. Adding to Nichia's woes, Rohm filed a lawsuit on July 2 at the Kyoto District Court claiming that Nichia is infringing a patent held by Rohm. The court has been asked to order Nichia to stop manufacturing and selling blue LEDs.

Toyoda wins one

The disputed patent at the heart of the ruling in favor of Toyoda Gosei relates to the basic structure of a blue LED. Toyoda Gosei successfully argued that this patent should be ruled invalid, because the claims of the patent are in the public domain since older patents relating to it have expired. In April 1999, Toyoda Gosei asked the Patent Office to revoke Nichia's patent, but the request was refused, prompting Toyoda Gosei to sue in June 2000.

Nichia has consistently maintained a policy of refusing to license out processes or technologies on which it holds a patent where it regards these as fundamental. Competitors, however, are producing blue LEDs using methods they claim they developed on their own, leading to patent conflicts. Nine lawsuits involving Toyoda Gosei and Nichia relating to patent infringements have so far been filed in the Tokyo District Court. Toyoda Gosei lost two cases last year, but has had two rulings in its favor this year (see table).

It is unlikely that the ruling against Nichia will challenge the company's overwhelming lead in blue LEDs, given the large number of patents it holds on related manufacturing methods and other processes.

Rohm strikes back

Rohm is also battling with Nichia in the courts, and seems to be hoping for a cross-licensing agreement to clear the way for it to commence mass production of blue LEDs. The Kyoto-based opto-electronics giant, which has established an alliance with Cree (see *Compound Semiconductor* February 2001, p8), is believed to have sounded out Nichia about cross-licensing last year. When that move failed, Rohm filed a complaint with the International Trade Commission in the US, citing infringement of several patents. Rohm was subsequently forced to withdraw the complaint, but has now filed a related lawsuit in Kyoto District Court. The patents in question relate to a method of reducing the operating voltage of an LED while maintaining high efficiency, which leads to a reduction in power consumption by about 10%.

Rohm is investing some 5 billion yen (~$41 million) to build a research and manufacturing facility for blue LEDs, and plans to roll out its newest product, developed jointly with Cree, as soon as possible after the legal issues have been sorted out. To facilitate this, and to try to prevent further lawsuits, Rohm asked the Tokyo District Court on July 9 to rule that its blue LED does not infringe upon Nichia's patents.

Recent patent activity

Date	Plaintiff	Defendant	Notes	Reference
December 1999	Nichia	Sumitomo	Nichia claims Cree LEDs, distributed in Japan by Sumitomo, infringe Japanese patent 2,918,139	Jan/Feb 2000, p10
June 2000	TG	Nichia	TG claims Nichia patent on basic LED structure is invalid	See above
August 2000	Nichia	TG	Tokyo District Court rules that TG has infringed Japanese patent no. 2,748,818. TG ordered to pay 100 million yen to Nichia	Sept/Oct 2000, p18
September 2000	Cree	Nichia	Cree sues Nichia over US patent 6,051,849 relating to lateral epitaxial overgrowth	Sept/Oct 2000, p19
November 2000	Nichia	TG	Court rules in favor of Nichia in second patent infringement case against TG	Feb 2001, p9
December 2001	Nichia	Cree, NCSU	Nichia files in US District Court claiming infringement of US patents 5,306,662, 5,578,839, 5,747,832 and 5,767,581	Feb 2001, p9
December 2000	Rohm	Nichia	Rohm alleges in a complaint to the US International Trade Commission (ITC) that Nichia is infringing US patents 6,084,899 and 6,115,399	Feb 2001, p8
March 2001	TG	Nichia	Tokyo High Court validates a TG patent (no. 2,737,053), previously ruled invalid in the lower courts	July 2001, p11
May 2001	Nichia	Sumitomo	Tokyo District Court dismisses Nichia's lawsuit (Dec 1999)	June 2001, p11
May 2001	Rohm	Nichia	Rohm withdraws its December 2000 ITC complaint against Nichia	June 2001, p11
June 13, 2001	TG	Nichia	Tokyo District Court rules Nichia patent invalid (June 2000 lawsuit)	See above
July 2, 2001	Rohm	Nichia	Rohm claims Nichia has infringed patent on reduced power consumption	See above
July 9, 2001	Rohm	Nichia	Rohm asks Tokyo District Court to rule that its LEDs do not infringe Nichia's patents	See above
July 2001	Nichia	Osram	Nichia withdraws complaint against Osram	See page 26

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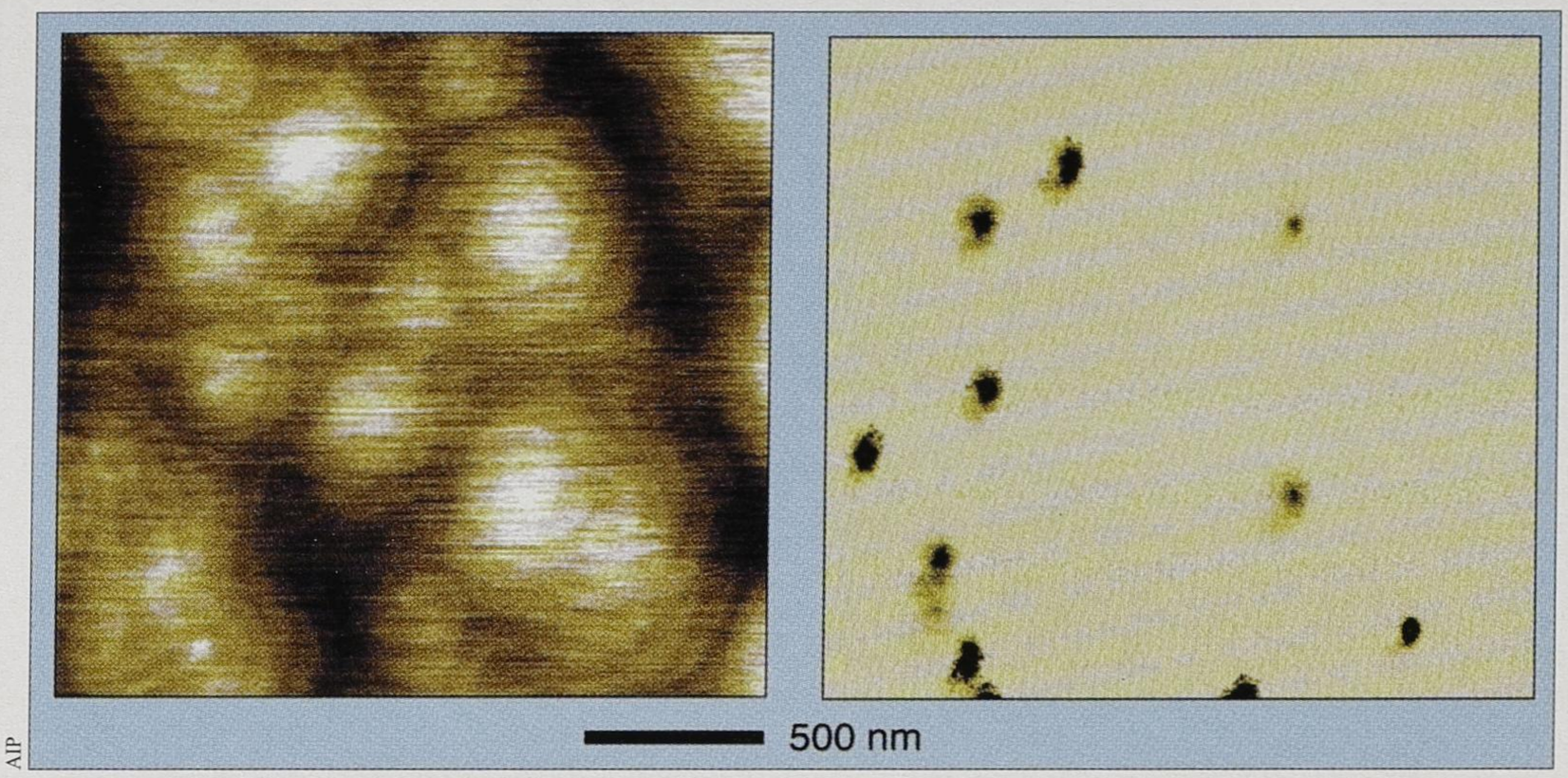
Defects linked to GaN device breakdown

Advances in the growth of GaN have seen reductions in dislocation density, background impurity incorporation and better interface control. This has resulted in much improved two-dimensional electron gas (2DEG) mobility, though problems of excess reverse bias leakage current are still a major barrier to the commercialization of III-nitride devices. J Hsu and colleagues from Lucent's Bell Labs, along with co-authors from Agere Systems and Massachusetts Institute of Technology have published work on the effect of growth conditions used in MBE on the electrical activity of screw dislocations in GaN films (see *Appl. Phys. Lett.* 2001 **78(25)** 3980).

The stoichiometry of GaN films grown by MBE has a large effect on surface morphology and the electrical activity of defects. Ga-rich films are characteristically smooth with monolayer steps, and any dislocations appear as hillocks. Ga-rich growth is known to enhance 2DEG mobility. Ga-lean films are pitted and have lower 2DEG mobility. However, reverse bias leakage current is 2–3 orders of magnitude below that seen in a Ga-rich film.

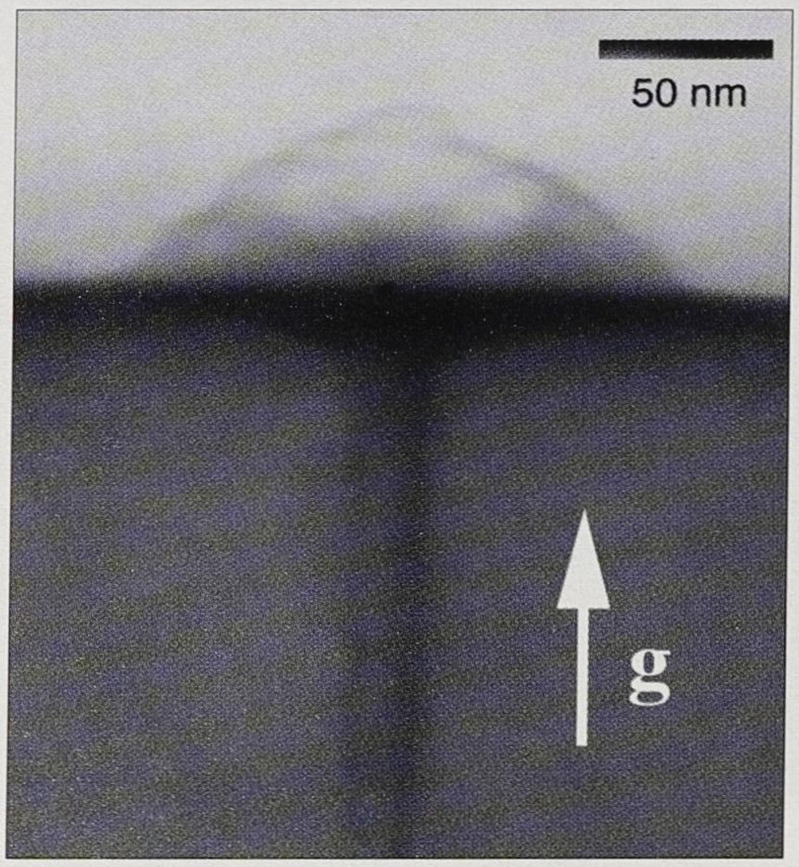
To investigate this difference in reverse bias breakdown current, the group used MBE to grow films onto GaN templates grown by hydride vapor phase epitaxy, under Ga-rich conditions. These growth conditions leave microscopic Ga droplets on the grown surface.

Scanning current-voltage microscopy (SIVM) was used to map the spatial variation in reverse bias current after the removal of the surface Ga droplets. Reverse bias current was found to be highest in small isolated regions that corresponded to the position of spiral hillocks formed where screw dislocations terminate (figure 1). This result indicates that dislocations with a screw component contribute more to gate leakage than pure edge dislocations.



AIP

Fig. 1. Topographic (left) and SIVM (right) images of a GaN film grown under Ga-rich conditions. The images measure 2 μm × 2 μm and were taken simultaneously under 6 V reverse bias.



AIP

Fig. 2. Cross-sectional TEM shot of a Ga particle at the surface where a screw dislocation terminates.

TEM micrographs of the material grown in Ga-rich conditions clearly show particles present at the surface where screw dislocations terminate (figure 2). These particles are not present where edge dislocations terminate. Energy-dispersive X-ray analysis revealed these to be Ga and not GaN. TEM was used to further investigate the effect of these Ga particles on the screw dislocations. This was done by comparing TEM shots of material grown under Ga-rich and Ga-lean conditions. The images from Ga-rich material showed weak contrast in the screw dislocation, suggesting a relaxed core structure. The dislocation core also widened towards the Ga droplet on the surface. Images of the screw dislocations in the Ga-lean material showed contrast remaining sharp up to the surface. The excess Ga appears, therefore, to change the dislocation structure and as a result affects the electrical activity.

The amount of Ga present at the dislocation seems to depend on the magnitude of the screw component in the dislocation, hence electrical activity is expected to be largest for pure screw dislocations. This finding is consistent with the lower leakage currents for films grown under Ga-lean conditions.

Cree introduces off-axis 3 inch SiC wafers

Cree has announced the extension of its SiC wafer range with the introduction of two new 3 inch, off-axis n-type wafers. These are available in both 4H and 6H polytypes. Cree was the first company to introduce 3 inch SiC wafers, until now only available as on-axis wafers. The off-axis wafers give an improved surface for SiC epitaxy, opening the way to high-volume device production on 3 inch wafers and offering users a cost advantage over 2 inch wafers. The 6H and 4H polytypes are 3.5° and 8.0° off-axis, respectively, and are immediately available.

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Sterling completes capacity increase

Sterling Semiconductor, a subsidiary of Uniroyal Technology, has announced the completion of a fivefold expansion of its SiC wafer production capacity. This is a key milestone in the company's intended aim to increase wafer production by a factor of ten during 2001. So far, the expansion of crystal growth furnace capacity has taken place at Sterling's Connecticut plant. Construction is underway at the company's Virginia facility, which will see the installation of more furnaces to complete the tenfold expansion.

Sterling is concentrating on the development of 3 inch SiC wafers and is establishing a 3 inch substrate line under US government funding. Earlier this year, Sterling was awarded a $1 million contract by the US Air Force to continue its research into semi-insulating SiC substrates (see *Compound Semiconductor* June 2001, p11).

ZnO nanowires make ultraviolet lasers

Researchers at the University of California and Lawrence Berkley National Laboratory have used ZnO nanowires to make room temperature ultraviolet lasers (*Science* 2001 **292** 1897). The nanowires were grown by a process involving vapor phase transport and condensation. A thin gold film deposited on sapphire was used to catalyze the growth. The process was very selective, with highly oriented ZnO nanowires growing only on the gold film. This selectivity enabled the team to demonstrate nanowire arrays by first patterning the gold coating. The wire diameters varied from 20 to 150 nm with 95% of the wires falling in the 70 to 100 nm range. The wire length could be varied from 2 to 10 μm by changing the growth time. Optical pumping at 266 nm with an Nd:YAG laser induced multiple sharp emission peaks between 370 and 400 nm, the most intense being at 385 nm. The single crystal, well-faceted wires act as natural laser cavities. This suggests a simple chemical approach could be available for the formation of nanoscale laser cavities without any etching or cleaving.

Anger drove Nakamura to leave Japan

Shuji Nakamura's new autobiography reveals why the key figure in the development of nitride-based LEDs and lasers left Nichia and Japan, writes ***Bob Johnstone****.*

Breakthrough with Anger
Shuji Nakamura
2001, Shueisha, Tokyo (in Japanese),
¥1600. ISBN 4-8342-5052-0.

When Shuji Nakamura left Japan in late 1999, five local television stations covered his departure. When he landed in the US to take up a professor's chair at the University of California at Santa Barbara, another Japanese camera crew was on hand to record his arrival.

Nakamura was, after all, the country's most famous researcher, the man who had single-handedly revolutionized the compound semiconductor industry by developing bright blue and green LEDs and violet laser diodes made of gallium nitride. Why then was Nakamura quitting both his native land and Nichia Chemical, the company where he had worked for 20 years?

Speculation in the Japanese media was rife. Now, a year and a half later, Nakamura provides the answer to this question. Simply put, he left because he was angry.

In an autobiography entitled *Breakthrough with Anger*, Nakamura lashes out. "There's something wrong with this country," he seethes, "industry and universities are terribly sick. That's why I left Japan."

The extent of his disillusionment may come as a surprise to those who know Nakamura as a friendly, easy-going guy who loves to laugh. But as Nakamura reveals how badly he was treated back home, the reader can well understand his bitterness.

A company man

It was anger that emboldened Nakamura one momentous morning in January 1988 to march into the office of Nichia president Nobuo Ogawa and make an outrageous proposal. Thus far, he had been a good company man, had done exactly as he was told.

But though his work was successful,



Shuji Nakamura was primarily responsible for Nichia's development of a nitride laser with a lifetime of 10 000 hours, reported in the Nov/Dec 1997 issue of *Compound Semiconductor*.

the results were a commercial disaster, and some of his seniors were calling for his resignation.

Now, in desperation, Nakamura decided that henceforth he would do what he wanted – shoot for the holy grail, a

Nichia's president sent written instructions to Nakamura telling him to stop work on blue LEDs immediately.

bright blue LED. And if his boss wouldn't let him, he didn't care, they could fire him if they liked. Nakamura made his demand: US$3.3 million in R&D funding, plus a year off to learn MOCVD at the University of Florida. Much to his amazement, Ogawa agreed. "That's the good thing about a family business," Nakamura comments, "you get a quick response."

But there are also bad things. While Nakamura was away in the US, a changing of the guard took place at Nichia. Nobuo's son-in-law Eiji became the company's president (in Japan, when there is no male heir, it is common for a son-in-law to adopt his father-in-law's family name). The old man had always supported Nakamura, but the relationship with his successor quickly soured.

Matters came to a head when the new president brought a senior LED researcher from another company to visit Nakamura's laboratory. Until that point, no-one at Nichia knew that Nakamura was working with gallium nitride, which was then regarded as a dead-end material.

Nakamura did everything he could to pretend otherwise, but the visitor figured out what was going on, and promptly told Eiji that Nakamura was wasting his time. Nichia's president turned pale. Later that day, he sent written instructions to Nakamura telling him to stop work on blue LEDs immediately.

But Nakamura was not about to give up. "I had already decided to ignore all instructions from the company, so I threw away the written instructions. For the next two months, written instructions came via the company's R&D chief, but I kept on ignoring them." During this time Nakamura invented two-flow MOCVD, the innovative method he used to make bright blue LEDs.

Patents and papers

Another bone of contention was Nichia's ban on its researchers publishing papers in academic journals or giving papers at conferences. Here again Nakamura, who is open by nature and aware that peer recognition depends on publication, decided to defy his superiors. "Of course at the same time I also applied for patents," he told me in mid 1999, "I figured that the company wouldn't be angry when they found out I had patents too."

Once the profits from sales of LEDs

started rolling in, American researchers would waylay Nakamura at conferences and ask him how much he was earning. When he told them his salary, which was still pegged to his lowly rank within the company, they were shocked. "If you were in the US," they told him, "you'd have been a millionaire long ago." They dubbed him "Slave Nakamura".

Just before leaving Japan, Nakamura and his wife, an elementary school teacher, calculated their total income over the past twenty years. It turned out that the amounts were almost the same. (Indeed, Nakamura was actually worse off, Nichia having spitefully refused him any retirement pay because Nakamura would not sign a non-competition agreement.) Lack of earnings differentiation is one reason why Nakamura characterizes the Japanese system as "communist".

Almost to the end, however, Nakamura retained a very Japanese sense of company loyalty. Even when Nichia's researchers rejected a discovery he made – how to deposit indium films just 10 Angstroms thick – that would have improved LED efficiency, Nakamura nonetheless applied for a patent in the company's name. "Thinking back, I realize how stupid I was," he writes.

Job offers from the US

When word got out that Nakamura was unhappy at Nichia, job offers from US universities and companies poured in.

"If you were in the US," American researchers told Nakamura, "you'd have been a millionaire long ago."

One firm offered a salary of $500 000 plus stock options worth $10 million. Not a single Japanese university or company showed any interest in recruiting him.

Nakamura reckons that snobbery was to blame for their reluctance: his achievements counted for little compared to the fact that he had graduated from a provincial university and worked for a no-name company. Meanwhile, as the rest of the world scrambles to adopt LED traffic lights, Japan lags behind.

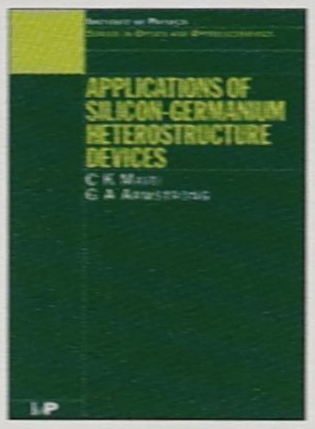
Nakamura's book is currently enjoying considerable success in Japan, where criticism is always better heeded when it comes from the outside. But Nakamura's writings deserve a wider public – an English language edition is under discussion – for the light that they shed on the mysterious process of innovation.

In this context, the invention of the very first laser is worth remembering. It was built in 1960 by Ted Maiman, a researcher working, like Nakamura, in isolation, against conventional wisdom and the wishes of his management, at the Hughes Research Laboratories in Malibu, California – just down the road from Nakamura's new home.

Bob Johnstone is a Japanese-speaking freelance writer based in Australia.

SiGe devices support RF and digital applications

Applications of silicon-germanium heterostructure devices
C K Maiti and G A Armstrong
2001, Institute of Physics Publishing, Bristol and Philadelphia.
ISBN 0-7503-0723-4.



The development of powerful growth methods such as MBE, MOCVD and other low temperature epitaxy techniques has given rise to a new area of research in bandgap engineering of silicon-based materials and paved the way for heterojunction bipolar and field-effect transistors and other fascinating quantum devices. This book considers the development of SiGe technology with particular reference to RF communication applications.

The book begins with reviews of state-of-the-art silicon and heterostructure SiGe devices, their potential in RF wireless communications, and the technologies essential for the growth and characterization of Group-IV alloy films. Further chapters cover the design and simulation of silicon heterostructure devices, the growth of strained silicon layers, strategies for enhancement of hole or electron mobility using MOSFET and MODFET structures, and the design and application of Schottky diodes and optoelectronic devices. The book concludes with an assessment of how SiGe technology compares with alternative technologies in the RF wireless communications marketplace.

The text is supported by an extensive survey of the literature, and computer simulation where appropriate. This book serves as an introductory text for device physics courses at senior undergraduate or graduate level in electronic and electrical engineering, applied physics and materials science, as well as a reference book for scientists and engineers in the field of high-speed device and circuit design.

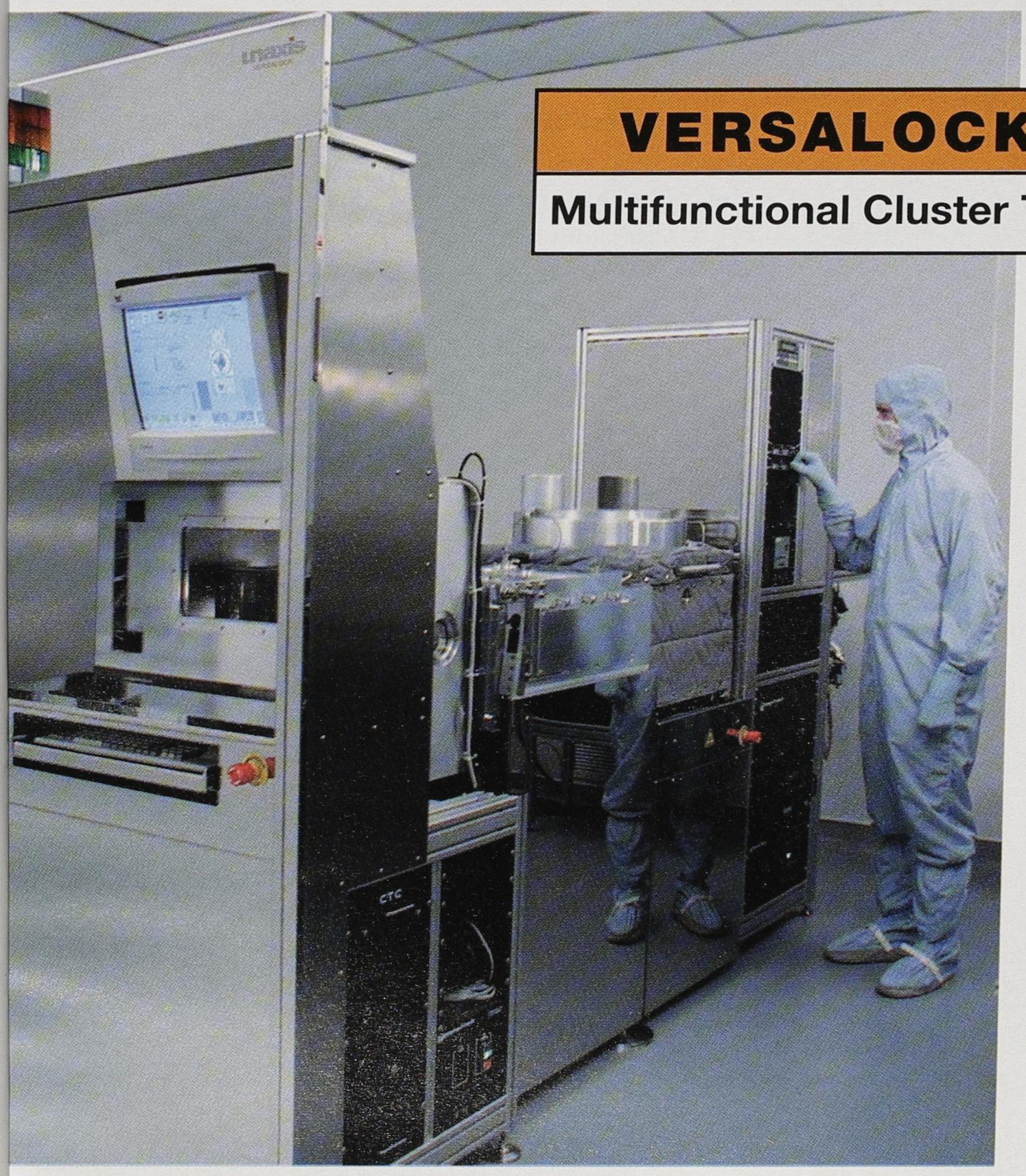
LED NEWS (continued from page 21)

Nichia withdraws complaint against Osram Opto Semiconductors

As this issue was going to press, we learned that Osram Opto Semiconductors has been successful in deterring a preliminary injunction filed against it by Nichia. The injunction, filed in Tokyo in December 1999, sought to prohibit the importation and sale of Osram's white LEDs in Japan. Nichia alleged that Osram's white LEDs infringe upon Nichia's Japanese patent no. 2,927,279. This protects the use of yttrium garnet as a phosphor for converting blue light from an InGaN LED into white light. However, Osram is using a different material to create white light, and Nichia has followed the judge's recommendation to withdraw the complaint.

"Nichia's withdrawal of its complaint means that uncertainty – not only on the Japanese market – is coming to an end and our customers will have ongoing access to Osram's white LEDs without obstruction," commented Rüdiger Müller, CEO of Osram Opto Semiconductors.

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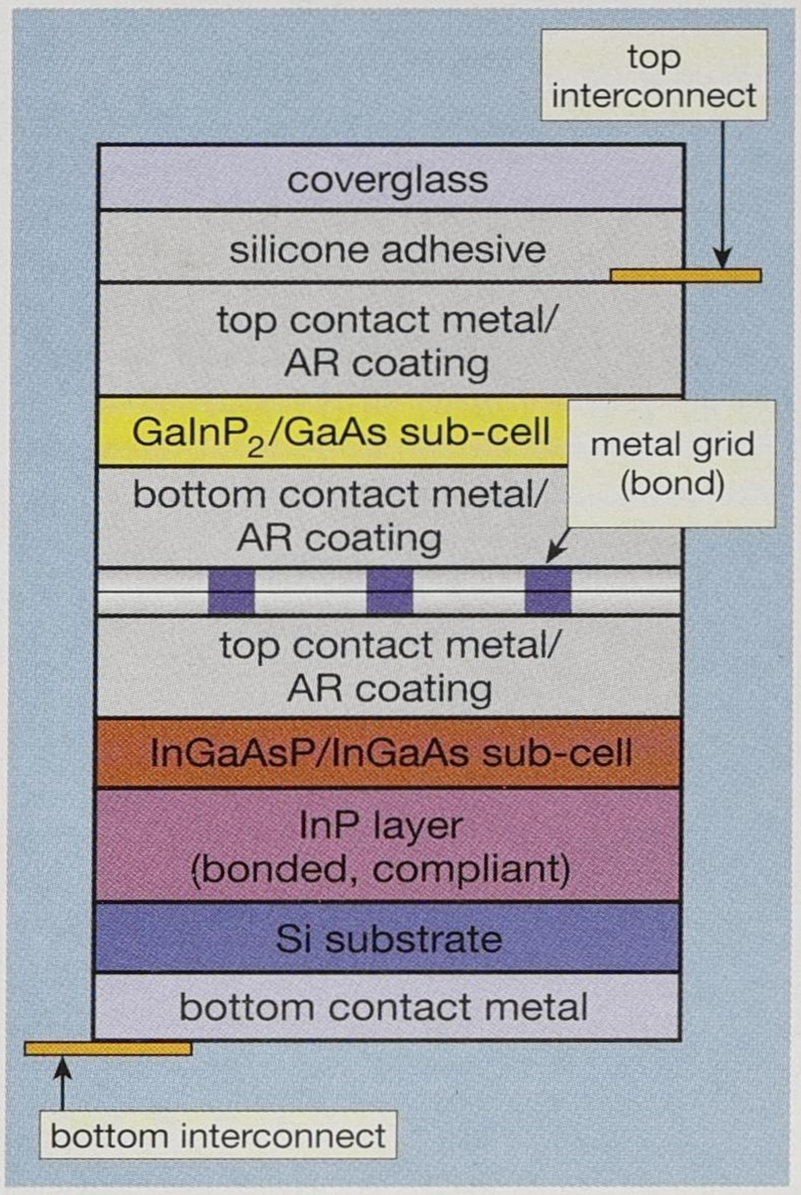
NASA Glen Research Center has initiated a three-year project to develop a 40% efficient solar cell. Tecstar (City of Industry, CA) will act as principal contract holder for the $1.5 million project, and will work with the California Institute of Technology (Caltech) and the National Renewable Energy Laboratory (NREL). The aim is to deliver lightweight prototype solar cells using concentrator arrays.

"NASA is looking for a high efficiency solar cell design with a low dollars/watt ratio," said Tecstar's VP of R&D, Frank Ho. "Under concentration, these prototype cells will enable more than 1000 W/kg of specific power, and will employ techniques to significantly reduce mass and cost."

Efficiency stacks up

Tecstar will employ a four-junction design that combines its mature $GaInP_2/GaAs$ dual junction cell with a further dual junction cell based on InGaAsP and InGaAs. The top and bottom cells are joined with a grid providing electrical connections to both cells, while at the same time allowing long wavelength light passing through the top cell to penetrate to the bottom InGaAsP/InGaAs collector (see figure).

The InGaAsP/InGaAs sub-cell is an optimized structure, which is grown by NREL on an InP-compliant layer on a silicon substrate. This compliant substrate, supplied by Caltech, is fabricated by growing a 2–4 μm layer of InP (and intermediate layers) on an InP substrate. This structure is wafer-bonded to a silicon substrate and the InP wafer is removed, leaving a thin compliant InP layer on Si. This procedure is key in reducing costs, since the InP wafer can be re-used.



In Tecstar's four-junction solar cell design, metal bonding is used to stack the $GaInP_2/GaAs$ and InGaAsP/InGaAs sub-cells. AR coatings are used to overcome refractive index differences between the GaAs and InGaAsP layers.

The top $GaInP_2/GaAs$ sub-cell is designed to provide 30.3% at a concentration of 15 suns (AM0), and the bottom collector will target 9.5% for the same conditions (see table). The structures are chosen from materials that convert solar energy into electricity in the 1.9–0.72 eV range.

Solar cell efficiencies

	Theoretical (1 sun, AM0)	Practical (15 suns, AM0)
GaInP (1.9 eV)	19.6%	
GaAs (1.43 eV)	12.1%	
Top sub-cell	31.7%	30.3%
InGaAsP (1.05 eV)	7.1%	
InGaAs (0.72 eV)	2.8%	
Bottom sub-cell	9.9%	9.5%
Total	41.6%	39.8%

The quadruple solar cell design will be used with 15x concentrators to achieve almost 40% efficiency.

"Monolithic quadruple cell designs with bottom cell junctions based on GaInNAs suffer from fundamental material problems associated with the incorporation of nitrogen," says Ho. "While a GaInNAs-based quadruple structure has been demonstrated, the current-voltage properties of the bottom cell severely limit the operation of the top cell. The approach we are taking can be considered as a medium risk one because we are employing well-established technology for both top and bottom cells, and using bonding to achieve the best combination to get us toward a 40% efficient device."

Tecstar's integrated diode protects solar cells in the dark

Tecstar has introduced a new multi-junction solar cell that contains an integrated GaAs bypass diode designed to reduce damage to solar cells in space.

The new device is based on Tecstar's commercially available triple junction $GaInP_2/GaAs/Ge$ solar cell – a space qualified device with an efficiency of 26.5% and an end-of-life power of 86%. The three-junction devices are grown monolithically on Ge substrates, and the cells are connected using $AlGaAs/GaInP_2$ p-n tunnel diode layers.

Known as TEC3i, Tecstar's new design features a GaAs diode bypass layer grown as a mesa structure on the top $AlInP_2$ window layer. The bypass diode protects the cell when the satellite is shadowed from the Sun by the Earth or by an antenna or panel. When in shadow, an unprotected device changes from a forward bias condition to reverse bias, which can cause damage. The monolithic bypass diode has been tested up to 100 000 extreme shadow cycles at a temperature of 120°C.

"The TEC3i is Tecstar's third generation monolithic three-junction design," said Frank Ho, VP of R&D at Tecstar. "We have grown an integrated bypass diode on top of the solar cell, which is connected to the Ge substrate to prevent the cell from burning out during a shadow cycle. The design offers advantages compared to discrete protection diodes. In particular, we can use masks to scale the diode size to accommodate customer requirements, depending on the solar conditions their cells will experience."

According to Tecstar, the TEC3i is in volume production and can be supplied in the form of epiwafers, cells, cell assemblies or complete solar panels.

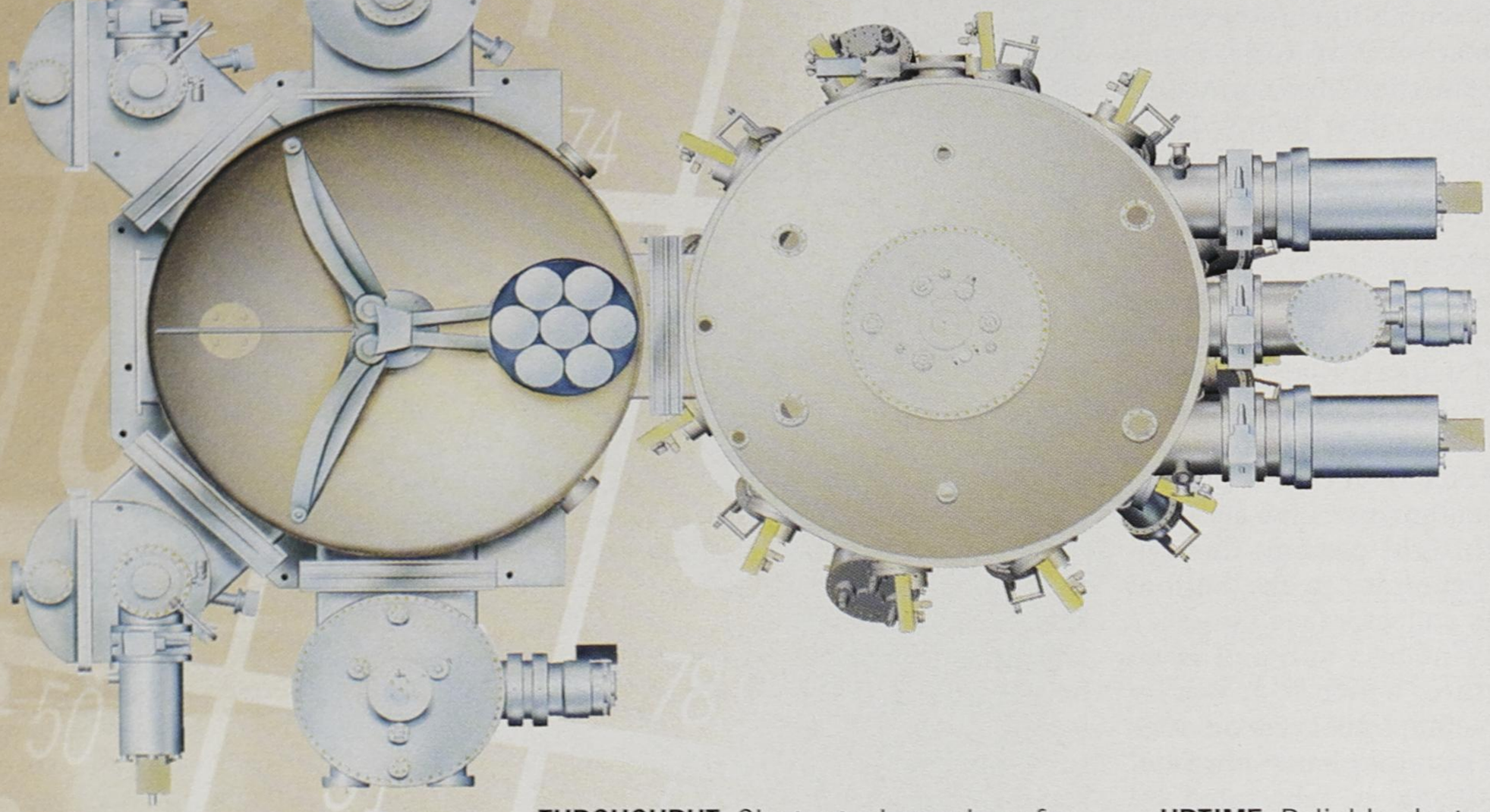
GaAs—SILICON STYLE

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RIGHT FROM THE STAR

Infineon sells IR business

Vishay Intertechnology will acquire Infineon's infrared components business – including the company's development, marketing and distribution activities in San Jose, California and production facility in Malaysia – for approximately $120 million.

Infrared components are used primarily as optical interfaces in PCs, cell phones, PDAs, industrial automation systems, set-top boxes, voice/data switching and data transmission equipment. The acquisition, which also includes a workforce of around 1200, is expected to close by the end of July, subject to customary regulations.

Following the sale, Vishay will add to its portfolio Infineon's optocoupler and solid-state relay product lines, as well as infrared data transmission modules, data access arrangement kits and custom opto-electronic modules. Vishay is currently the largest manufacturer in the US and Europe of passive components such as resistors, capacitors and inductors, and a major producer of discrete semiconductors, including diodes and transistors. Headquartered in Malvern, Pennsylvania, the company also produces infrared LEDs, in addition to power and analog switching ICs.

"This acquisition will enable Vishay to significantly strengthen its current position in the optoelectronics sector, and specifically in the growing infrared components portion of that market," commented Felix Zandman, Vishay's chairman and CEO.

Vishay will initially take 19% ownership of Infineon Technologies Krubong, the recently opened production facility in Malaysia; the transfer will be completed in 2002.

"This divestiture is another important step to streamline our communications portfolio," said Ulrich Schumacher, Infineon's president and CEO. "With the sale of the infrared components business and our consumer electronics business to Micronas last November, we have now completed our plan of concentrating our wireline activities for the present. We will continue to expand our strategic core activities in the field of local area networks and wide area networks, as well as in network access."

Philips ready to mass-produce OLED displays

Philips Mobile Display Systems (MDS), a business group of Philips Components based in Sunnyvale, California, has unveiled production OLED technology suitable for small displays, including cellular phones and pagers.

OLED technology holds considerable promise for small display screens. High contrast images are possible with a wide viewing angle, and the displays can be made lightweight and thin in a range of colors. A further benefit is low power consumption, and as OLEDs are self-emissive screens, they do not require backlighting in the manner of LCD screens.

Philips MDS says its polymer OLED technology is based on passive-matrix displays consisting of a series of emissive polymer thin films sandwiched between two electrodes. Such displays are cheaper than active matrix displays – which employ Si-based thin-film transistors to drive the pixels in large area, high definition video displays – and are suitable for basic display requirements (see figure).

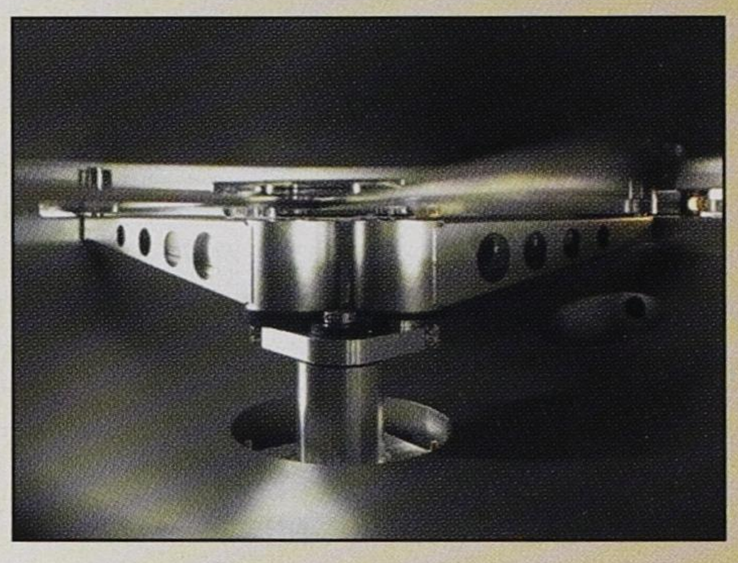
The company's monochrome PolyLEDs can be filtered to produce green, yellow, amber and red with 16 grayscale levels. The power consumption is 90 mW in graphics mode with 80% of the pixels turned on, and 4 mW in standby mode. The resolution is 65 × 102, which meets basic mobile phone display requirements, and the response time is of the order of microseconds.



Philips' passive matrix OLED technology is production-ready for mobile display applications.

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Applied Epi

Maskless photolith process developed

Intelligent Micro Patterning has established a 7000 sq. ft facility at St Petersburg, FL, to manufacture its new maskless photolithography process tool.

Intelligent Micro's system uses micro-optics developed and licensed from the University of South Florida to project images directly onto substrates without the use of photomasks. Designed as a drop-in replacement for mask photolithography tools, the system targets prototyping environments for applications such as MEMS, high-density packaging and multi-chip modules.

"Maskless photolithography is a revolutionary way of fabricating a wide variety of semiconductor and other electronic devices," said CEO Jay Sasserath. "By eliminating the need for photomasks, operating costs can be significantly reduced. Additionally, since our customers do not need to wait for new photomasks to be manufactured, devices can be prototyped quickly, reducing time to market."



INTELLIGENT MICRO PATTERNING

Intelligent Micro's maskless photolithography system has patterned Novolac photoresist with a resolution of 50 μm.

The company's SF-100 system converts IC designs from an electrical signal to an optical signal via its smart filter technology. The optical image is then transferred to the wafer surface and the pattern alignment monitored by optical microscopy. A white light source provides the illumination with a resolution of 20 μm, and patterns are typically produced on substrates up to 200 mm square, using a manual step-and-repeat method based on $20 \times 10\ mm^2$ image fields.

"We've observed that the SF-100 easily processes all of the standard Novolac photoresist materials that we've tested, as well as a large number of other photosensitive materials," added Sasserath. "This is critical for allowing the SF-100 to be used as a drop-in replacement for other exposure systems used in existing development processes."

VCSEL burn-in and test contract for Aehr

Aehr Test Systems, a company that supplies burn-in and parallel test systems based in Fremont, CA, has received its first wafer-level burn-in system order from a VCSEL manufacturer. The order marks the first phase of a development partnership, and the system is scheduled for delivery in the first half of 2002.

The silicon industry employs wafer-level burn-in and test to reduce costs by identifying known-good die for use in multi-chip modules and systems-in-a-package. Aehr's FOX contact system is typically used to test all pads on a wafer simultaneously, providing cost-effective burn-in and testing of DRAM chips.

"This is an opportunity for Aehr Test to penetrate the emerging market for test equipment for optical communications devices," said president and COO, Carl Meurell. "Contacting thousands of laser diodes simultaneously on a GaAs wafer will be a challenge, but we believe that burn-in at the wafer level can offer manufacturers a big cost-saving advantage.

"We anticipate that the success of the first phase of this partnership will lead to follow-on orders for wafer-level systems and contact systems for VCSEL wafer burn-in," added Meurell.

Trion Technology expands in Florida

Trion Technology, a manufacturer of plasma etchers and deposition equipment based in Tempe, AZ, has acquired additional manufacturing and clean room space in Clearwater, FL. The 12 000 sq. ft facility will support East Coast sales and the growing demand from compound semiconductor and optoelectronics markets, said marketing manager Forrest van Benthuysen. Trion's products include PECVD systems, RIE and ICP etchers for metal, oxide and nitride etch, and systems for resist removal and cleaning.

Processing equipment news: WIN buys more tools

WIN Semiconductors, a Taiwanese manufacturer of GaAs MMICs, has placed an order for a ZBA electron beam lithography tool from **Leica Microsystems**. Leica says this is the third ZBA e-beam writer it has installed in the region. "Leica's e-beam tool offers a mature solution for industrial deep submicron lithography," said Fritz Hohn, president of Leica's Semiconductor Equipment Division. "In addition, the system is designed for integration with Leica's existing metrology, analysis and measurement systems."

KDF of Rockleigh, NJ, has won a contract to manufacture physical vapor deposition systems for **Tokyo Electron Limited** (TEL). KDF will build TEL's Eclipse system, a single-wafer, high-volume PVD tool used for front-end semiconductor applications. Two years ago KDF acquired all of TEL's in-line batch PVD products and support personnel.

WIN Semiconductors has also ordered a 901G plasma etcher from **Tegal** of Petaluma, CA. WIN will use the tool to produce PHEMT MMICs and HBTs used in cellular phones and other handheld communication appliances. This is the second 901G etcher to be installed at WIN's 6 inch GaAs facility.

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ENABLING BANDWIDTH...
RIGHT FROM THE START

Veeco acquires probe manufacturer

Veeco Instruments of Santa Barbara, CA, has acquired ThermoMicroscopes, a subsidiary of Thermo Electron Corporation, for an undisclosed sum.

ThermoMicroscopes will be renamed TM Microscopes, and will continue to manufacture atomic force and scanning probe microscopes, near-field optical microscopes and probes. Employees will remain at the company's location in Sunnyvale, CA, and will become part of the Veeco Metrology Group.

"Both companies' SPM and AFM products are complementary," said TM Microscope's president Don Kania. "We will now be able to offer the most complete product line available, from low-cost research microscopes to general purpose industrial tools and fully automated systems. We see synergies in existing products, intellectual property, basic technologies and in new products already under development and those planned for the future."

"This purchase broadens our AFM product line, adds proprietary tip technology, and allows us to offer a versatile research microscope product line that is ideal for a variety of material science and nanoscience applications," said Edward Braun, Veeco's chairman, president and chief executive officer.

Veeco is a supplier of process equipment and metrology tools to optical telecommunications, data storage, semiconductor and research markets.

Showa Denko forms alliance with NTT-AT

Showa Denko and NTT Advanced Technology Corporation (NTT-AT) have entered into an agreement that will see Showa Denko manufacturing InGaP HBT epiwafers for NTT-AT. These epiwafers will be used to fabricate PAs for use in cellphone handsets. Demand for InGaP HBTs is expected to grow steadily over the next few years as third-generation cellular services are launched. InGaP/GaAs PAs offer advantages over AlGaAs/GaAs PAs, including higher power efficiency and lower operating voltages.

Showa Denko produces substrates and epiwafers, including both LEDs and electronic devices. The agreement includes a commitment to tie-up NTT-AT's epitaxial growth and device evaluation capabilities with Showa Denko's volume manufacturing facilities.

Showa Denko has begun a capacity expansion to increase output to 500 InGaP HBT epiwafers per month by September 2001. The expansion is expected to continue, reaching 2000 wafers per month in 2003.

Epitaxy equipment news and sales

RF Micro Devices has qualified Applied Epi's GEN2000 MBE system for production of GaAs HBTs. The GEN2000 is designed to accommodate 4 × 4 inch and 7 × 6 inch wafers.

Aixtron has sold its 100th AIX 2600G3 MOCVD reactor with cassette-to-cassette wafer handler. The reactor will be used by Agilent Technologies, UK, for the growth of InP-based laser structures.

Virginia Tech has ordered an **Aixtron** AIX 200/4 reactor to grow GaN heterostructures used in optoelectronic devices.

The **Institute of Electronic Materials Technology** in Warsaw, Poland, has ordered an additional AIX 200/4 RF-S system from **Aixtron**, to be used in the growth of GaN-based lasers and LEDs. The institute, whose first AIX 200 reactor is used to fabricate GaAs and InP devices, plans to purchase a further AIX 200/4 system for similar InP structures.

Showa Denko has added to its existing capacity with the purchase of an **Aixtron** AIX 2600G3 (which accommodates 8 × 4 inch or 5 × 6 inch configurations). The system is intended for the fabrication of wireless communications structures.

PEOPLE NEWS

Uniroyal Technology Corporation has named **David Miller** as president of its Optoelectronics business segment in Tampa, FL, where it manufactures high brightness LEDs. Miller began his career at GE Research Laboratories, followed by spells at Bell Labs and most recently as president of the Airtron Division of Litton Systems, a leading supplier of GaAs substrates.

Infinite Group has named **Richard Stoltz** as director of intellectual property development for the company's Infinite Photonics subsidiary. Infinite Photonics supplies laser diodes based on its patented GCSEL technology platform.

Tunable laser manufacturer **Bandwidth9** (Fremont, CA) has appointed **Kenichi Iga** to its technical advisory board. While at the Tokyo Institute of Technology, Iga first proposed and pioneered the research of surface-emitting semiconductor lasers.

One of the leading developers of MOCVD technology, **Dan Dapkus**, has received the 2001 David Sarnoff Award from the IEEE. The award cites "contributions both to the establishment of MOCVD as a dominant technology for epitaxial materials growth, and to the first MOCVD quantum well laser". Dapkus joined Rockwell in 1976, and moved to the University of Southern California in 1982.

Nova Crystals of San Jose, CA, has appointed **Lois Eckmann** as the company's new CFO and VP of finance. The company has also named **Ray Milano**, VP and general manager for Vitesse, to its board of directors. Milano leverages a 25-year career in optoelectronics and components at Vitesse, and will help guide Nova's optical component development.

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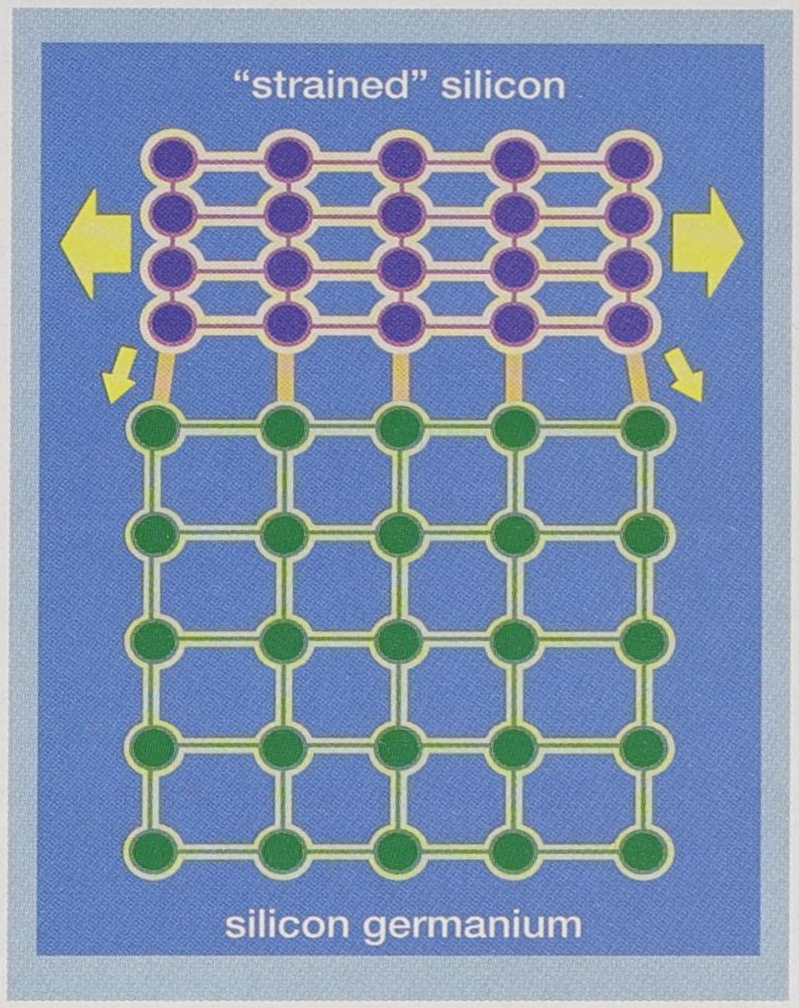
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Silicon takes the strain for RF applications

The novel combination of well known processes such as wafer bonding, ion implantation and virtual substrate growth are being brought together by IBM and others to push silicon microelectronics into new regions of RF performance. ***Bob Metzger*** *reports.*

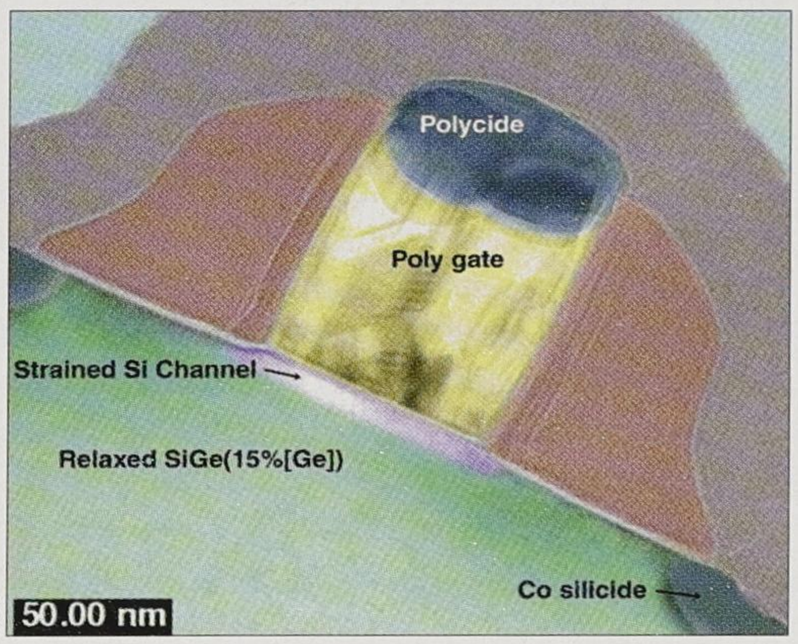
The device enhancements made possible by placing a semiconductor material under strain have long been exploited by the III-V community in applications such as In-rich channels of both GaAs- and InP-based HEMTs, and a wide range of GaInAsP lasers. Both electrical and optical enhancements come about through strain-induced band-structure modifications. These can enhance carrier mobilities through changes in the slope of energy bands, split degenerate bands or modify the energy gaps between subbands, improving optical and carrier confinement, as well as population inversions in semiconductor lasers.

Device enhancements made possible through the use of strained materials have been well recognized by Si researchers for more than a decade. Initial research focused on the use of relaxed $Si_{1-x}Ge_x$ buffer layers, in which strain in subsequent layers could be induced by growing either Si or $Si_{1-y}Ge_y$ (where y differs from x) layers. This approach has been used in the fabrication of both n- and p-channel SiGe HEMT structures (Arafa *et al.*). Despite enhanced mobility and transconductance, as compared with a typical CMOS device, the complexity and fabrication issues involved in SiGe HEMTs were very similar to those of III-V strained channel HEMTs. Also, performance fell well short of the capabilities of III-V devices, resulting in a diminished interest in this area of research.



IBM

Fig. 1. The smaller Si lattice becomes strained when grown on the larger SiGe lattice.



IBM

Fig. 2. TEM cross-section of a device using a strained silicon channel grown on a relaxed SiGe buffer.

Strained silicon CMOS

Recent strained Si research has focused not so much on trying to emulate III-V devices, but attempting to exploit the enhanced material properties due to strain, using a more conventional CMOS process. At the 2001 VLSI Symposium, held in Kyoto, Japan, recent results presented by IBM researchers (Rim *et al.* and Huang *et al.*) have shown that when strain is introduced into a fairly standard CMOS process, carrier mobilities can improve by as much as 70%, and current drive by 35%.

The IBM strained silicon (SS) process relies upon the UHVCVD growth of a graded SiGe buffer on a Si substrate. Once the graded buffer reaches a critical thickness, the strain energy in the material becomes too great and the crystal lattice relaxes. The lattice constant of the relaxed material now reflects that of the new SiGe alloy. In the IBM approach, once relaxation is obtained a fully relaxed $Si_{1-x}Ge_x$ buffer region in which x can range typically from 0.15 to 0.3 is grown. This buffer now acts as the effective substrate material for all subsequent growth. Onto this buffer layer a 20 nm layer of Si is grown which will become the channel region of subsequent devices. The mismatch in lattice constant between the relaxed SiGe buffer and the silicon channel results in the silicon lattice being strained. The more Ge in the relaxed SiGe buffer, the greater the strain in the Si region. Figure 1 illustrates the effect of the Si lattice being strained as a result of being grown on the relaxed SiGe buffer.

From here on, fabrication follows a fairly standard advanced NMOS process, utilizing a polysilicon gate with a length of 110 nm on a 2.2 nm gate oxide. Figure 2 shows a TEM cross-section of the device. There are some subtle process issues involved in the fabrication of SS CMOS devices. Due to the strain in the Si layer, arsenic and phosphorus diffusion are enhanced while boron diffusion is suppressed. This results in a larger gate overlap capacitance for the SS device as compared with a control device (unstrained Si grown with no SiGe buffer), and a smaller effective electrical gate length for a given polysilicon gate length.

Higher mobilities from strained Si

Figure 3 on page 38 (Rim *et al.*) illustrates the resulting mobility as a function of vertical effective field in the SS devices, compared with both the control device, and the universal effective mobility observed for doped silicon. The

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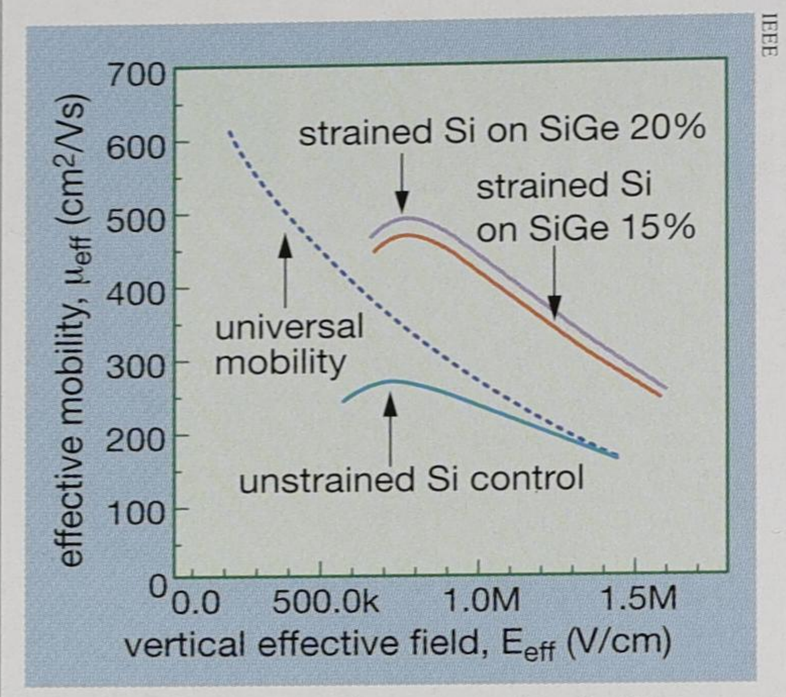
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Fig. 3. Mobilities in unstrained silicon and strained silicon grown on SiGe buffers of different compositions.

resulting mobility is 70% higher than that observed in the control device, while the DC I-V characteristics for the SS device appear quite typical, with both the control and SS devices showing comparable subthreshold slopes of approximately 85 mV/decade. The smaller bandgap in the SiGe and the dislocations present in the buffer due to relaxation do lead to larger leakage current in the SS device, but typical I_{off} for the SS device is at the 1×10^{-11} A level (1–2 orders of magnitude greater than the control device). This is not large enough to have an adverse effect on the device, or on VLSI circuits using the device. As a consequence of the enhanced mobility, the observed current drive of the SS device is 35% greater than that of the control device.

SOI delivers RF performance

While such a device may have many high-speed digital applications, it still utilizes a "lossy" Si (or in this case SiGe buffer) substrate which will suffer from capacitive coupling, making this structure ill suited to many RF applications. A second group of researchers at IBM (Huang *et al.*) are addressing this issue by combining the SS technique with a SOI process, where the oxide in the SOI decreases the capacitive coupling. Most SOI processes currently rely on separation by implanted oxygen (SIMOX). This process requires a very high temperature anneal which is not compatible with high levels of Ge in the buffer. Instead, a wafer-bonding and hydrogen-induced layer transfer technique is used which allows for a Ge content in the buffer layer of up to 30%. In this process, the relaxed SiGe layer is implanted with hydrogen and the surface then polished by a chemical-mechanical planarization (CMP) process. This reduces surface roughness due to the cross-hatching present in the relaxed SiGe surface from 6–8 nm rms to approximately 0.5 nm rms. This reduction is needed for successful wafer bonding. The polished SiGe wafer is then bonded to a Si handle wafer that has a 300 nm thermal oxide on the surface. During subsequent thermal treatment, the wafer splits along the peak of the hydrogen implant, transferring approximately 500 nm of the relaxed SiGe layer onto the handle substrate. The SiGe layer is now bonded to the 300 nm oxide layer, thereby forming an SOI structure.

With the Ge content of the buffer ranging from 15 to 25%, a standard CMOS process is then implemented. Enhancement in electron and hole mobilities of 50% and 20% respectively is observed in the SS/SOI structures as compared with control SOI structures. SOI CMOS-based devices are already strong RF competitors to III-V devices in the 900–2400 MHz regime. The performance enhancements described, combined with the ability of such a process to support high-speed digital functions (as required in the baseband portion of a cell phone/radio), will make IBM's new SS technology highly competitive in terms of performance and cost as compared with III-V-based solutions.

Amberwave joins the race

While manufacturers are often hesitant to design systems based on devices provided by a sole source, this will not be the case with SS devices. Amberwave of Salem, NH, has also recently announced its own patented SS technology (εMOS), which provides electron and hole mobility enhancement factors of between 1.5 and 2.2, and is actively seeking partners to commercialize its technology.

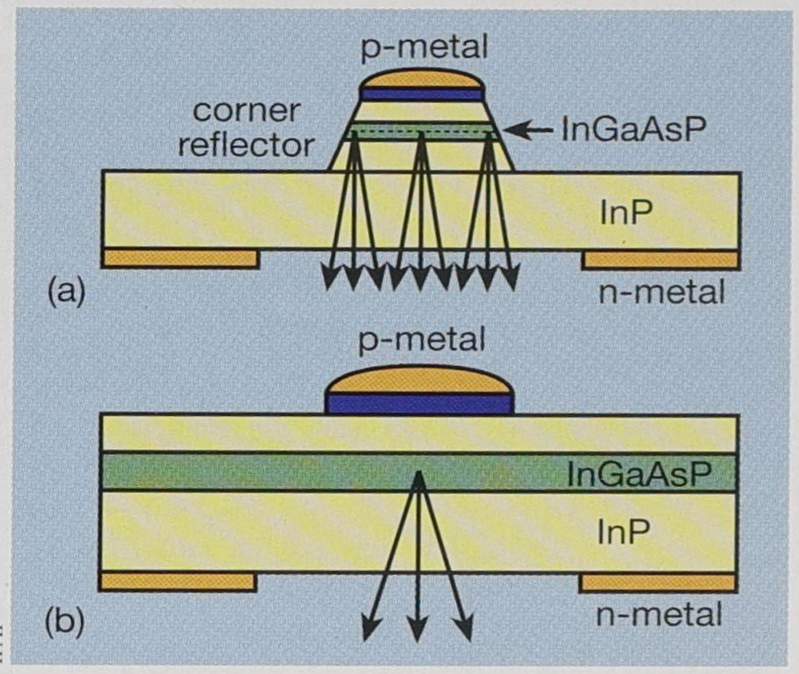
Further reading

M Arafa *et al.* 1996 *Electron. Dev. Lett.* **17** (12) 586.
L J Huang *et al.* Carrier Mobility Enhancement in Strained Si-On-Insulator Fabricated by Wafer Bonding *Proceedings of the 2001 IEEE VLSI Symposium, Kyoto, Japan.*
K Rim *et al.* 2001 Strained Si NMOSFETs for High Performance CMOS Technology *Proceedings of the 2001 IEEE VLSI Symposium, Kyoto, Japan.*

High-radiance LEDs use corner reflectors

Although surface-emitting LEDs (SE-LEDs) usually give higher output powers than edge-emitting LEDs, the former type of device is easily saturated as current density increases. The major mechanism for this saturation is in-plane superluminescence. A new type of SE-LED that does not saturate at high injection currents has been proposed by Park and colleagues at the Korea Advanced Institute of Science and Technology (*Jap. J. Appl. Phys. Pt. One* 2001 **40(4B)** 2741).

The new device uses 45° corner reflectors at the edges of the active layers to direct some of the in-plane luminescence to the emission surface. The device structure comprises InP cladding layers and InGaAsP active layers deposited by MOVPE on an InP substrate. A newly developed etch is used to form the 45° reflector. The etch gives smooth 45° sidewalls in all crystal directions and also gives the same etch rate for InP and InGaAsP. The fabrication of a microlens is also described: this involves microinjection of a liquid that is subsequently UV-cured. Control of the amount of injected liquid gives either a concave or convex microlens.



IPAP

An SE-LED structure with 45° corner reflectors (a) and a conventional SE-LED structure (b).

The performance of the SE-LED with corner reflectors compares well against a conventional SE-LED, which exhibits saturation at an injection current of 100 mA. The new SE-LED shows no saturation phenomena up to 500 mA current. At 400 mA, the output power of the SE-LED with reflector is about four times that of the conventional SE-LED. The new LED structure also shows a much sharper emission spectrum as the injection current is raised, with a peak centered on 1525 nm for the structure described.

GaAs-based QC laser at room temperature

For the first time, room-temperature operation has been achieved in a quantum cascade laser manufactured in the GaAs/AlGaAs material system. H Page and colleagues from Thales-CSF, France (*Appl. Phys. Lett.* 2001 **78(22)** 3529), described pulsed operation at 300 K of a GaAs/$Al_{0.45}Ga_{0.55}As$ heterostructure. This offers the maximum band offset of 390 meV for this material system without inducing the presence of indirect barrier states, thus achieving better electron confinement and countering the loss of injection efficiency with temperature. The device emitted at a wavelength of around 9 μm, and had a peak power of 600 mW at 233 K.

Metamorphic InGaAs photodiodes

$In_{0.53}Ga_{0.47}As$ photodiodes are usually grown lattice-matched to InP, but can also be grown metamorphically on GaAs substrates. A paper from J Jang *et al.* (*Elec. Lett.* 2001 **37(11)** 707) described a double heterojunction PiIN InGaAs/InAlGaAs/InGaAs photodiode grown by MBE using a 1.5 μm linearly graded InAlGaAs metamorphic buffer. The device structure also featured a chirped superlattice graded bandgap layer and an optically transparent drift region to reduce device capacitance. A low dark current of 500 pA at 5 V bias, a responsivity of 0.6 A/W, and a –3 dB bandwidth of 38 GHz for 1.55 μm light were achieved. The authors are with the University of Illinois at Urbana-Champaign, Raytheon RF Components and the University of Notre Dame (all in the US).

Thermoreflectance probes facet reliability

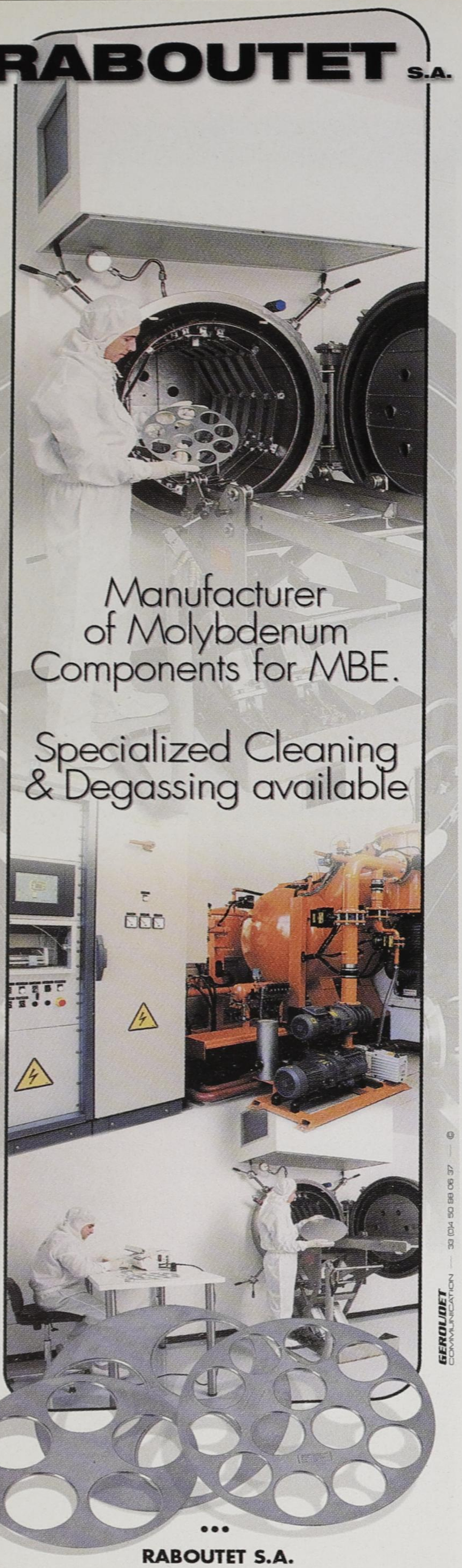
Emmanuel Schaub of the National Research Laboratory of Metrology (Tsukuba, Japan) has applied thermoreflectance measurements to characterize the heating at the facets of GaAs laser diodes (*Jap. J. Appl. Phys. Pt. One* 2001 **40(4B)** 2752). Heating of the output facet by absorption of incident light limits the available optical output power, as excessive heating results in catastrophic optical damage (COD) to the facet. This issue is a barrier to increasing the output power of devices such as 980 nm laser diodes used to pump EDFAs.

The thermoreflectance measurement technique used by Schaub gives not only the surface temperature, but also the optical absorption rate, a key factor responsible for COD. Different absorption rates for coated and non-coated facets have been determined using the technique, and differences between absorption rates for new and aged laser diodes were also observed.

Fiber amplifier boosts 1480–1510 nm band

One route to increasing the bandwidth of fiber-optic networks is to fully utilize the low-loss region of silica fibers (1450–1650 nm). Traditional erbium-doped fiber amplifiers are only suitable for a narrow part of this band. T Kasamatsu *et al.* from NEC have demonstrated that thulium-doped fiber amplifiers can operate in the 1480–1510 nm wavelength band with high optical efficiency (29%) and high output power (+21.5 dBm). An optimized two-stage pumping scheme was developed, using pump laser diodes at 1.4 and 1.56 μm (*Phot. Tech. Lett.* 2001 **13(5)** 433).

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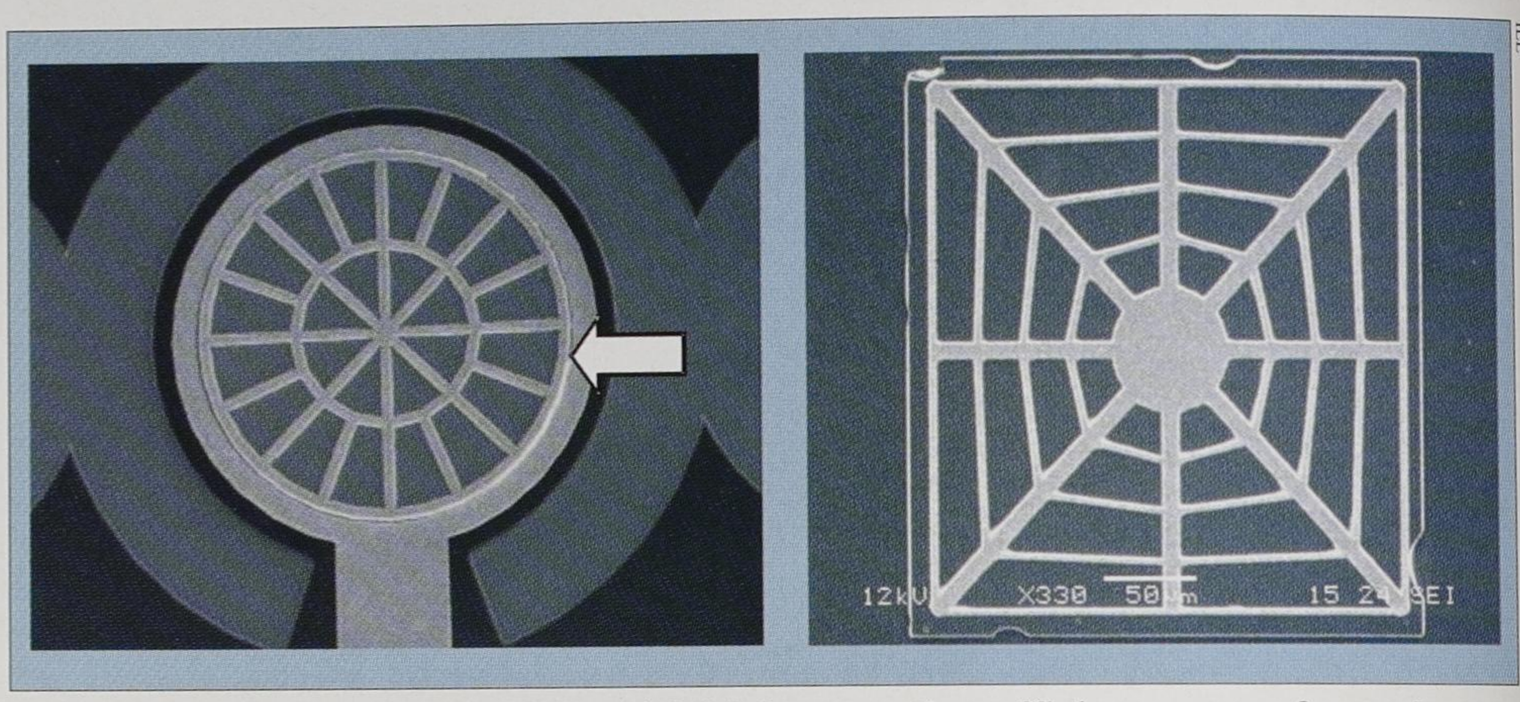
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Efficient AlInGaP micro-cavity LEDs on germanium



IEE

AlInGaP/Ge micro-cavity LEDs with high extraction efficiency were formed using two mask designs for the top metallization. Shortcomings in the initial mask design (left), in which metallization extended to the edge of the device, lead to problems with non-uniformity of current injection, high serial resistance and poor reliability. The arrow indicates a discontinuity at the circular edge. A new mask design is shown on the right.

Conventional LEDs have a theoretical light extraction efficiency limited to 2% due to the total internal reflection at the semiconductor–air interface. Modak and co-workers from IMEC in Belgium (*Elec. Lett.* 2001 **37(6)** 377) described AlInGaP LEDs based on Ge substrates that feature an internal micro-cavity to enhance the extraction efficiency to 5.2%.

The micro-cavity device or MC-LED consists of a 5-period Zn:$Al_{0.95}GA_{0.05}As$/$Al_{0.55}Ga_{0.45}As$ top DBR and 26.5-period Si:AlAs/$Al_{0.55}Ga_{0.45}As$ bottom DBR. The quantum-well region and the cavity consists of three compressively-strained $(Al_{0.1}Ga_{0.9})_{0.43}In_{0.57}P$ quantum wells, with $(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$ as both barrier and spacer layers.

MC-LEDs processed with an initial mask design (see left-hand figure) had a wavelength of 640 nm and exhibited an internal quantum efficiency of 5.2% at 4 mA, as well as producing 1.9 mW of optical power at 20 mA. Modak and colleagues say this demonstrates that high performance optoelectronic devices can be formed on Ge, as an alternative substrate to GaAs.

Dual-wavelength lasers for CDs and DVDs

Systems capable of playing all types of CD and DVD disks, including write-once CD-R media, generally require two lasers, which operate at 650 or 780 nm. Two separate lasers can be used, or two chips can be placed in a hybrid package. A more elegant solution is to use monolithically integrated dual-wavelength chips, as described by K Nemoto *et al.* of Sony (*Appl. Phys. Lett.* 2001 **78(16)** 2270) and T Onishi *et al.* of Matsushita (*Phot. Tech. Lett.* 2001 **13(7)** 550). In both methods, the necessary epilayers for a 780 nm AlGaAs-based laser were grown first. These layers were removed in the area where the second laser was to be positioned. Then, the epilayers for a 650 nm AlInGaP-based laser were grown; these were subsequently removed from above the AlGaAs laser. In the Sony device, the gain-guiding stripes in the 650 and 780 nm lasers were formed by wet etching and ion implantation, respectively. Matsushita used real refractive index guided self-aligned structures, achieving 100 mW and 10 mW output powers for the 780 and 650 nm lasers, respectively.

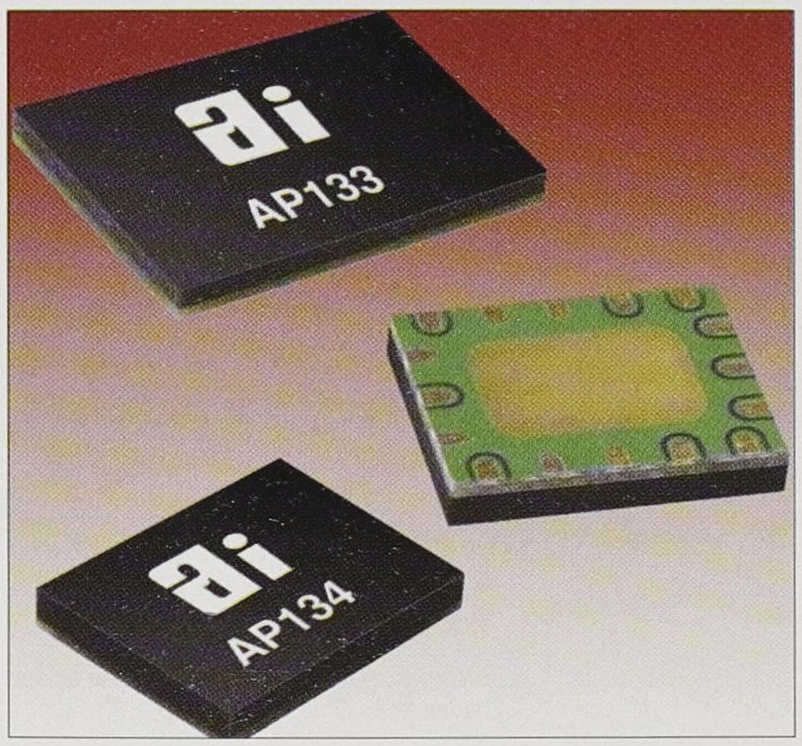
WIRELESS PRODUCTS

Alpha tri-band InGaP PA module

Woburn, MA. Alpha Industries has introduced its first tri-band PA module employing InGaP HBT technology. The AP134 is designed for use in dual-mode wireless handsets and is compliant with General Packet Radio Service (GPRS).

The new module is a fully integrated 50 ohm input/output package that incorporates a silicon bipolar logic controller. Developed for customer-specific wireless handset platforms, the AP134 is part of a family of products addressing GSM-based applications expected to begin volume production by December 2001.

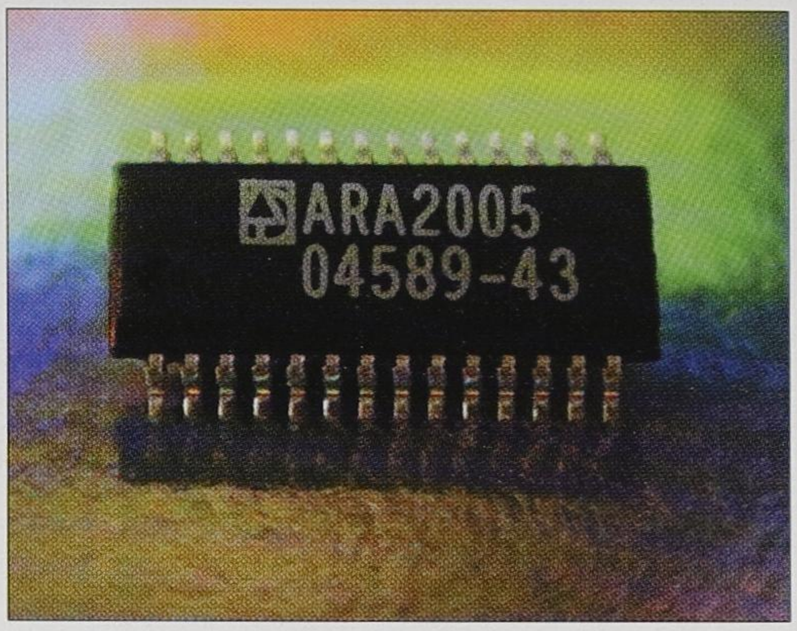
Operating from a 3.2 V power supply, the module footprint is 10 × 8 × 1.6 mm in a MCM land grid array type package. A PAE of 55% and output power of 34 dBm



gain are achieved during GSM operation, and 50% and 31.5 dBm PAE and gain for DCS/PCS modes, respectively.
www.alphaind.com

CATV amplifier from Anadigics

Warren, NJ. Anadigics has released a new GaAs cable television (CATV) chip that provides the reverse path amplification and the output level control functions necessary in two-way CATV system designs. The ARA2005 has been developed for high-speed cable



modems, telephony over cable systems and open cable set-top boxes.

Produced using the company's 6 inch GaAs wafer manufacturing capability, the ARA2005 exceeds MCNS/DOCSIS harmonic performance requirements at +60 dBmV output levels, and operates from a single +5 V supply.

Anadigics' amplifier supports the 5–100 MHz frequency range with a typical noise figure of 3 dB. The ARA2005 also demonstrates a second harmonic distortion level of –75 dBc and third harmonic distortion level of –60 dBc. Both the input and output are matched to 75 ohms.

Sampling now, the device is housed in a 28 pin SSOP and is priced at $2.85 in quantities of 10 000.
www.anadigics.com

M/A-COM unveils new HBT process

Lowell, MA. M/A-COM has introduced two new amplifiers for cellular band and PCS band TDMA/CDMA wireless handsets. The MAAPSS0003 and MAAPSS0006 are two-stage PAs fabricated using the company's new InGaP/GaAs iHBT process, and are intended to offer improved performance and reliability compared to its existing AlGaAs-based HBT emitters.

Operating from a single 3.0–3.5 V supply, the devices feature drive and bias control circuitry elements and are available in 3 × 3 mm or 4 × 4 mm FQFP-N packages. In the 824–849 MHz frequency range of operation, M/A-COM's PAs typically provide 29 dBm of output power and 35% linear efficiency.

The MAAPSS0006 also pairs with the company's MD59-0054 upconverter/driver IC. Both devices are priced at $1.99 in quantities of 100 000.
www.macom.com

Fujitsu unveils modulator driver

San Jose, CA. Fujitsu Compound Semiconductor has developed a 10 Gbit/s modulator driver IC. The FMM3109PG is designed for non-return to zero operation in optical networks and features a rise/fall time of 40 ps, and measured jitter of 4 ps.

The power consumption is rated at 0.5 A, and the output voltage is 3 Vpp for the modulator-integrated laser and differential input modulator. Internal termination is set at 50 ohm, and the device features a typical output voltage swing of 3.0 V and a single 6.8 V power supply. The FMM3109PG is housed in a 24 pin hermetic package.
www.fcsi.fujitsu.com

Integrated CDMA module from RFMD

Greensboro, NC. RFMD's new RF3404 product is a fully integrated, dual-band tri-mode receive module incorporating LNAs, SAW filters and mixers for CDMA handset and PDA applications. The device is based on SiGe and employs two RF SAW filters and integrated passive components. This



reduces the component count in the dual-band receive portion from 25 external components to just three.

RFMD's module contains the receive chains for both the cellular and PCS

bands. Each chain contains an LNA, RF image SAW filter, mixer preamplifier, mixer, LO input amplifiers and LO transmit VCO buffer amplifier, integrated into a land grid array laminate module package measuring 8 × 8 mm.

The cellular band exhibits a gain of 25 dB, with a typical noise figure of 2.0 dB, and the PCS band gain is typically 25 dB with a noise figure of 2.2 dB. At both frequencies, the IP3 point is –9 dBm.

Both components and fully assembled engineering evaluation boards are currently available from the company.
www.rfmd.com

TriQuint LNA suits CDMA handsets

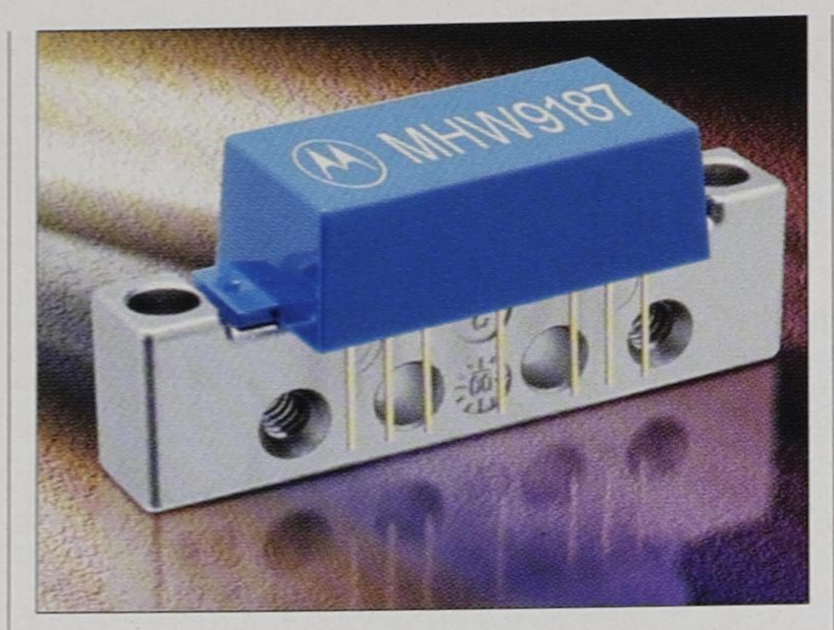
Hillsboro, OR. TriQuint has released the TQ3M31, an analog and CDMA cellular and PCS band dual-band LNA. The device offers tri-mode, dual band CDMA (IS-95 standard) operation resulting in a phone capable of operating in all geographic markets.

Housed in a leadless 3 × 3 mm package, TriQuint's device features low power consumption and operates from a 2.7 V power supply. On-chip integration of mode and gain select functions allows a choice of CDMA or AMPS modes and the ability to adjust the gain and current consumption. The TQ3M31 can also be combined with the company's TQ5131 and TQ5631 mixer ICs to form a complete tri-mode RF receiver front-end.

In the cellular mode, the gain is typically 13.0, and 13.5 dB for the PCS frequency, with noise figures of 1.4 and 1.5 dB, respectively. The IP3 power output figure is 10 dBm for cellular and 8 dBm for PCS bands. The device can be purchased for $1.50 in 1000 quantities.
www.triquint.com

Motorola releases CATV amplifier

Phoenix, AZ. Motorola's new MHW9187 amplifier targets 870 MHz CATV applications and is based on the company's high output power doubler. This device is the first in a series based on the company GaAs HVPHEMT 2 process, which Motorola says leads to improved output and reduces the number of cascaded



amplifiers required in a system. A complete series of preamplifiers are also in development based on the process.

The MHW9187 operates in the 40–870 MHz range and is specified for 79, 112 and 132 channel performance. The device is housed in a CATV package at a cost of $38 in quantities of 10 000.

"The MHW9187 is designed to provide the highest output in order to lower system distortion and to drive longer lines than was previously possible," said Lynelle McKay of Motorola's Wireless Infrastructure Systems Division.
www.motorola.com

Low noise figure from SiGe LNA

Sunnyvale, CA. Stanford Microdevices has introduced the SGA-8343, a SiGe-based HBT LNA offering high gain and linearity across the DC to 6 GHz band. Manufactured using an external foundry process, Stanford's device is designed to offer 0.9 dB of noise at 0.9 GHz and 1.1 dB of noise at 1.9 GHz, and features a gain of 24 dB at 0.9 GHz and 19 dB at 1.9 GHz. The third-order output intercept point (IP3) is +28.5 dBm.

The SGA-8343 is housed in a standard SOT-343 surface-mount plastic package, and is priced at $0.26 each in quantities of 10 000.
www.stanfordmicro.com

OPTO PRODUCTS

Hamamatsu builds TIAs into receivers

Bridgewater, NJ. Hamamatsu has introduced two InGaAs PIN photodiodes with built-in transimpedance amplifiers suited to optical fiber systems, including Fibre Channel, Gigabit Ethernet and SDH.

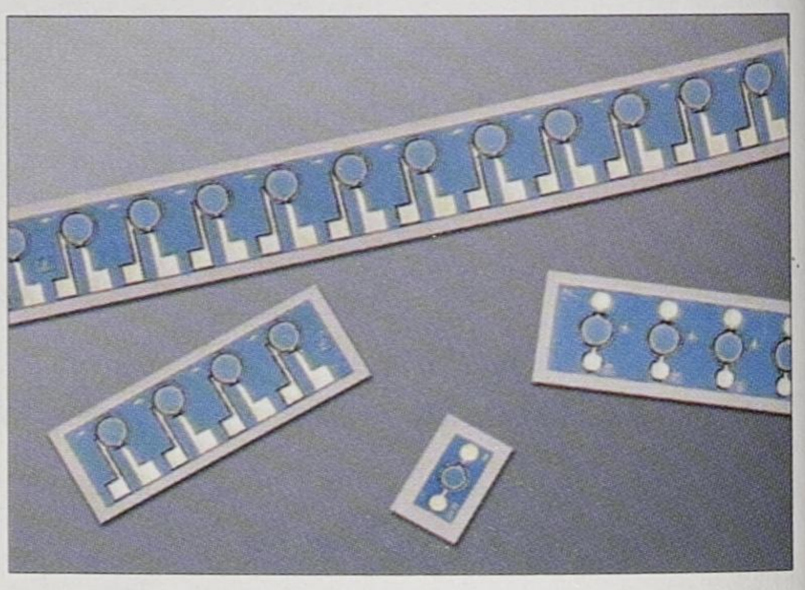
The G8338 and G8339 are receivers that exhibit peak sensitivities at 1.3 and 1.5 µm and feature a dynamic range of –37 dBm to –5 dBm at data rates up to 155 Mbit/s. The photosensitivity is 27 V/mW. Both devices operate at a supply current of 25 mA and an output bias voltage of 1.5 V, and are designed to be stable in the –20° to +70°C temperature range.

The G8338 is available in a TO-18 package and features an active area of 0.08 mm. A flat window is a standard fixture for the G8338, which can also be modified to accept a lens for efficient and easy coupling to an optical fiber. The G8339 series is available in five different packages based on board mounting of SC, LC or FC connectors.
usa.hamamatsu.com

High-speed GaAs PINs and PIN arrays

West Lafayette, IN. OptoLynx has unveiled a line of high-speed GaAs PINs and PIN arrays targeting 850 nm optical links operating up to 10 Gbit/s.

The 10G PIN receiver features a 40 µm diameter active area and exhibits a typical responsivity of 0.48 A/W and



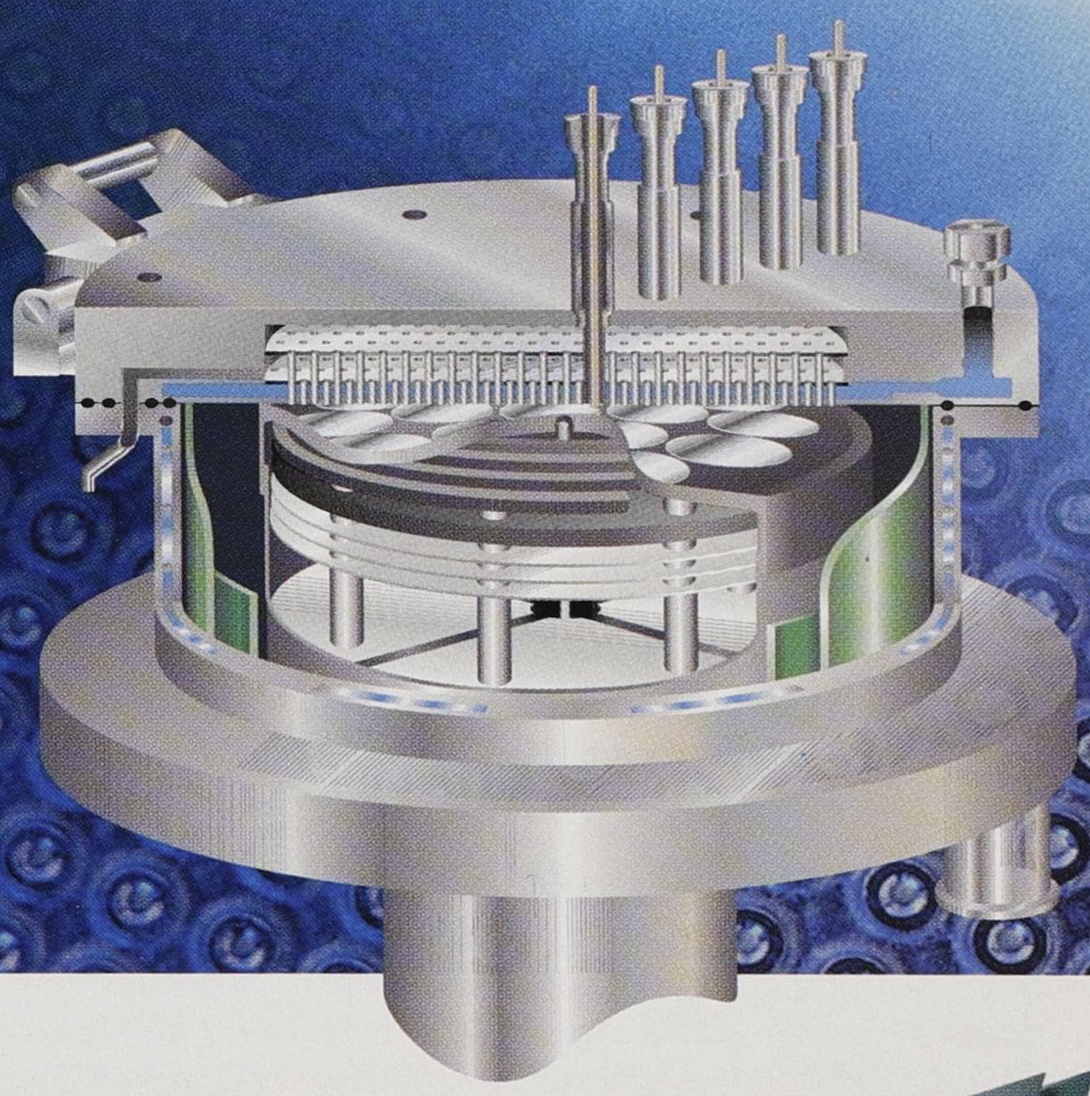
0.28 pF capacitance. The 3.125G PIN is based on a 100 µm diameter active area, and offers 0.55 A/W responsivity and a capacitance of 0.45 pF. Both devices exhibit a dark current of 50 pA, and operation is achieved using a 1.5 V bias.

Both the 3.125G and 10G are available as single element detectors or as 1 × 4 and 1 × 12 arrays. Applications include serial and parallel Gigabit Ethernet, Fibre Channel, VSR SONET and proprietary links.
www.optolynx.com

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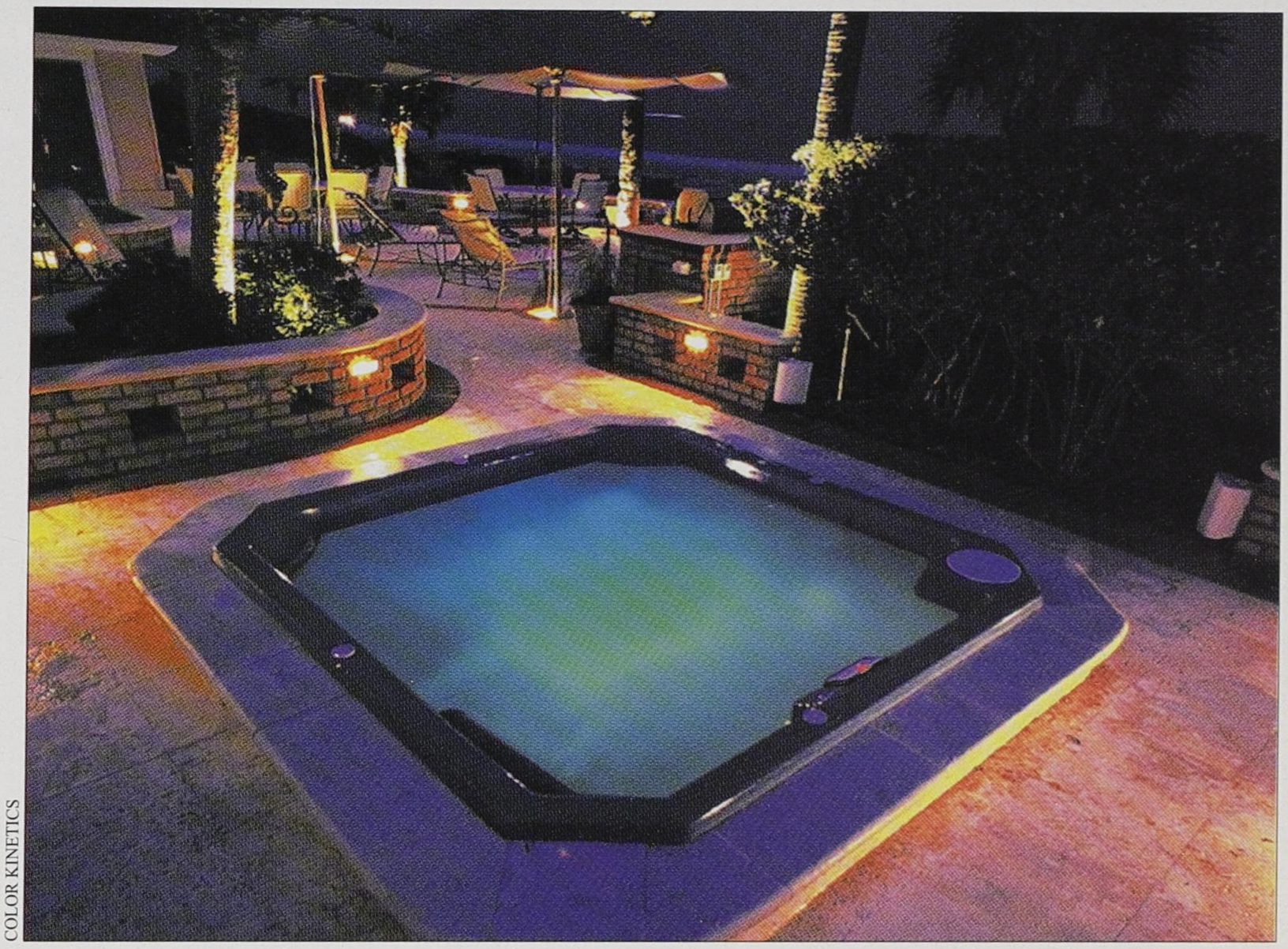
LEDs shine at LightFair 2001

Lighting companies are rapidly recognizing the benefits of LEDs and incorporating them into a wide range of products, writes ***Robert Steele*** *of Strategies Unlimited.*

LightFair International, North America's largest architectural and commercial lighting trade show and conference, was held this year on 29 May – 1 June at the Las Vegas Convention Center. Over 400 exhibitors were on hand to display the latest in commercial lighting products to the more than 17 000 attendees. While the vast majority of exhibitors and products had nothing to do with LEDs, it was clear that LED-based products are increasingly making inroads into the lighting industry. Approximately 10% of the exhibitors offered products in which LEDs are used.

In general, LEDs are not being employed in applications that could be considered "illumination" – they are still too expensive for that purpose. However, they are used in a variety of decorative, architectural, theme and accent lighting applications. Many of these applications involve situations in which the frequent replacement of incandescent lamps is physically difficult and/or costly. While some companies specialize in LED lighting, other conventional lighting companies are introducing LEDs as part of a broad spectrum of lighting products, some of which happen to use LEDs.

In addition to the exhibit floor, three LightFair conference sessions had significant LED content, and one was entirely devoted to LEDs. A workshop entitled "Understanding new and emerging light source technologies" featured a presentation by Makarand "Chips" Chipalkati, marketing and technical manager for LED light sources at Osram Sylvania. Another workshop entitled "LEDs... what the technology delivers today for architectural applications" offered an overview by Nadarajah Narendran of RPI's Lighting Research Center, as well as presentations by Osram Sylvania, GELcore, Philips Lighting/LumiLeds and Color Kinetics. A seminar entitled "Competitors or compliments: will LEDs replace fiber optics?" offered a panel discussion and spirited debate on the pros and cons of each type of light source.



COLOR KINETICS

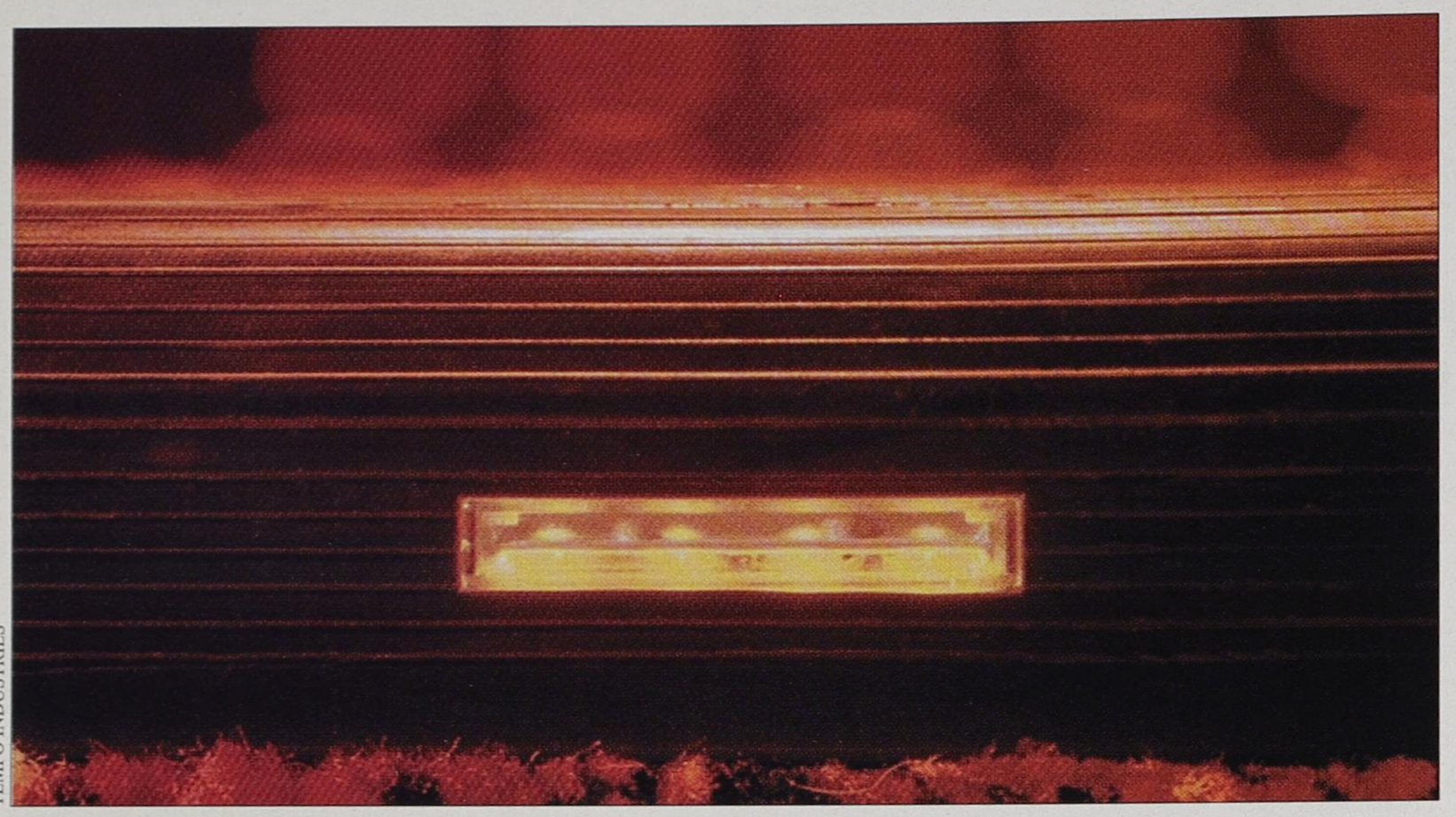
Fig. 1. Color Kinetics has developed the Colorscape underwater LED lighting system, capable of a wide range of color-change effects.

From the content of these sessions, and the audience response to them, it was clear that there is a great deal of interest in the lighting community regarding LEDs. There is also a thirst for knowledge about LEDs – their properties and operating characteristics, cost, reliability, luminous efficacy, lumen maintenance, and many other issues. For white lighting, issues of color rendering and color temperature are of keen interest. The LED supply industry has been slow to come to terms with the needs of the lighting community, and further penetration of lighting applications will require the LED suppliers to do a better job of educating lighting companies on the attributes and benefits of LEDs. Some suppliers have started to do this, but there is still a long way to go.

An amazing variety of LED lighting products were on display at LightFair 2001, and some of these are summarized in the following paragraphs.

Signage

Perhaps the most ubiquitous product was the LED EXIT sign. Because of their energy efficiency and long lifetimes, high-brightness LEDs have virtually taken over the EXIT sign lighting business, and numerous companies offer these products. Interestingly, one company, LightPanel (West Lebanon, NH), thinks it has a solution that will replace LEDs. LightPanel makes a green electroluminescent material for EXIT signs that has a 30-year life, and is more efficient than LEDs.



TEMPO INDUSTRIES

Fig. 2. LED step-lighting installation manufactured by Tempo Industries; such products are widely used in theaters with stadium-style seating.

The company claims to be doing a lot of LED replacement business, and says that these signs are getting a good reception in California because of the energy crisis. LightPanel uses a direct view technology, rather than indirect view in the case of LEDs, so a high level of light emission is not required for good visibility.

Teledyne Lighting and Display Products (Hawthorne, CA) has a background in custom LED displays for military aircraft. On the civilian side it has been manufacturing LCD backlights, including microdisplays and displays up to 6 inches in width, and has also provided the LED backlit red diamond symbol for all 5000 Arco gas stations.

Teledyne is now entering the commercial LED lighting business, with a focus on signage (both channel letters and backlights). The company has a channel letter system with LEDs interconnected along a wiring string. It can use several types of LED, including standard T-13/4 and high-flux lamps, which are placed in a lensed housing. Teledyne is working with sign OEMs, and it believes LEDs are competitive with neon if all costs are properly accounted for. The company is also making chip-on-board sources and socket-compatible incandescent replacement assemblies.

Architectural and accent lighting

Color Kinetics (Boston, MA) has been a pioneer in the use of LEDs in architectural, retail and decorative lighting applications using its patented Chromacore technology that can be used to digitally produce up to 16.7 million colors. One of its latest products on display at LightFair is an underwater version of its ColorBlast digital lighting fixture that can be used for illumination of swimming pools, fountains and reflecting pools (see figure 1). Color Kinetics also introduced a new line of LED consumer products, including Sauce – a color-changing wand for children – and a multicolor nightlight.

Tokistar Lighting (Anaheim, CA) focuses on accent lighting using LEDs, especially strip lighting. The lamps are widely spaced so the cost is low. Tokistar uses special optics to get better directionality of the light, and also has custom color-changing garden and path lights. LEDs are used because of their low power consumption. Tokistar says that white is still a problem with LEDs – they look like "dirty yellow" – so it still uses incandescents for white light applications.

FarLight (Torrance, CA) makes obstruction lights, architectural lights, transportation lights etc using LEDs in fixtures that are very heavy duty in appearance. The company's specialty is optics, and it has a patented process with which light can be directed in any pattern in any direction. The company has used fiber optics in the past, but now uses Lumi-Led's Luxeon LEDs (see below) exclusively. Most of FarLight's products use just a single Luxeon source, but some use multiple Luxeon sources. The main drivers for LED applications are ease and cost of maintenance and low energy consumption. Most uses are in areas that are hard to access, such as airport runways, and the LEDs themselves are expected to last the lifetime of the fixture.

Louis Poulsen (Fort Lauderdale, FL) makes products such as architectural lighting, area lights, path lights and market lights. It has introduced a new line of LED lights in the US in different colors, including white – the company has had success with these in Europe and especially the UK. One fixture that has 172 blue LEDs won an award at LightFair. The fixtures are constructed from stainless steel throughout, and the LEDs are mounted on a printed circuit board along with the transformers, which are very compact. This is a modular unit that can be removed and replaced as a unit. The lifetime of the transformers is estimated at 65 000 hours, which makes them the limiting factor in the lifetime of the fixture. The company reports a high level of customer interest and a high level of awareness about LEDs.

Tempo Industries (Irvine, CA) is working exclusively with LEDs to make products for theater (cinema) lighting and strip lighting. It considers LEDs to be more reliable and more energy efficient than incandescent lamps, and the cost is "acceptable". The company switched to LEDs about three years ago. One year prior to that move, there was a big change in the theater industry, when it switched to stadium-style seating with more stairs. Theater stairs all need to be lit for safety, and LEDs provide a high-reliability source (see figure 2). Tempo is now also doing exterior contour lighting of buildings, cove lighting, etc including RGB color-change lighting. Tempo sees RGB lighting with color changing effects as a big driver in the LED lighting business.

Modular International (Pittsburgh, PA) has been making LED products for about three years and offers LED marker lights, path lights, accent lights, etc in all colors, including white. It has ruggedized versions that can be placed in roads and can stand up to vehicle traffic including large trucks; these have been used at an airport in Germany. One line of products, including the ruggedized version, runs off a 24 V source, while other products have built-in transformers so they can run directly off 120 V AC. One of Modular's products is a circular blue marker light. There is now a law in Pennsylvania that all wall-mounted fire extinguishers in

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buildings have to be designated by a blue marker light, and this is Modular's target market for this product.

Special-T Lighting (Burbank, CA) has been manufacturing fiber-optic lighting systems for 13 years and is now making LED lighting products as well, mainly for commercial venues such as fast food restaurants. It has strip lights in all colors, plus RGB assemblies with which it can produce color-changing effects. According to Special-T Lighting, there is a growing interest in, and requests for, LED sources among architects and other customers. The low maintenance aspect of LEDs is a real driver. High cost is still an issue, but this applies mainly to blue and white LEDs rather than red and yellow. However, the company acknowledges that fiber-optic systems are also expensive.

Super Vision (Orlando, FL) has been in fiber-optic lighting since 1998 and has used LEDs since the beginning of the year. It is making LED strip lights, flexible strips, and neon replacements. It thinks neon replacement is a good application for LEDs because neon requires high voltage, is breakable, and is subject to failure from bad weather. Reliability is a major factor in favor of LEDs.

RSA Lighting (Chatsworth, CA) has a new strip lighting product for which it developed a special reflector package for the LED chip: this is being manufactured by a Japanese company. The strip light is viewed as a source for multiple lighting applications.

TIR Systems (Vancouver, Canada) introduced its new Destiny series of architectural lighting products, which incorporate Luxeon LED arrays from LumiLeds (see below). The first two products in the series are an illuminated pole for decorative landscape and public area applications, and a matching wall-mounted "color bar" that can be used as a vertical design element on the exterior of almost any commercial or corporate structure.

Bruck (Costa Mesa, CA) is a German lighting fixture company that obtained a line of LED outdoor architectural lights as a result of a recent acquisition. Bruck's LED fixtures have been used on bridges, at the San Diego Zoo, on Nordstrom stores, and many other sites. These are decorative lights in various colors that can be used as a low wattage source to replace 50 W incandescent bulbs that burn out frequently. Bruck focuses on applications with high replacement costs. Its LED fixtures have a built-in "smart chip" transformer. The company also offers an LED MR-16 lamp, which is used for color accents, for example in the children's reading area of a library to give a color splash (see figure 3).



BRUCK LIGHTING SYSTEMS

Fig. 3. Bruck Lighting Systems' MR 16 fixture is used for applications such as color accent lighting.

Specialty lighting

Watt-Man (Charlottesville, VA) makes LED assemblies for incandescent bulb replacement. EXIT signs comprise its biggest business, but it has a number of other products as well, including all kinds of signal lights, among which are offshore navigational aids. Maintenance is the biggest issue for its customers, and the company is selling to applications that have high maintenance and replacement costs. Watt-Man guarantees its LED products for five years.

Illumination Polymer Technologies (Naperville, IL) makes a polymer diffusing material for LEDs. It is using this material to make a variety of products such as displays and signs, and light wands for aircraft ground control (e.g. for the navy). Portable products such as wands have very high battery life. IPT also makes battery-powered point of sale displays, and is working with the toy industry on new applications.

Lighting and Electronic Design (Henderson, NV) has a Turbo Flare LED-based emergency flasher product that is being used by 1200 police departments around the world. It is made from a special plastic, is very rugged and can be run over with a truck. In addition, the company has been doing theater lighting for years. It also makes rope and strip lights with LEDs, which can be used for cove lighting. The company developed a cluster light with a special lens that is being used on the roller coaster ride at the new Disneyland California Adventure. These are in white and blue, and outline the shape of Mickey Mouse. Disney needed a very-long-life product because of the height of the roller coaster. LED also has an MR-ll lamp product and is doing cluster-changing-effect cove lighting with a RGB strip.

Boca Flasher (Boca Raton, FL) is doing a lot of LED sign work, such as marquee replacements for incandescent bulbs. It targets applications where replacement costs are high. Boca equipped all of WalMart's distribution centers with LED red/green "jelly jar" signal lights. This was a case where replacement costs for incandescent bulbs were a significant problem, since a worker had to go up on a scissors lift every time a bulb needed changing. Boca is also selling to companies that work under lighting maintenance contracts. LED incandescent replacements are a real money saver for them.

Technical Consumer Products (Aurora, OH) makes LED cluster lamps for signs, color bulb replacements, signal lights and night lights. It targets applications where maintenance costs are high, mainly in industrial and commercial settings, such as signal lights for factory floors. The company has sold amber signal lights to the US Navy for use on its dockyards. TCP is experimenting with different applications, such as a white LED lamp cluster for use in elevators.

LED suppliers

GELcore (Cleveland, OH), the joint venture between GE Lighting and Emcore, has offered LED traffic signals since its acquisition of Ecolux last year. At LightFair it exhibited LED crosswalk signals, as well as its new line of channel letter lights and MR-16 lamps.

LumiLeds Lighting (San Jose, CA) used the occasion of LightFair to introduce its new Luxeon line of high-flux LEDs. These devices are available in blue, green, blue-green, amber, red-orange, red and white, as both single devices and in the form of linear, rectangular and circular arrays. Some of the amber, red-orange and red devices are based on LumiLeds' new high-efficiency truncated inverted pyramid structure (see *Compound Semiconductor* April 2001, p59).

The fluxes obtainable from single de-

vices range from 11 lumens in blue to a maximum of 55 lumens in red-orange. Luxeon arrays can produce up to 792 lumens in red. LumiLeds is working with lighting OEMs in Europe and the US to introduce its new Luxeon line. The Luxeon products will be in full production by mid-summer, and the performance will be improved from current versions. In particular, the output of the white version is expected to be significantly higher than the current 18 lumens.

Osram Opto Semiconductors (Regensburg, Germany) is now offering its LED lamp module products on a commercial basis. These modules integrate discrete high-brightness LED lamps into forms and functions targeted for specific lighting applications. In the US the Osram Sylvania sales force is being used to sell these products. Osram offers strip lights, channel letter lighting systems, marker lights, traffic signal modules, etc. It also offers "effect lights", which are a 2 × n array with lensing to achieve a four-degree viewing angle for architectural lighting effects.

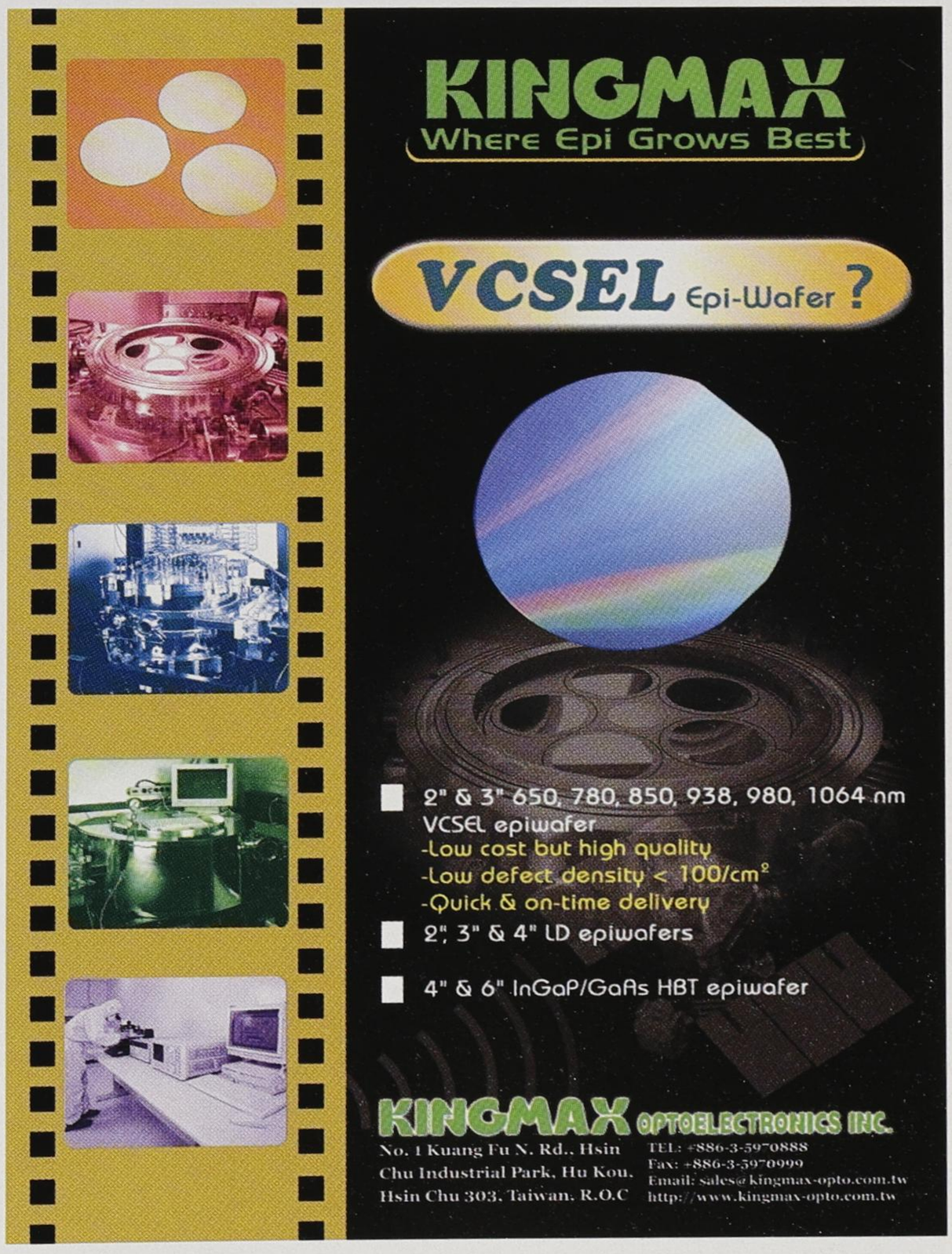
Oriol (Santa Clara, CA) is a start-up that makes GaN chips and lamps. It claims a capacity of 17 million units per month. The company says that its approach has many fewer process steps than the conventional GaN process and so is cheaper. Oriol's intellectual property has been developed through several universities, including Berkeley, the University of Illinois, and two universities in Korea. It has 13 patents applied for and 20 more in process. The company is over one year old, but it has just started production at its facility in Santa Clara. Packaging is being done in Taiwan, Hong Kong and Korea.

Opto Tech (Hsinchu, Taiwan) has two principal LED businesses. It is the world's largest producer of LED chips, with a capacity of 1.5 billion chips per month. It also has a full-color LED sign business. At LightFair 2001, Opto Tech introduced its line of new lighting products. These include strip lights, channel letter lights, neon replacements, and cluster lamps.

Norlux (Carol Stream, IL), a subsidiary of Uniroyal Optoelectronics, is using a chip-on-board approach to mount multiple high-brightness LED chips to get high flux. It has developed a low thermal resistance package for this purpose. It appears to be a PCB-type material, but uses a special layer with low thermal resistance. Norlux also employs an encapsulant to cover and protect all the chips. The red package produces 120 lumens, and is priced at $35 in large quantities. The company has other single colors as well as a three-color package that can produce varying colors, including white. Norlux is working with lighting OEMs to develop custom applications and products.

Robert V Steele (rsteele@strategies-u.com) is director of Optoelectronics for Strategies Unlimited, a market research firm based in Mountain View, CA, that specializes in compound semiconductors, including LEDs. The company's annual conference on high-brightness LEDs, Strategies In Light, will be held in San Francisco on 6–8 February 2002.





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MIOMD 2001 conference

This year's Mid-Infrared Optoelectronic Materials and Devices conference featured developments that are enabling mid-infrared lasers and detectors to operate both at higher temperatures and further into the infrared, reports ***Yves Rouillard****.*

Mid-infrared lasers and detectors have made tremendous progress over the past decade, with room temperature laser emission now possible in the 1.7–12.0 μm wavelength range. The most recent advances were described at this year's Mid-Infrared Optoelectronic Materials and Devices (MIOMD) conference on April 1–4, in Montpellier, France. 120 delegates met to discuss advances in frequency converters, quantum cascade lasers, MQW lasers, VCSELs, LEDs, detectors and thermophotovoltaic devices.

Detectors track industrial processes

According to S Smith of Edinburgh Instruments, Scotland, gas sensors are required for industrial processes with detection limits of the order of 1% for food packing to less than 1 ppm for trace gas detection. Examples of wavelengths required for analysis include 3.4 μm for CH_4 and 4.2 μm for CO_2 gases, 4.6 μm for CO, and 5.5 μm for the explosive Semtex.

Beyond the 4.5 μm wavelength, however, low-cost filament lamps (with product costs of $100–500) are no longer favored as infrared emitters, and Smith described advances in InSb diode detectors operating at 300 K for use as potential replacements. Using immersion optics, devices with a detectivity D* of 2.6×10^9 cmHz$^{0.5}$ W^{-1} were possible at 5 μm.

Leak detection is another important area for industrial process monitoring, particularly for pipelines carrying CH_4. To date, specially adapted vehicles have been used to traverse pipelines, according to F Bournazaud of French company GDF. The "car" is equipped with a flame ionization detector. However, the low response time of the detector limits the speed of the car to 20 km/h. Bournazaud revealed that laser diode detectors, developed in collaboration with gas detector manufacturer Oldham, are allowing the measurement collection rate to be considerably increased.

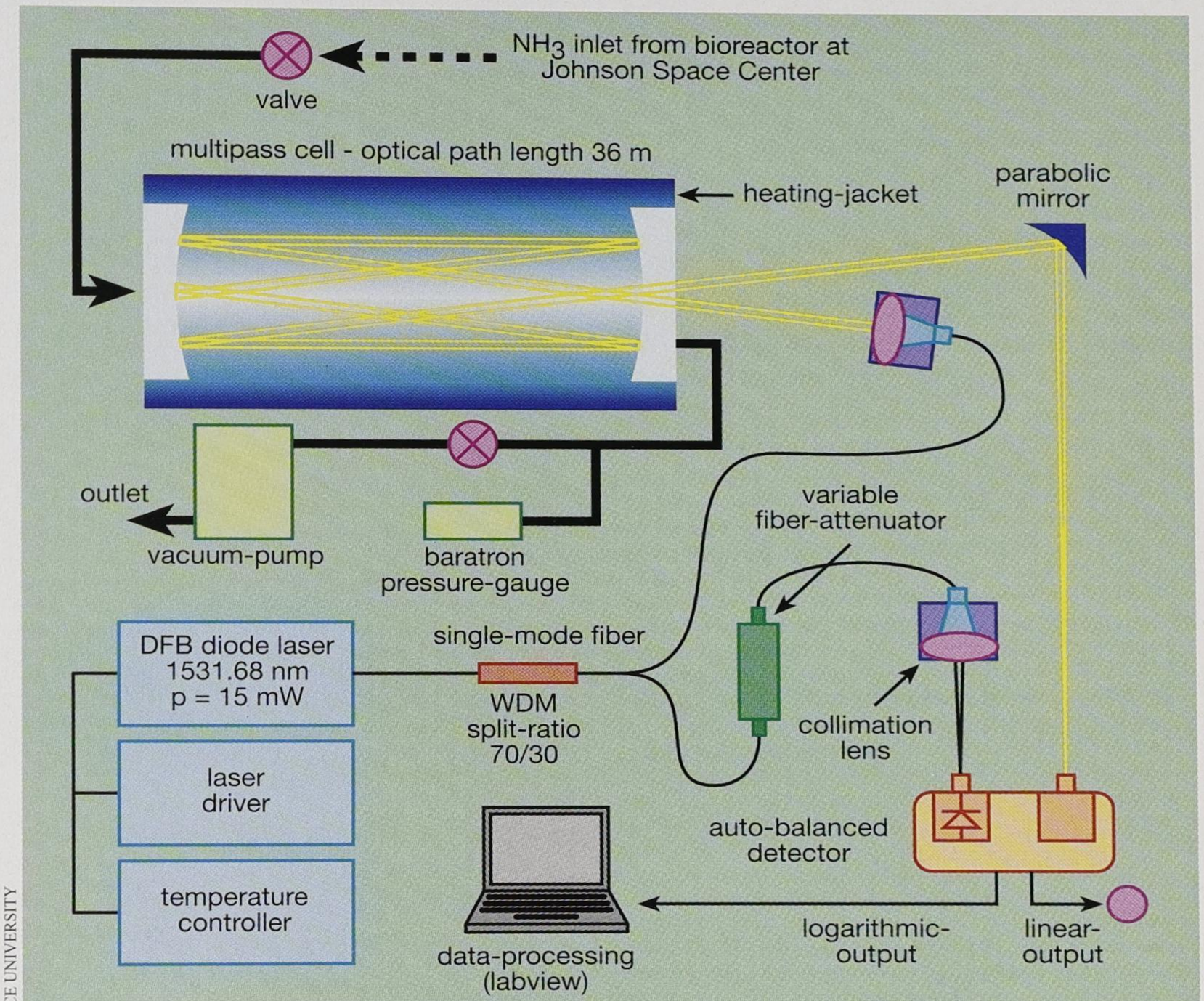


Fig. 1. Schematic set up showing the use of a 1531 nm DFB telecom diode laser to detect NH_3. The detector features a 36 m path length that senses low concentrations of NH_3 in a bio-reactor developed for water processing at the NASA Johnson Space Center.

Fiber for infrared applications

New kinds of fiber are needed to counteract the lack of transmission beyond 2.5 μm using silica fiber. A Katzir of the University of Tel Aviv, Israel, discussed developments in extruded single crystal silver halide ($AgCl_xBr_{1-x}$) fibers adapted for transmission in the 3–30 μm spectral range. Using such fibers, CO_2 laser power densities could exceed 15 kW/cm^2, which is sufficient for material heating and cutting, or endoscopic laser surgery.

The Tel Aviv group has produced fibers with diameters of 0.5–1.0 mm and lengths up to 10 m. Minimum losses are still as high as 0.2 dB/m at a wavelength of 10 μm, largely as a result of the relative lack of maturity of the approach. However, once fully developed, this new fiber could address fiber transmission limitations.

Telecom lasers aid spectroscopy

Absorption spectroscopy techniques that

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use near-infrared vibrational overtones and combination bands play an important role in detection schemes for gas sensors in the 1–3 μm, and 3–25 μm spectral regions using fundamental bands.

Different sources are envisaged depending on the exact wavelength and detection limits required, and F Tittel (Rice University) described a number of variations. Candidates include telecommunications lasers, difference frequency generation and quantum cascade (QC) lasers.

An example of a gas sensor configuration for NH_3 detection that makes use of a 1.5 μm DFB telecom laser is shown in figure 1. The schematic shows the set up required to detect NH_3 employed at the NASA Johnson Space Center on a bio-reactor developed for water reprocessing. According to Tittel, fiber pigtailed telecom DFBs operating in CW mode are highly suitable. Where appropriate, Yb and Er/Yb fiber amplifiers can also be used to boost power and provide fiber-beam delivery. Quantum cascade lasers have also been employed, operating in pulsed mode at room temperature, or alternatively CW mode lasers operating at liquid nitrogen temperature.

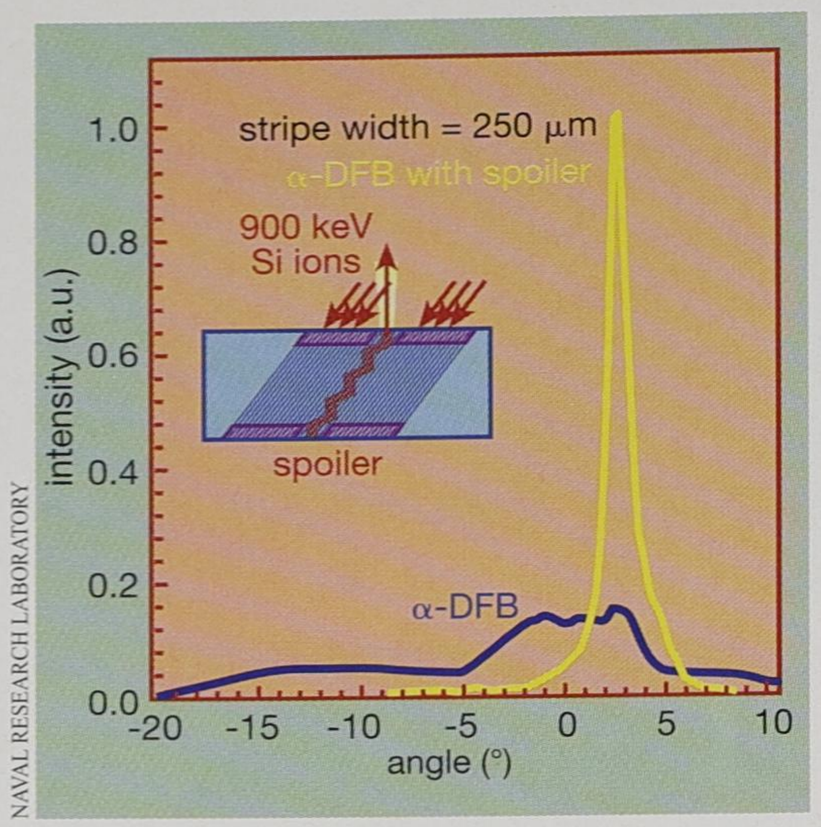
Finally, optical parametric oscillators (OPOs) can be used as frequency converters. These devices employ $LiNbO_3$ crystals to pump the near-infrared telecom laser diodes, and can be integrated into a portable NH_3 sensor. Sensitivities in the three approaches were found to range from 10^{-6} to 10^{-8} cm^{-1}.

Cavity ring-down spectroscopy

Cavity ring-down spectroscopy (CRDS) was introduced in the 1980s as a way to enable absorption measurements using pulsed laser sources, which, according to D Romanini (University of Grenoble), would otherwise have remained unsuitable for absorption spectroscopy.

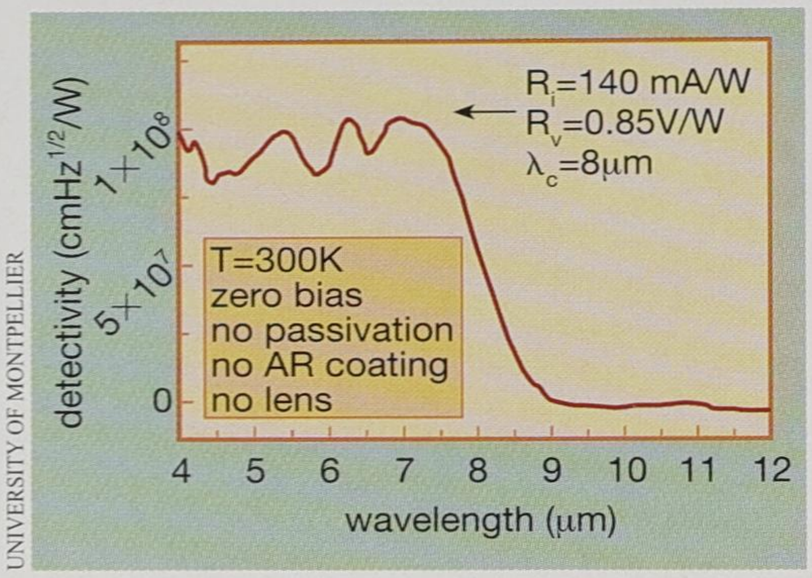
CRDS uses a short light pulse coupled into a stable optical cavity formed by two highly reflecting mirrors. The light entering the cavity on one side oscillates or "rings" back and forth many times between the two mirrors, and the time behavior of the light inside this cavity is monitored.

Being dependent on the rate of absorption rather than the magnitude, the advantage compared to conventional absorption spectroscopy lies in the intrinsic insensitivity to light source fluctuations, and the very long effective path lengths (many kilometers) in a sample with a volume of a few cubic centimeters.



NAVAL RESEARCH LABORATORY

Fig. 2. Silicon ion bombardment has been used to fabricate α-DFBs with "virtual mesas" and more restricted regions (called "spoilers").



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Fig. 3. CW optical output power of a GaInSbAs/GaAlSbAs QW laser versus current at different temperatures (cavity length = 0.95 mm).

Two CRDS set ups were described: one allows the cavity length to be altered using a piezo element (a swept-cavity scheme), and the second takes advantage of optical feedback in the cavity. The detection sensitivity is 3×10^{-10} $cmHz^{0.5}$ W^{-1} for the swept-cavity scheme, and trace concentrations of CH_4 as low as 10 ppb can be detected using this approach.

A Vicet presented a tunable diode laser absorption spectroscopy sensor developed at the University of Montpellier. The sensor is based on a GaInAsSb/AlGaAsSb QW laser diode. The diode is grown on GaSb substrates by MBE and fabricated into a narrow (5 μm) ridge laser to provide single-mode, CW operation up to 140°C. Tunability from 2.2 to 2.4 μm permits the detection of CH_4, CO, H_2O, HF and NH_3 in ambient air. For an optical path of 13 m, the detection limit for CH_4 was 0.17 ppm.

VECSELs

Diode-pumped tunable vertical external cavity surface emitting lasers (VECSELs) show great potential for mid-infrared devices operating up to 3 μm in CW mode. In particular, the external cavity maintains a diffraction-limited beam output at high power levels, reducing the line width in single-mode operation and rendering the system insensitive to feedback.

A Garnache of the University of Southampton described a VECSEL. The device is a monolithic structure consisting of a bottom Bragg mirror, QW active region and an external cavity comprised of a void surmounted by a dielectric mirror. For spectroscopy applications, the cavity void is filled with the gas to be analyzed.

The device is pumped by an 830 nm GaAs-based diode. The VECSEL emission is centered on 1 μm using a GaAs structure, and 2.2 μm if a GaSb structure is used for the VECSEL active region.

The principal advantage is that the effective optical path inside the external cavity can be as high as 18 km, which allows for high sensitivity. In addition, a broad tunability of up to 60 nm allows for a much wider detection range. The potential sensitivity of this new kind of compact spectrometer is $\delta I/I < 10^{-8}$.

Micro-cavity light emitters manufactured using an MBE-grown CdHgTe active region and two evaporated YF_3/ ZnS Bragg mirrors were presented by E Hadji (CEA-Grenoble). Evaporated mirrors allow the emission wavelength to be tailored and the line width to be fitted to the absorption band of a particular gas.

These devices feature a total micro-cavity region of around 5 μm, and are pumped using an uncooled infrared GaAs laser diode to produce emission ranging from 2 to 6 μm. An important wavelength lies at 3.3 μm, used primarily in the detection of CH_4.

By employing a piezoelectric actuator to control the movement of the mirror, a tuning range of 300 nm was possible, while the sensitivity to CH_4 was of the order of 1 ppm. The cavity volume of such a device also lends itself to scaling, and a 1 cm^3 cavity would make a laser sufficiently compact to allow integration into a gas detection micro-system.

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II-VI devices

Edge-emitting lasers based on II-VI materials (i.e. lead-salts) are typically used for chemical gas analysis and atmospheric pollution monitoring. This is a result of the ability to access emission wavelengths out to 30 μm, and achieve high CW output powers at temperatures up to 223 K.

II-VI surface emitters are also now beginning to emerge, and T Schwarzl (University of Linz) described a 3.1 μm VCSEL with laser emission up to 65°C. The lasers were based on two PbEuTe/EuTe Bragg mirrors and nine PbTe QWs in the active region, optically pumped using a 1.97 μm source.

Substrates

In terms of world sales volumes of compound semiconductor substrates, the quantity of wafers used for mid-infrared devices is small compared to GaAs and InP for wireless and optoelectronics applications). According to I Grant of Wafer Technology, sales are led by GaAs with $300 million, followed by InP with $50 million. The remaining $5 million of the market can be broken down as 50% for InSb, 36% for InAs and 14% for GaSb.

Frequency converters

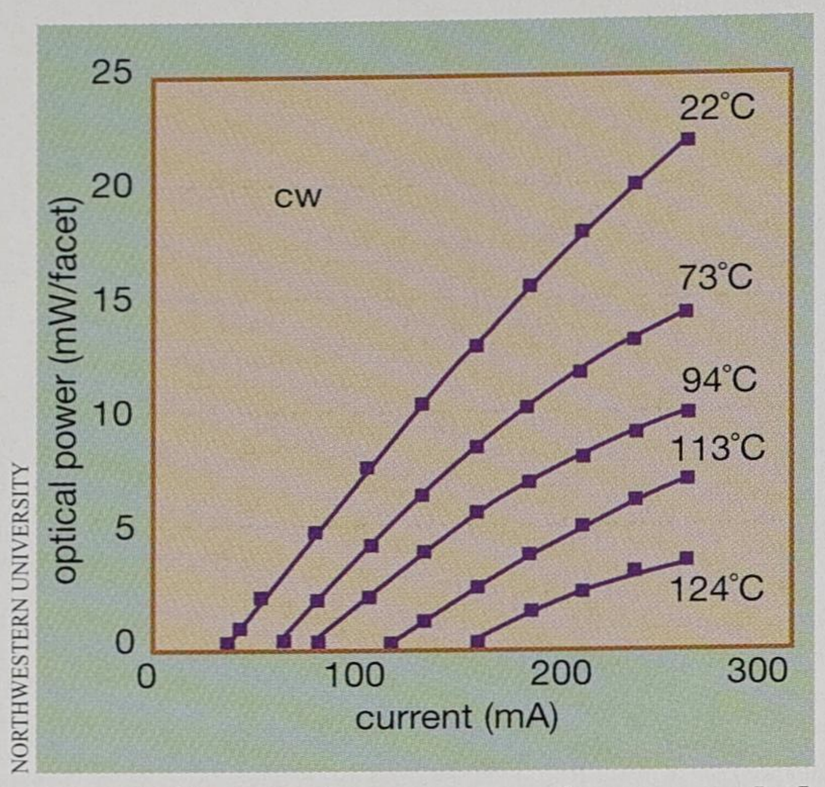
Optical parametric oscillators are nonlinear optical devices that convert a fraction of the output of a laser (i.e. the pump) into two outputs – the signal and idler – at longer wavelengths.

V Berger and colleagues (Thomson CSF) discussed the feasibility of a parametric oscillator made from GaAs/oxidized Al and integrated onto a GaAs chip. Berger's device uses frequency conversion of the laser emission into an idler portion in the 1.8–2.3 μm range, which is achieved by tuning the pump laser emission from 1.008 to 1.012 μm.

M van Herpen and colleagues from the Nijmegen Catholic University have employed OPOs in the detection of ethane, butane and pentane. The set up uses a YAG pump laser emitting at 1.064 μm, a signal laser at 1.5 μm and a periodically poled lithium niobate crystal.

Quantum cascade lasers

J Cockburn (University of Sheffield) proposed a novel GaAs/AlAs structure that achieved lasing at 7.2 μm. By inserting monolayers of InAs into the active region, the maximum lasing temperature could be increased to 250 K, in this case at the longer wavelength of 8.3 μm. The best quantum cascade lasers recorded threshold current densities of 3.2 kA/cm^2 and peak power of 800 mW at 10 K. This was achieved with a structure based on InGaAs/InAlAs for the active region. Cockburn noted that further optimization is required for room temperature operation.



NORTHWESTERN UNIVERSITY

Fig. 4. Spectral response of an uncooled type-II photodiode.

A Müller from Alpes Lasers in Switzerland reported excellent results for a quantum cascade laser with an output power of 0.06 mW at 9.3 μm. The device emits under CW operating conditions at room temperature. 700 mW pulsed power could be achieved at ambient temperature, while 90 mW was available up to 450 K.

Mid-infrared lasers

J Meyer (Naval Research Laboratory) described a method of achieving high-quality beam profiles for devices employing wide pump-stripes. This is based on an angled-grating distributed feedback device (α-DFB). In this structure, a diffraction grating is etched into the top GaSb separate confinement region at an angle of 16° with respect to the facets.

For an optically-pumped laser emitting at 4.46 μm with a 50 μm wide stripe, the result is a reduction in beam divergence from 25° for a conventional Fabry–Perot cavity to 1.4° FWHM for the α-DFB. The use of ion bombardment to fabricate α-DFBs with "virtual mesas" and more restricted regions (called "spoilers") has led to considerable improvements in beam quality in devices with active stripes as wide as 300 μm (figure 2).

Princeton Lightwave's D Garbuzov summarized his group's work on MBE-grown GaInAsSb/AlGaAsSb lasers in the 2.0–2.7 μm range. For diodes operating around 2 μm (indium content of 20%), emphasis was laid on broadening the waveguide region out to 0.8 μm and reducing the number of quantum wells to 2. This leads to a decrease in internal losses to 2 cm^{-1}. Ridge diodes 200 μm in width exhibited a differential efficiency of 53% (for a cavity length L = 2 mm), a threshold current density of 115 A/cm^2 and a record CW output power of 1.9 W. By increasing the indium content to 40%, CW lasing has been obtained up to 2.7 μm at room temperature.

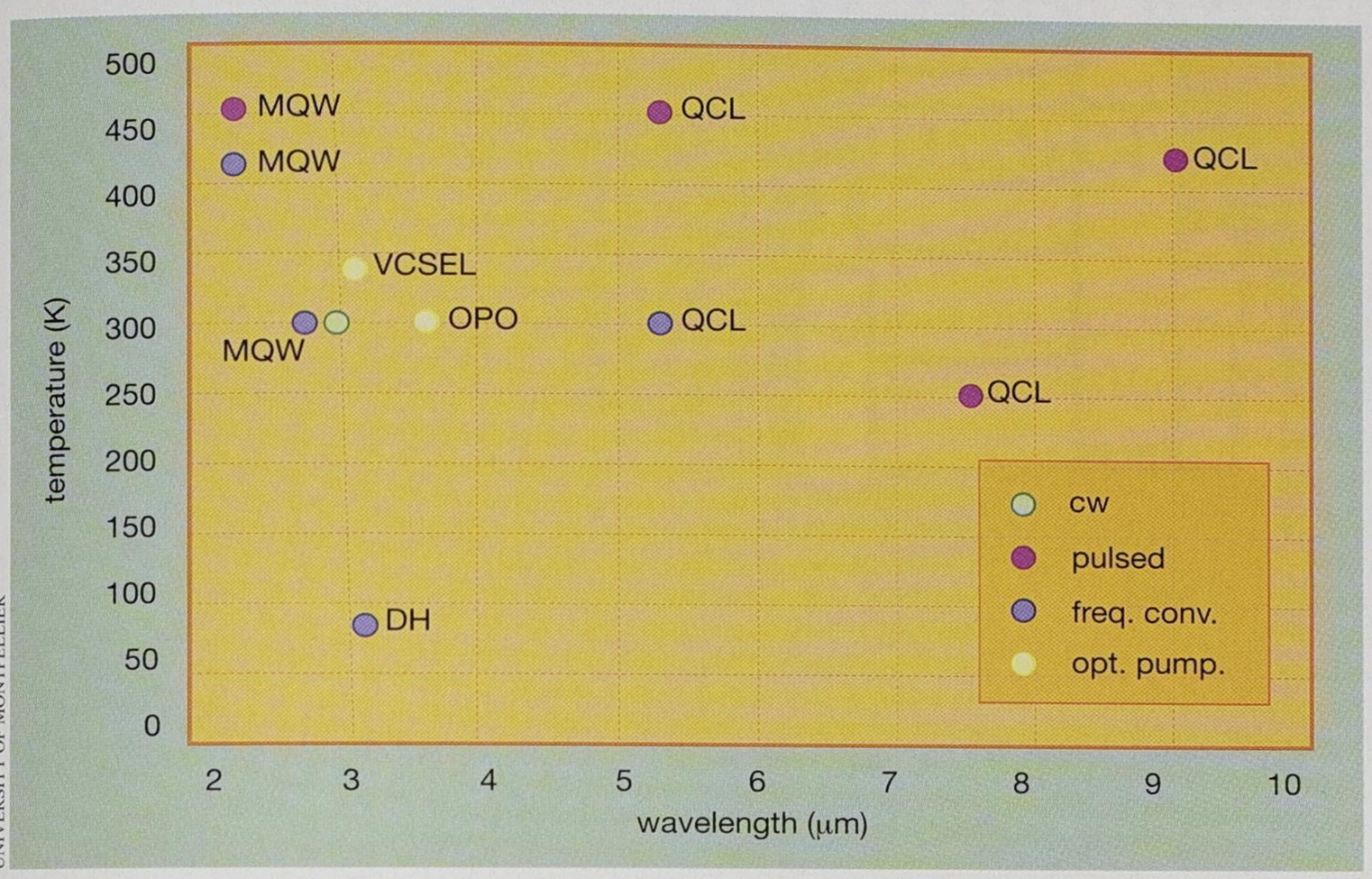
In the 2.3–2.6 μm range, laser diodes exhibit threshold current densities around 300 A/cm^2 and CW output powers of more than 100 mW. Ridge diodes with a width of 5 μm were processed for spectroscopy applications. At 2.33 μm, these devices exhibit a CW output power of 20 mW, with 1 to 2 mW available in a single longitudinal mode.

D Yarekha from the University of Montpellier discussed laser diodes based on GaInAsSb/AlGaAsSb. The devices were grown by MBE on n-GaSb (Te) substrates. The undoped active region comprises three 10 nm $Ga_{0.65}In_{0.35}Sb_{0.84}As_{0.16}$ QWs and four 30 nm $Ga_{0.65}Al_{0.35}SbAs$ barriers.

Laser structures emitting at 2.26 μm exhibit differential efficiencies that change from 80% to 33% for cavity lengths (L) in the 0.45–2.25 mm range, and a threshold current density of 180 A/cm^2 (L = 2.25 mm). The CW performance of a device with a cavity length of 0.95 mm is shown in figure 3 as a function of temperature.

With a ridge width of 5 μm, the CW output power reaches 40 mW at ambient temperature. The important feature is the high-temperature CW operation, which reaches 140°C, and up to 180°C in pulsed mode. Yarekha attributes the performance to the incorporation of high concentrations of indium and arsenic, which provides a higher conduction band offset and improves the electron confinement.

M Rattunde (Fraunhofer Institute) has also investigated GaInAsSb/AlGaAsSb laser diodes emitting in the 1.73–2.35 μm range in CW mode. Rattunde detailed lasers that emit at 1.94 μm and feature an internal quantum efficiency of 77% and threshold current density of 121 A/cm^2 (for an infinite cavity length).



UNIVERSITY OF MONTPELLIER

Fig. 5. Overview of the maximum lasing temperatures as a function of wavelength for different types of mid-infrared emitter reported during this year's MIOMD meeting in Montpellier.

Mid-infrared LEDs and detectors

B Matveev from the Ioffe Institute in Russia spoke of the possibility of operating LEDs in the range 5–7 μm at up to 80°C. In particular, the superior features of negative luminescence over electroluminescence for temperatures over 60°C were elucidated.

D Smith from Edinburgh Instruments, Scotland reported a detectivity D* of 4.5×10^9 cm $Hz^{1/2}$ W^{-1} for an uncooled InSb diode, which employed immersion optics and operated at a spectral wavelength of 6 μm (the best performance at this wavelength).

Northwestern University's M Razheghi related improvements obtained using submicron lithography for detectors used out to 16 μm. The processed devices were type II InAsSb superlattices exhibiting 10^8 cm $Hz^{1/2}$ W^{-1} at room temperature (figure 4). The R_0A value is two orders of magnitude better than that found in CdHgTe devices.

Uncooled InAsSb detectors were also covered in G Marre's presentation. Marre noted that the main advantage of this detector is an ability to grow structures that are lattice matched to GaSb substrates.

Conclusions

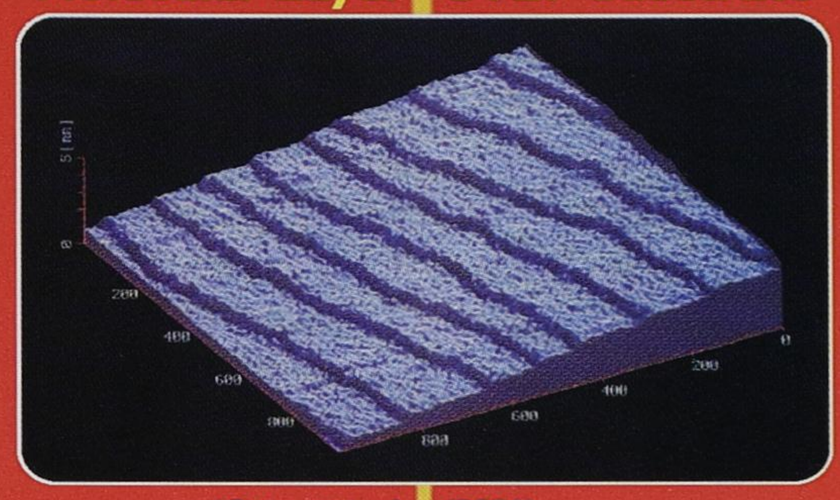
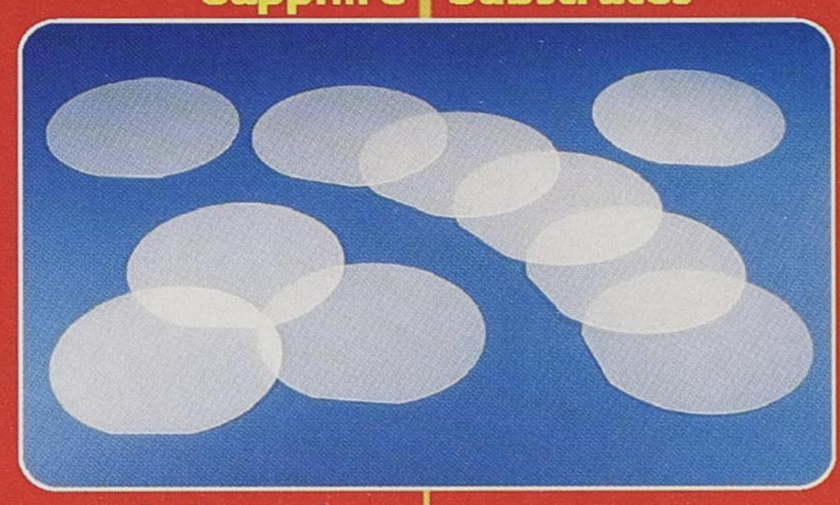
Figure 5 shows a summary of the maximum operating temperatures achieved by laser devices discussed at the conference. It highlights three regions of the spectrum corresponding to a specific kind of device.

In the 2–3 μm range, GaInAsSb/AlGaAsSb MQW laser diodes are the most interesting devices, featuring CW operation out to 2.7 μm (e.g. Garbuzov) for temperatures up to 140°C (Yarekha). For the 3–4 μm range, and when portability is not an issue, the frequency conversion approach achieved by OPOs appears to be the solution (e.g. van Herpen). Optically pumped II-VI VCSELs can also be considered at this wavelength, as they are now able to operate above room temperature at 3.1 μm (Schwarzl). Above 4 μm and up to 24 μm, it is now clear that a quantum cascade laser with an embedded DFB grating provides a promising new mid-infrared coherent radiation source.

A very significant breakthrough was announced during the meeting: the first demonstration of a QC laser emitting at 9.3 μm in CW mode at room temperature (Müller).

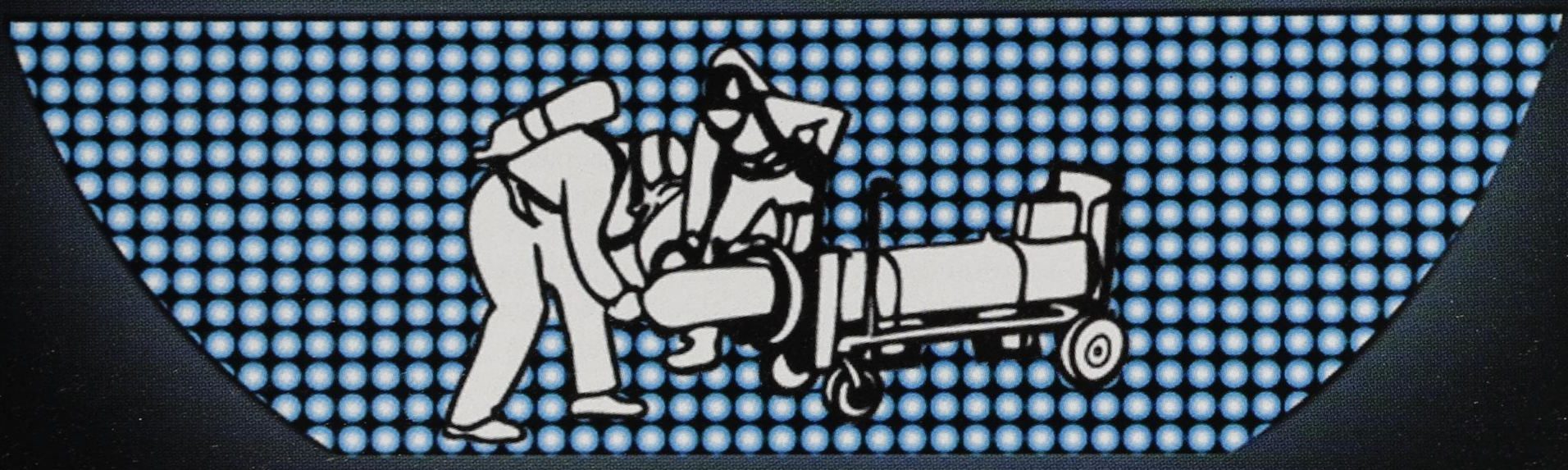
For detectors, cooled CdHgTe still dominates the market for military applications, although research laboratories point to the superior properties of InAsSb in the field with the possibility of room temperature operation (Marre, Razhegi).

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E-mail: yves.rouillard@univ-montp2.fr.

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III-Nitride semiconductor electronics

Bob Metzger *takes a look at the activity in the much researched field of III-N electronics, and discovers how GaN may one day challenge silicon's dominance of microelectronics.*

GaN and its related alloys have become synonymous with blue-violet LEDs and lasers. The ability to fabricate devices emitting in this portion of the electromagnetic spectrum is the result of the large direct bandgap in these alloys (3–6 eV). Other properties of III-N semiconductors include high electron mobility, high breakdown electric field and good thermal conductivity. This combination of properties has led to an explosive growth in the investigation of these material systems for various devices, including HEMTs, HBTs, photodiodes, and even masers. Recognizing just how rapid and broad this development has become, *IEEE Transactions on Electron Devices* recently devoted an entire issue to III-N semiconductor electronics, providing a snapshot of where this broad range of electronics device development lies.

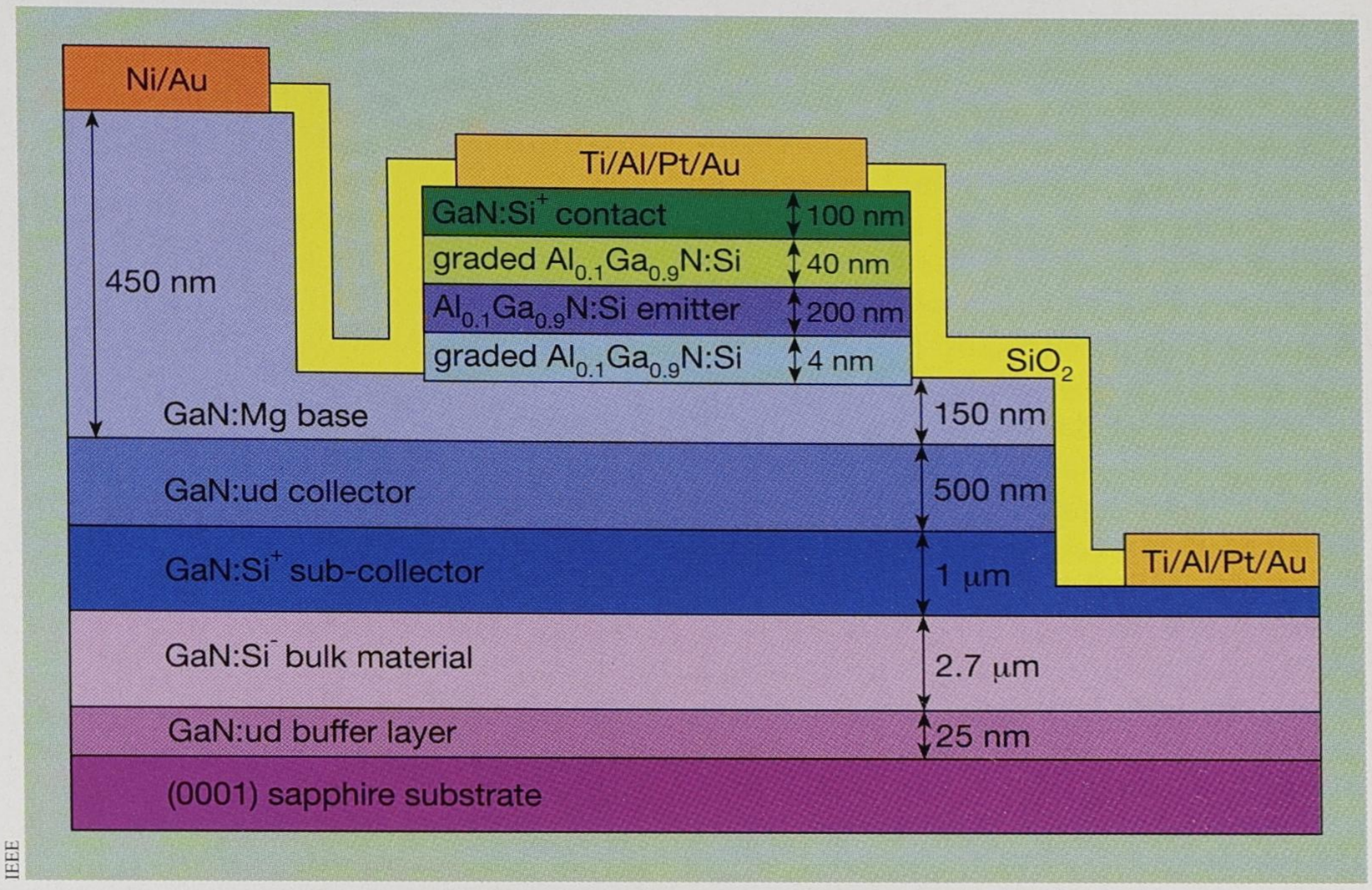


Fig. 1. An HBT structure showing the emitter formed by selective growth through the SiO_2 mask after growth of the collector and base (after Shelton *et al.*).

HEMTs

Of all the electronic devices being fabricated in the GaN material system, development in the area of AlGaN/GaN HEMTs is the most advanced. Work in this field is far from complete and many challenges still remain before the full potential of HEMTs using this material system is realized. These challenges include the lack of a cheap, lattice-matched substrate, with growth typically done on either sapphire (13% lattice mismatch) or SiC (3% lattice mismatch). As a result, dislocation densities in the region of 1×10^8 cm^{-2} are generated, which can subsequently degrade device performance.

Due to the strong spontaneous and piezoelectric polarization in these materials, large charges can be induced in the material. Although this effect can be exploited, producing 2-dimensional electron gases (2 DEGs) up to 1×10^{13}cm^{-2}, other induced charges within the device and at the surface must be controlled or eliminated in order to optimize device operation. Charged states, particularly surface states, adversely affect RF power generation, and a great deal of work is being done to passivate device surfaces. While very large RF power levels are being generated, they still fall short of what would be expected based on the DC characteristics of the devices, where DC to RF dispersion is characterized by drain current collapse at high-voltage operation. Despite these challenges, impressive DC and RF characteristics for GaN HEMTs are being obtained.

Currently, some of the best DC HEMT characteristics are being reported from Cornell University, with a 2DEG density of 1×10^{13} cm^{-2}, and mobilities of 1500 and 1700 cm^2/Vs for devices grown on sapphire and SiC, respectively. Thick GaN buffers in the 3–4 μm range are critical in obtaining these mobility values. The buffers provide a substrate on which to grow GaN-based device layers with a lower number of dislocations. For devices grown on sapphire, a maximum I_{DS} of 900 mA/mm and g_m of 220 mS/mm is obtained, while for growth on SiC, a maximum I_{DS} of 1160 mA/mm and g_m of 300 mS/mm are seen (Eastman *et al.*).

Researchers at the University of Illinois have reported a 0.12 μm gate-length HEMT grown on SiC that exhibited record values of f_t and f_{max} of 101 and 155 GHz, respectively. These devices operated at a current drive of 1.19 A/mm with a g_m of 217 mS/mm. Although noise performance is not as critical a parameter in power sources as it is in an LNA, it can still add overall noise to a system. These high-performance HEMTs showed outstanding noise characteristics, where for 8 and 12 GHz operation noise figures of 0.42 and 0.77 dB were obtained (Lu *et al.*).

RF power

Despite these challenges, and the fact that electron mobilities fall far short of those achieved in GaAs HEMTs, AlGaN/GaN HEMTs are currently operating at RF

power levels nearly 10 times higher than those achievable with GaAs. The best results are typically obtained from devices grown on SiC. Although SiC is much more expensive than sapphire, the closer lattice match results in lower defect material, and the superior thermal conductivity of SiC enables easier heat dissipation in high-power devices.

Researchers at the University of California at Santa Barbara (UCSB) and Hughes Research Laboratories (HRL) are vying for the highest RF power numbers. UCSB researchers are using flip-chip mounting of their devices onto AlN substrates to improve the thermal behavior of the HEMTs (Wu *et al.*). A 2 mm-wide device delivered 9.2–9.8 W at 8 GHz operation with a PAE of 44–47%. Using these devices, a flip-chip amplifier was fabricated using a 4 mm device that generated 14 W at 8 GHz. The high-power work performed at HRL (Micovic *et al.*) focused on a single-stage power amplifier fabricated by combining four 1 mm devices to deliver a total power of 22.9 W with a PAE of 37% at 9 GHz. Both of these results represent the current state of the art, and it is expected that these numbers will continue to improve.

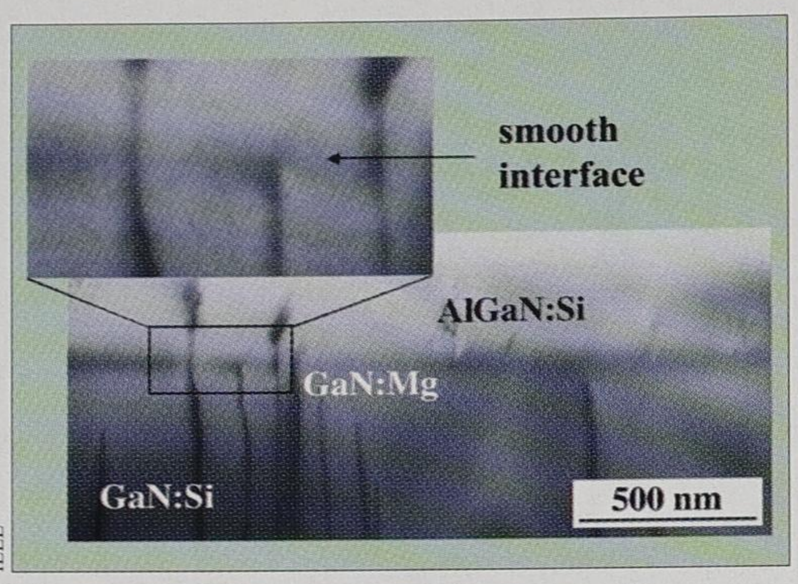
Surface passivation: a crucial step

A critical element in obtaining these RF powers has been the use of Si_3N_4 for surface passivation, which in many cases has doubled the observed RF output power.

Current collapse in the drain has been a major obstacle to the development of reliable high-power HEMT devices. UCSB researchers have reported that the apparent cause of current collapse is a charging up of a second virtual gate physically located in the gate-drain access region. Due to the large bias voltages present in the device during a microwave power measurement, surface states in the vicinity of the gate trap electrons, thus acting as a negatively charged virtual gate. The maximum current available from a device during a microwave power measurement is limited by the discharging of this virtual gate. Once again this points out the critical nature of surface passivation in these devices, a major challenge in light of the strong polarization fields present in the material (Vetury *et al.*).

HBTs

One of the primary reasons for using an HBT structure as compared to a BJT



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Fig. 2. TEM image of the smooth interface formed by selective area regrowth (after Shelton *et al.*).

structure is that the band offset between the wider bandgap emitter and smaller bandgap base allows very high base doping levels while still maintaining good DC gains. In turn, the high base doping decreases the base sheet resistance, which increases f_{max}, thereby making HBTs excellent candidates for RF applications.

An ideal GaN HBT would combine all the HBT advantages with the high-voltage, high-power capabilities inherent in GaN. Unfortunately, the acceptors used for p-type doping typically have energy levels from 100 to 400 meV above the valence band, resulting in incomplete ionization of the dopants. To date, the maximum hole concentration in GaN is in the high 10^{17} cm^{-3} region (two orders of magnitude lower than base doping found in GaAs and InP HBTs). Furthermore, the most frequently used p-type dopant, Mg, is prone to penetration into the emitter region due to its high vapor pressure (and therefore large ambient background in both MOCVD and MBE systems) and rapid diffusion behavior.

Selective epi confines dopants

While the deep acceptor level and incomplete ionization of p-type dopants has not been resolved, progress is being made on containing Mg within the base region. A collaborative effort between Emcore, Nortel, the universities of Illinois and Texas, Honeywell and Lawrence Berkeley National Laboratory, has seen the development of a selective area growth approach to forming the emitter. This is done after the base and collector structure have been grown and fabricated as illustrated in figure 1. In addition to limiting the effect of p-type doping in the emitter, it also eliminates the need to obtain selective etches that stop at the base region, as would be required in a conventional HBT processing sequence. A 150 nm PECVD SiO_2 layer was used to define the regions for selective growth. Smooth interfaces were obtained at the regrowth surface as shown by the TEM shot in figure 2. With a base doping of 2×10^{17} cm^{-3}, the device showed a room temperature DC gain of eight when operating in the common emitter mode (Shelton *et al.*).

Researchers at UCSB have also reported the use of selective regrowth to lessen the impact of Mg movement. UCSB is using lateral epitaxial overgrowth (LEO) in a manner similar to that used in GaN laser growth, in order to improve material quality in the vicinity of the device. By reducing dislocations, they observed a reduction in collector-emitter leakage currents by four orders of magnitude. With a base carrier concentration of 8×10^{17} cm^{-3}, the device exhibited a room temperature DC gain of six. The UCSB group hopes to further improve the gain through bandgap grading between the base and emitter (McCarthy *et al.*).

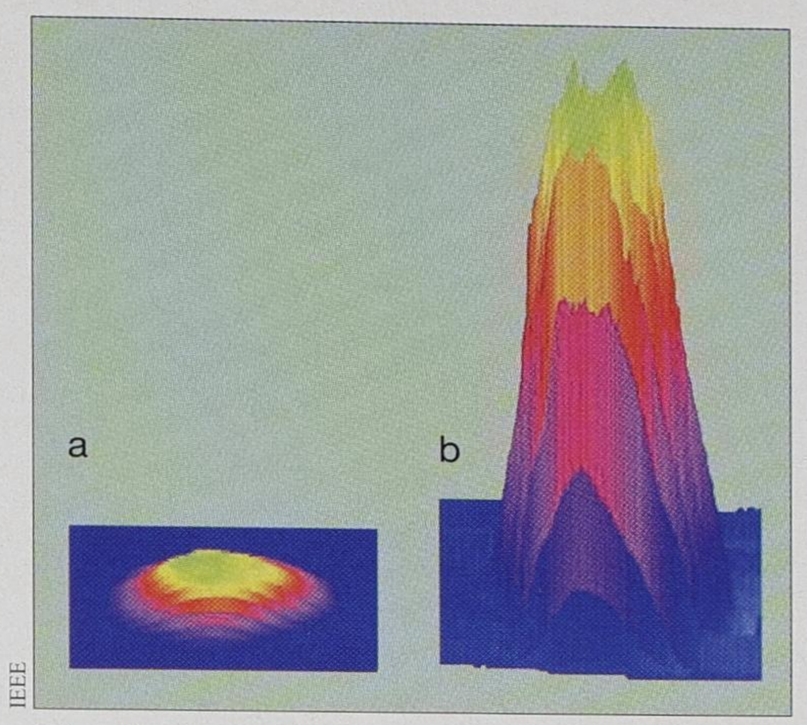
Detectors

The large direct bandgap of GaN and its alloys make it an ideal candidate as a detector in the 200–400 nm region, and suitable for such applications as UV-flame and missile launch detection. The ability to detect strictly in the UV allows the detector to differentiate between a flame and something that is merely hot (and typically has a large IR component to its radiation).

A group led by the University of British Columbia has reported using $Al_{0.33}Ga_{0.67}N$, which has a band edge at 300 nm, for solar blind PIN photodetectors. It is difficult to grow a thick n-type $Al_{0.33}Ga_{0.67}N$ top contact layer and instead n-GaN is used. However, to maintain high UV/solar rejection ratios the photocurrent due to minority-carrier holes generated in the relatively low-bandgap GaN must be suppressed. Through simulations, they have shown that the introduction of $In_xGa_{1-x}N$ quantum wells in either the p or n GaN regions suppresses the unwanted solar-generated photocurrent by encouraging recombination. The placement of a p-type delta-doped layer in the p-GaN window material suppresses tunneling of the unwanted carriers. As a result, the UV/solar rejection ratio is improved by nearly three orders of magnitude as compared to the baseline GaN/

AlGaN/GaN structure (Pulfrey *et al.*).

Researchers at Lincoln Laboratories have reported the development of avalanche photodiodes for solar-blind UV detection at 280 nm using $Al_{0.4}Ga_{0.6}N$. The advantage of an APD as compared to a PIN is that it does not require a second gain stage since signal multiplication takes place during detection. When operating in the Geiger mode, a single electron in these structures experiences avalanche gains greater than 10^6. Breakdown in this alloy occurs at a field strength of 3.5–4 MV/cm corresponding to 10^5 V in this structure. Figure 3 shows APD detection with the device biased at –20 V (operating in the linear regime as a PIN detector), and near breakdown at –90 V, where avalanching takes place during detection. Such devices are expected to outperform PIN diodes operating in the linear mode, and have the potential to displace bulky and expensive photomultiplier tube (PMT)-based sensors for solar-blind UV detection (Verghese *et al.*).



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Fig. 3. Raster plots of photocurrent in (a) device biased at –20 V (operating as a PIN detector), and (b) device biased at –90 V where avalanching takes place during detection (after Verghese *et al.*).

MISFETs

While HEMTs, HBTs and detectors are the electronic devices most often discussed with respect to GaN, a host of other devices and applications are beginning to emerge.

With the ongoing improvement in surface passivation through the use of Si_3N_4, researchers are realizing that this insulator might have applications in GaN-based MISFET devices. Researchers at Cornell have reported MISFETs showing good maximum channel currents of 750 mA/mm. At 4 GHz, with a 28 V bias these devices delivered 4.2 W/mm with 14.5 dB of gain and 36% PAE (Chumbes *et al.*). In other work along these lines, researchers at Yale have developed a $SiO_2/Si_3N_4/SiO_2$ (ONO) insulator stack deposited by jet vapor deposition. The resulting interface state densities between GaN and the ONO were observed to be as low as $5 \times 10^{10}\,cm^{-2}\,eV^{-1}$, a value comparable to that observed in a good Si/SiO_2 interface. Despite the challenges posed by surface states in this material system, excellent passivation is now possible, with the density of these states reduced to a point where MIS structures are possible (Gaffey *et al.*).

THz power

Another interesting application not typically considered is the generation of power at THz frequencies through the fabrication of masers. Due to the high value of the optical phonon energy and strong interaction of carriers with optical phonons, GaN is a good candidate for low-temperature, high-frequency generation of power in the THz regime. Simulations carried out by a group led from the Semiconductor Physics Institute of Vilnius, Lithuania, show that a dynamic negative differential mobility persists in GaN up to 80 K, thereby permitting RF power generation through the application of applied bias. Over an electric field of 1–12 kV/cm the resulting generation frequency ranges from 0.2 to 3 THz, with microwave power generation in the THz regime possible with an efficiency of 1–1.5% (Starikov *et al.*).

SAW devices

Researchers from the Kyungpook National University, Korea, are examining the use of GaN for surface acoustic wave (SAW) filters, which have a wide range of uses in applications requiring telecom/datacom information transmission. Thin-film piezoelectric materials such as $LiNbO_3$, $LiTaO_3$, quartz, ZnO and AlN have all been used for several decades in SAW devices. While GaN exhibits the piezoelectric characteristics that would make it well suited to SAW devices, the material also needs to be highly resistive in order to minimize transition losses. Taking advantage of the fact that Mg-doped films can become semi-insulating when Mg-H complexes are formed, films were grown under conditions to deliberately form these complexes, producing GaN layers with resistivities higher than 10^7 Ωcm. The MOCVD Mg-doped GaN films exhibited very-high-surface acoustic wave velocities of 5800 m/s and low insertion losses of –7.7 dB, making them good candidates for SAW filters operating in the GHz regime (Lee *et al.*).

GaN for microprocessors

And lastly, Ohno and Kuzuhara of NEC predict that when Si devices can no longer be reduced in size, GaN may become the material of choice. A fundamental limit of any device appears to be that operating voltages must exceed approximately 10 kT, which at room temperature is about 250 mV. This voltage limit will be reached in approximately 20 years for MOSFETs with channel lengths of 10 nm. At 250 mV, these devices will fail due to avalanche breakdown. Ohno and Kuzuhara point out that the significantly higher breakdown fields in GaN (as well as other large bandgap materials) would allow further miniaturization for 20 years after the Si MOSFETs reach this limit. While GaN devices are not as fast as GaAs or InP devices for a given gate length (due to slower electron velocities), the much shorter channel lengths possible before avalanche breakdown occurs, allow for a significant reduction in transit times. These devices could potentially operate much faster than any Si-, GaAs- or InP-based devices (Ohno *et al.*).

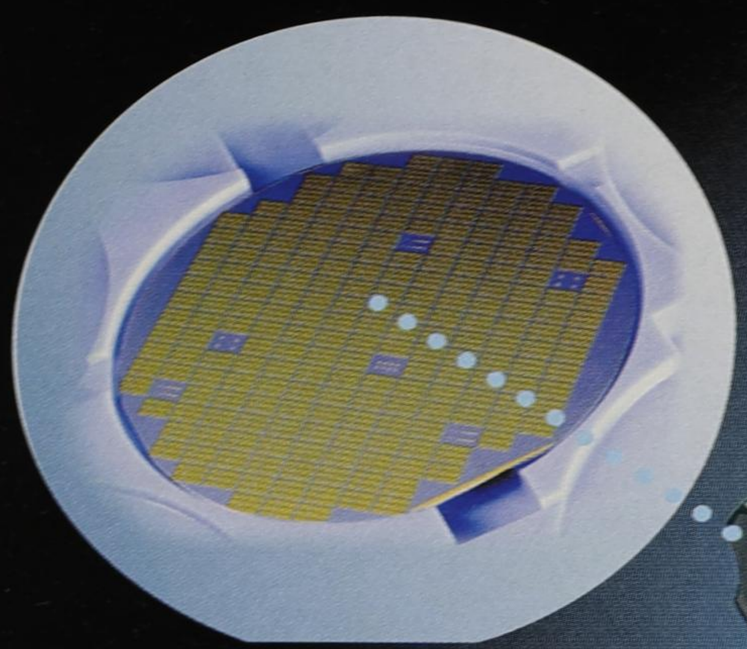
Perhaps, decades from now, the real application for GaN will be in the fabrication of microprocessors and DSPs, with RF and high-voltage devices representing a minor niche market.

Further reading

Chumbes *et al.* 2001 Special issue on group III-N semiconductor electronics *IEEE Transactions on Electron Devices* **48(3)** 416.
Eastman *et al.* ibid. 479.
Gaffey *et al.* ibid. 458.
Lee *et al.* ibid. 524.
Lu *et al.* ibid. 581.
McCarthy *et al.* ibid. 543.
Micovic *et al.* ibid. 591.
Ohno *et al.* ibid. 517.
Pulfrey *et al.* ibid. 486.
Shelton *et al.* ibid. 490.
Starikov *et al.* ibid. 438.
Verghese *et al.* ibid. 502.
Vetury *et al.* ibid. 560.
Wu *et al.* ibid. 586.

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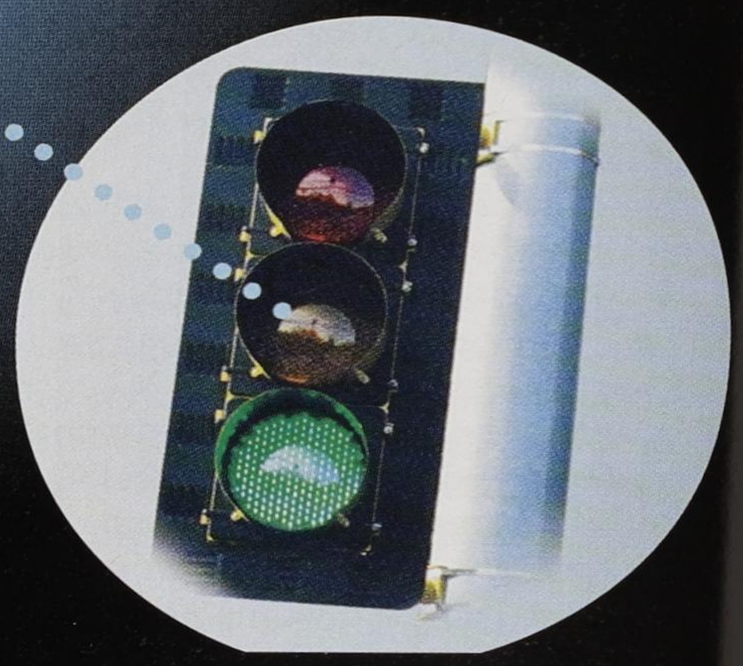




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Early implementation of SPC at Lasertel

Statistical process control (SPC) is one of the keys to creating an efficient manufacturing process for the production of semiconductor lasers, writes ***Stewart Wilson*** *of Lasertel.*

Traditionally, high-power semiconductor laser companies have created and assembled products by hand, using experienced engineers in a research and development setting. This is typically a slow process, further handicapped by a high scrap rate. Today, the demand for high-volume manufacturing is making the creation of handcrafted diode lasers a thing of the past. To succeed in the current marketplace, companies must take the alchemy of semiconductor laser production and transform it into an efficient manufacturing process.

This has been at the core of the startup success at Lasertel, a high-volume manufacturing facility in Tucson, Arizona that makes high-power semiconductor lasers (see *Compound Semiconductor* May 2001, p63). Along with lean manufacturing and demand-flow tools, Lasertel has used statistical process control (SPC) to streamline production, improve repeatability and yield, and reduce the overall costs of its single- and multi-emitter diode lasers.

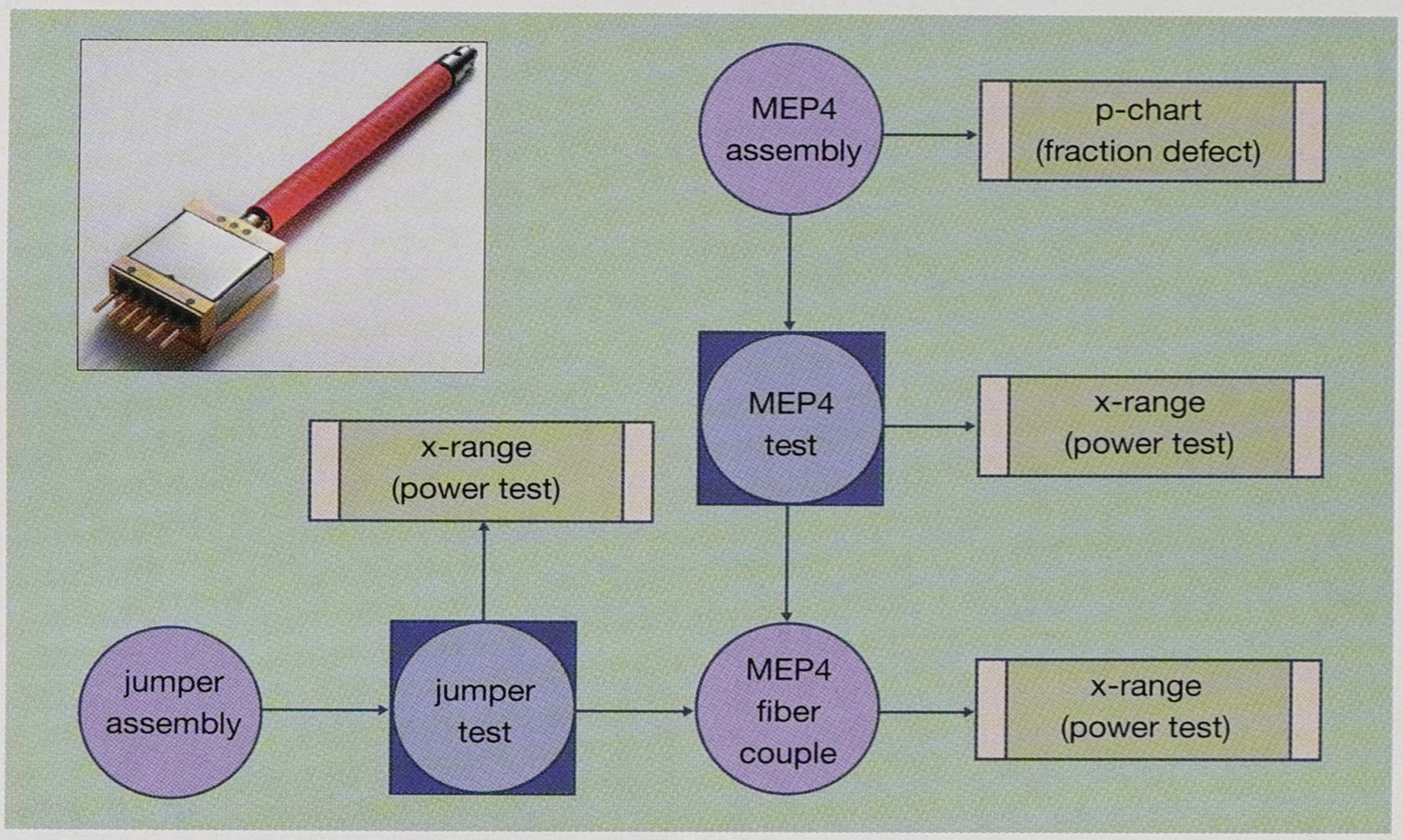


Fig. 1. Simplified process flow diagram of the Quad Blaster multi-emitter package (MEP – see inset) and some of the SPC controls used.

SPC theory

An ongoing and continuously evolving process rather than a quick-fix quality management system, SPC uses statistics to identify variation in a process. Steps are then designed and implemented to correct these variations, bringing processes under ever-tighter control. Traditionally, manufacturers controlled quality by inspecting products coming off the line, auditing factory processes, and taking corrective action when yields started to slip. With SPC, companies monitor their processes throughout production, analyzing data and taking corrective action in real-time.

Such real-time data collection, analysis and process correction requires significant investment by a company, and certainly demands top-level management support. To objectively pinpoint variations, SPC analysis needs a foundation of statistical information; obviously it works better as its database of information grows. Indeed, some startups have often viewed SPC as not that valuable, feeling that data sets are too small to be statistically valid, and that too many variables affect brand-new processes. However, the experience at Lasertel has been quite the opposite – SPC has offered significant start-up advantages.

Implementing SPC at Lasertel

A key to Lasertel's SPC implementation was its lean manufacturing methodology, incorporated into the design, start-up and operation of production early on. This methodology – which maintains a small WIP (work in process) inventory, helps improve yield and reduces scrap – has paved the way for the successful implementation of SPC. Integrating lean manufacturing principles, such as a flow-enhanced floor plan, a visual factory, paperless travel, cross-trained employees and one-piece flow, has led to Lasertel's efficient and easily monitored operation.

In addition to lean manufacturing, Lasertel organized its flow of production to incorporate inspection, verification and data collection at all critical steps. Examples include the following:

- Every piece of equipment has its own SPC system. Data is extracted from microscopes set to analyze visual defects, or spectrometers that measure reflectivity, and control charts analyze raw power, temperature, water settings and other parameters.
- All stations, from bonding to lensing to fiber coupling, have customized tracking databases. Data is either collected automatically or entered by the operator.
- Tests are designed to measure and report on performance, environmental factors, processes and material quality. In measuring operator performance, for example, the inspection yield per operator has varied from 36% to 90%, achieving 100% at some stations. While a low yield may indi-

cate a need for more training, it can just as easily point to a problem with equipment or with raw materials.

● Programmers work in close partnership with line managers and suppliers to automatically extract data from all areas, pulling it together with the help of customized SPC software to produce real-time reports.

Data is entered into touch-screen PCs at each station so that the real-time advantage of SPC is maintained, rather than being slowed by report filing and paper administration. With this initial commitment to an efficient process, Lasertel was able to use SPC tools almost immediately, enabling more objective decisions based on real-time information and allowing problems to be addressed proactively.

For example, during chip-on-submount bonding which forms a building block for a laser package, the quality of the bond is monitored to determine whether there are voids or other defects that may impact performance, and whether performance falls within specification because of that bond. Rather than have a quality department that actively audits the final products, SPC integrates inspection within the line. Operators at each station test or inspect the product, enter relevant information, perform their task, and send it to the next step. Defects are caught early, and this points directly to a possible process problem and saves the time it would later take to identify where the problem originated. It also saves money by minimizing the loss of value-added product that would occur if the defect was not caught prior to submount attachment.

SPC analysis

A myriad of statistical analysis tools can be tailored to each company's unique processes and perfected through trial and error. Some of the basic SPC analysis tools used at Lasertel include:

● **Flowcharts** that graphically represent process flow, showing process inputs, activities and outputs in the order in which they occur.

● **Check sheets** that list items inspected in a standardized format so that required information is gathered in the same way each time.

● **Attributes charts** that qualitatively plot defect information with constant sample sizes (C-charts), varying sample sizes (U-charts), actual number of defects (NP-charts), or percentage of defects (P-charts).

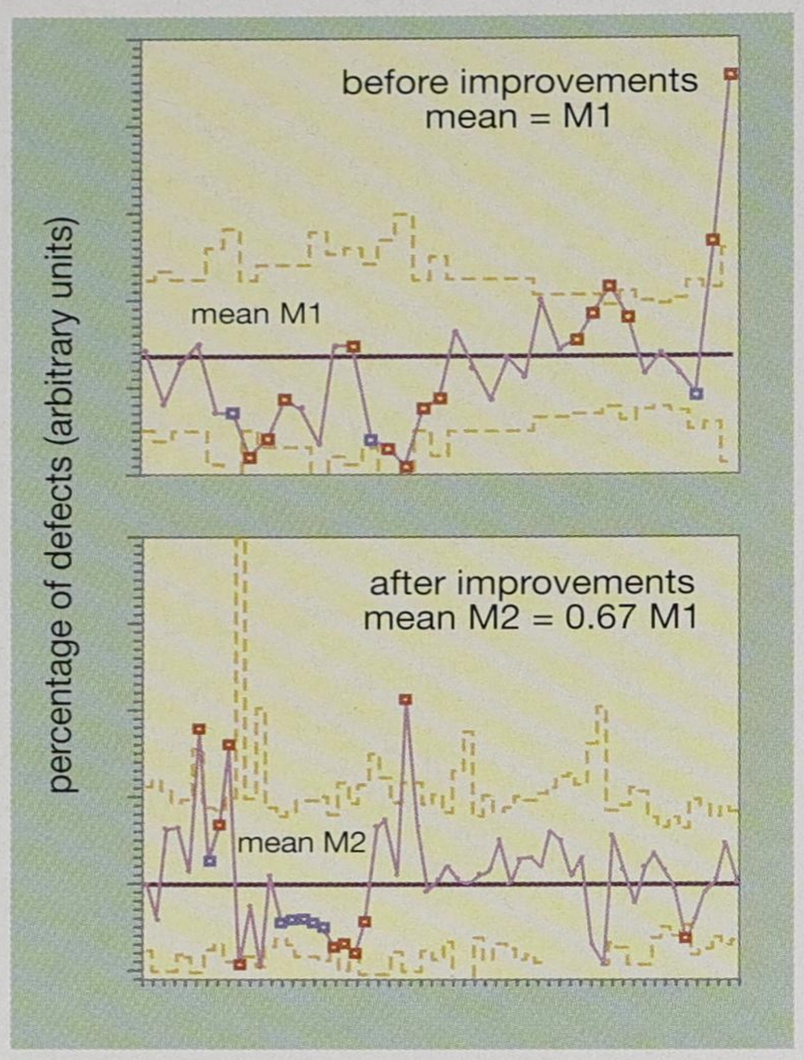


Fig. 2. Attributes P-chart for the Quad Blaster assembly, before and after process improvements. The mean percentage of defects dropped to 0.67 of its previous value.



Fig. 3. Manufacturing station for fiber jumpers.

● **Pareto charts** that identify the problems of greatest concern and provide a prioritized order in which to address these problems.

● **Cause-and-effect diagrams** that show the interrelationships between groups of causes and effects, usually in the form of a tree or fishbone diagram.

● **Control charts** that shows statistics on important characteristics of a product to provide information for correction and improvement of processes.

To date, Lasertel has made a great deal of use of the X-bar and R-bar control charts. These charts plot data as a histogram to show average (X) values of samples and variations in the range (R) of data subsets. A basic X-bar chart has a center line and upper and lower control limits, most often set at ±3 standard deviations from the mean. A certain number of points in a row outside the limits indicates that the process is out of control. As the process gets tighter through SPC, the allowable number of points can be adjusted, further fine-tuning production.

Once SPC has indicated a variation or potential problem in a process, a Lasertel team of engineers, technicians and operators immediately addresses it. If the cause is not apparent, a design of experiments may be used to run tests that vary critical characteristics to see what occurs. When certain cause-and-effect relationships are known through prior experience, fault tree analysis is used to track the origin of a problem. Gauge R&R (repeatability and reproducibility) studies are crucial for making sure measurements are valid. They test whether the same result will occur if the same part is measured with the same machine over and over again or if it is measured on several different machines.

SPC at fiber coupling

SPC has already contributed to significant improvements in Lasertel's semiconductor laser production. One of the best examples to date is a turnaround in fiber coupling. Through tight SPC tracking, it recently proved possible to resolve low power readings at the fiber coupling stage. The flow chart in figure 1 shows a simplified version of process flow in the fiber coupling of Lasertel's Quad Blaster, a four-channel multi-emitter package, along with some of the SPC analysis controls we used to monitor the process.

First, the Quad Blaster is assembled and an attributes P-chart (percentage of defects) is used to qualitatively measure defects. Second, the package is tested and an X-bar/R-bar chart (X-range chart) is used to monitor power. Lastly, a fiber jumper is coupled to the Quad Blaster, and another X-range chart is used to monitor the power after coupling.

Initial monitoring of the P-chart revealed a greater percentage defect than expected, suggesting that it should be possible to improve the process and have

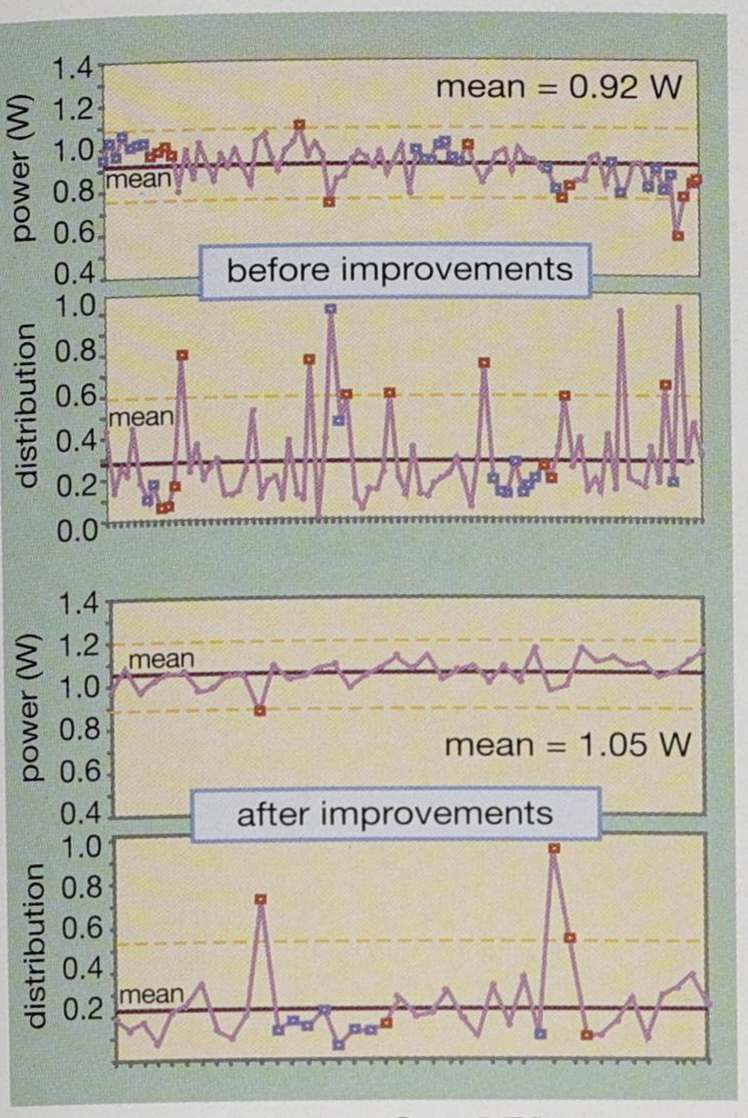


Fig. 4. Results for the Quad Blaster package, before (top) and after (bottom) process improvements. The top charts show fiber-coupled power for a single fiber of the Quad Blaster, while the lower charts show the distribution of results around the mean.

an impact on the final yield. Several modifications were introduced, which were verified by a reduced mean percentage of defects on the P-chart (figure 2).

However, after process optimization of the Quad Blaster assembly and revised test criteria we continued to see low yield and poor process control at fiber coupling. Since our charting of the fiber jumper line (figure 3) indicated that we were manufacturing good jumpers, we performed a gauge R&R test on the jumper test measurement. We found that our current measurements were not adequately quantifying the jumpers and, hence, we were not properly filtering all the low-performing ones. We developed and implemented a new technique for quantifying the jumper performance and immediately saw a 14% increase in mean fiber-coupled powers, from 0.92 to 1.05 W (see figure 4). Perhaps more importantly, there was also a tighter distribution about the mean, indicating better process control. As a result of these findings and our improvements, we were able to increase the lower control limit from 0.76 to 0.90 W. In this way, SPC continues to refine the process.

Conclusion

Lasertel has benefited from a startup infrastructure that is based on its lean manufacturing and mathematical controls. A top-down commitment to establishing SPC throughout the semiconductor laser production line, starting with epitaxial wafer growth, continuing through photolithography, and finishing with final packaging, has helped to more than double throughput less than one year into production.

As Lasertel continues to use SPC to narrow the acceptable range of variation in our processes and document normal parameters, complex processes continue to be standardized. Machines can be calibrated even more accurately, and preventative maintenance can be scheduled more often. Formulas for applying metals, and the complex ratios for layering and temperature control can be broken into a series of more simplified steps.

The end result is that as processes are tracked and continuously improved, technical staff will be able to turn more of the operation over to trained operators and technicians, production will become more streamlined, volume will continue to grow, yield will improve, and prices will go down. In a market currently challenged by high scrap rates and low-volume manufacturing, SPC has helped Lasertel create a repeatable recipe for success.

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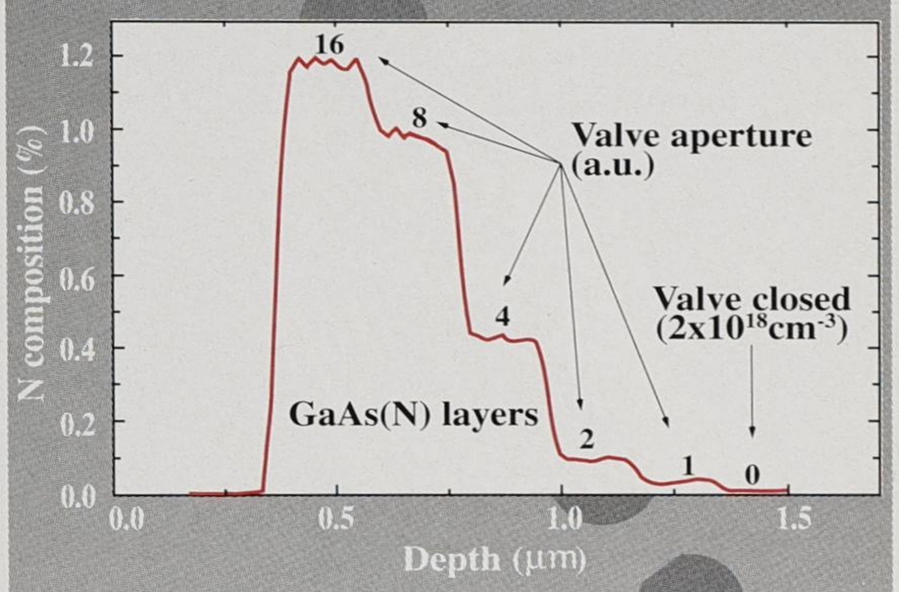
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Data drives fab yield improvements

The ability to rapidly analyze data and provide feedback to improve the production process is a key part of the yield management strategy for setting up a new GaAs fab, writes ***Paul Burgess*** *of Filtronic Compound Semiconductors Ltd.*

Almost two years ago, Filtronic plc purchased a former DRAM fabrication plant in County Durham, UK. The company's aim was to mass-produce GaAs-based chips for mobile telecommunications applications. However, the mass-production techniques developed and refined by mainstream semiconductor manufacturing for silicon have not so far been applied to the processing of what has often been regarded as a niche material. In order to meet market projections and reduce costs, Filtronic needed to successfully implement these mass-production approaches in a new environment, which adds additional complexity to the already challenging process of ramping up a semiconductor fabrication facility to volume production.

This feature describes the experiences of Filtronic Compound Semiconductors Ltd in implementing a data-driven yield management system to support the fabrication of GaAs-based RF products. Key business requirements were the rapid delivery of working prototypes to prospective customers, followed by a rapid stabilization of the production process. In spite of the need to utilize manufacturing technology that is out of mainstream semiconductor manufacturing, these requirements were successfully supported through the development and deployment of a custom solution built using SAS technology for data warehousing and exploitation.

The need for a data warehouse

The telecommunications industry is very competitive, with margins reduced to a bare minimum. The raw materials used throughout the processing sequence are expensive; GaAs wafers are approximately 50 times more expensive than Si wafers, high purity chemicals are used throughout, vast quantities of de-ionized water are required and the manufacturing area has to be maintained in an ultra-clean environment. Furthermore, equipment with a very high capital cost is required to fabricate the wafers.

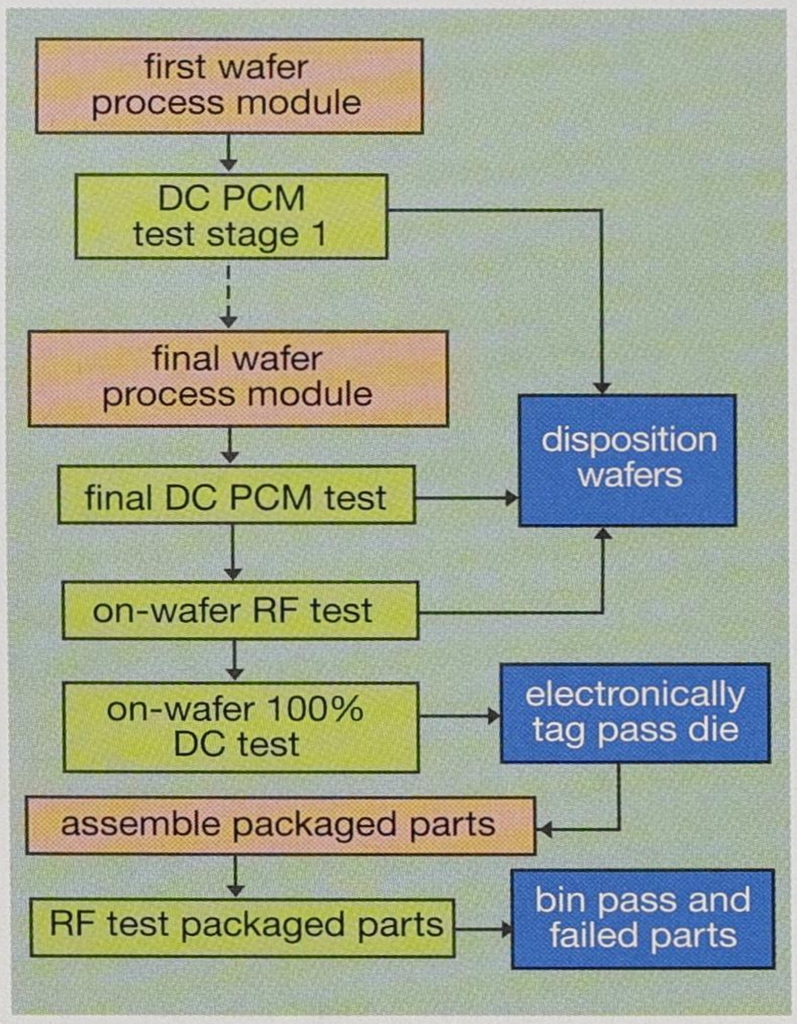


Fig. 1. Manufacturing and test flow, with test disposition points shown.

The requirement for the fab was to develop a stable production process, as soon as possible, to enable parts to be sampled to potential customers to support rapid prototyping and help gain market share for Filtronic. The next step was to improve that process, increasing device yields and reducing wafer scrap to predictable levels in order to be in a position to satisfy the demand generated by the prototyping. In both phases the ability to rapidly analyze data from the production process and turn that data into useful information for engineering use was a key part of Filtronic's yield management strategy.

The initial requirement for a data warehouse was the storage, analysis and reporting of the electrical test data. The quantity of this data is potentially very large, with the fab capable of producing 30 000 wafers per year, with each wafer containing up to 80 000 individual die, each being tested on the wafer and again when packaged. A key requirement was for the data warehouse to be scalable and therefore "future proof", i.e. capable of handling the quantities of data required to support any realistic business planning scenario.

In view of the fact that sources of electrical test data were to be brought on stream one at a time, the data warehouse also had to be modular. Aside from the issues of functionality, covered later, the general solution requirements were below industry average implementation cost, a short implementation cycle, and low ongoing cost of ownership.

Fabricating and testing chips

The process of fabricating chips on a GaAs wafer is a complex one. It starts with the deposition of epitaxial layers onto the bare GaAs wafer to produce the base layer for device operation. The wafers are then processed in groups of up to 12 (called a lot) through a series of process modules. These deposit and pattern conducting and insulating layers onto the wafer. There may be up to 10 such process modules, so that it takes 10 to 20 days to fabricate the finished device. The final process in the sequence is to dice the wafer into individual die ready for packaging. The wafers used are 150 mm in diameter, and the die size can be as small as $500 \times 500\ \mu m^2$. Therefore, there may be up to 80 000 devices on a single wafer. There are several different process routes, each to produce a different device type for a specific application.

Electrical testing forms an integral part of the manufacturing process. It is used both to ensure the operation of the final product and to monitor the fabrication

process and ensure stable operation. Figure 1 illustrates the manufacturing and test flow. There are four basic stages of electrical test. The first is the process control monitor (PCM) test, performed at several stages as the wafers are being fabricated in the line. This is typically a test performed at low frequency (DC) on approximately 80 specially fabricated areas on each wafer. The data collected correlates directly with physical parameters of the wafer. For example, the resistance of a metal track relates directly to the thickness of the metal and its patterned width.

The second stage of electrical test is performed on finished wafers prior to dicing. This test is performed at RF frequencies, to simulate the operating conditions of the circuits. Again this data correlates with the physical parameters of the wafer and also with the DC PCM test data. After both the DC PCM and on-wafer RF test measurements, the lot is dispositioned and abnormal wafers scrapped.

The third test stage is the on-wafer 100% DC testing of the finished die, to ensure that each individual die operates to specification. Each die is electronically tagged as pass or fail.

The final stage is testing of the assembled component. The assembly operation consists of placing completed die into a package and is typically done off shore. Testing can be performed in the assembly location or the components can be returned for testing on site. This test is performed at RF frequencies and again ensures that the finished device operates to specification.

This test strategy highlights problems as soon after they arise as possible. It also reduces process, test and assembly overhead, by scrapping abnormal wafers as soon as possible.

Implementing the data warehouse

The project commenced in April 2000 with a period of consultancy from SAS. During this time, the data model and hardware requirements were established, the data warehouse was implemented and priority reporting functions were set up. This phase, completed in October 2000, resulted in a functioning data warehouse and a strong base for further expansion. Since then the application has been continuously developed, with further sources of data added, and reporting functions improved.

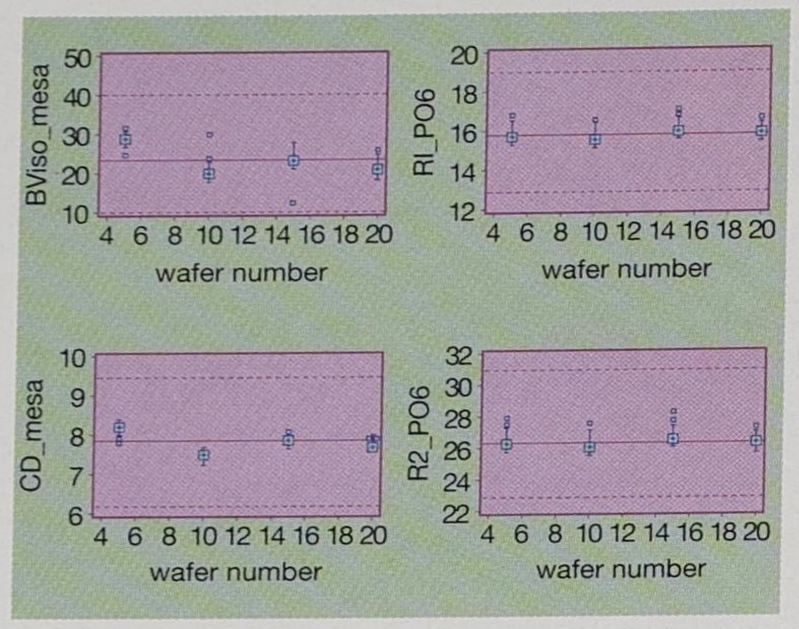


Fig. 2. Box plot of wafer number vs electrical parameter, generated immediately after lot measurement.

SAS version 8 was used to implement the data warehouse. A client server solution was adopted to satisfy the requirements for fast data processing and storage of large amounts of data. Filtronic purchased a powerful Compaq DL380 server, with a 2 Gbyte RAM and 85 Gbyte hard drive. This approach provides faster data retrieval rates, along with data management benefits gained from having a central repository of data.

Data model

A form of a Star Schema Data model was chosen for fast data retrieval and query analysis. This also provides a scalable, extendible long-term solution. DC PCM and 100% DC test data were the first data to populate the database.

The data is loaded directly into the database, immediately after test completion, and is split into several tables. These include fact tables containing raw data, lookup tables containing specification limits, test dimension tables containing categorical information (test machine ID etc), summary tables and pass/fail tables. Each table has a header with key fields, allowing the tables to be linked for analysis and reporting.

As further sources of data are brought on line, they can simply be added to the model by creating additional tables for each source.

The SAS application

A front-end application has been written for the data warehouse, using SAS/AF. This allows common tasks to be performed easily and without the need for any knowledge of SAS programming. Tasks are either administration, such as loading the data to the database and deleting unwanted

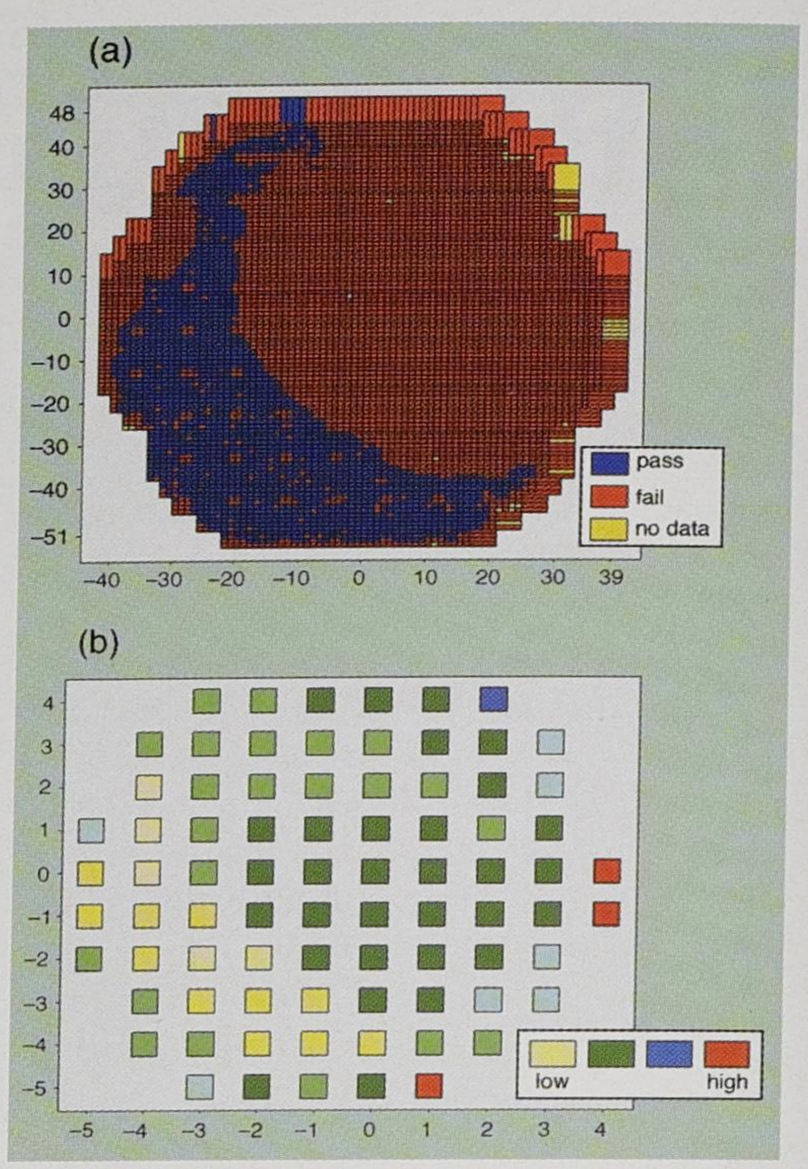


Fig. 3. (a) Wafer map for 100% DC test – blue indicates a pass die, red a fail die. (b) Wafer map for a single parameter DC PCM test, for the same wafer as (a).

data, or reporting, i.e. the generation of standard reports for engineering analysis or summary reports for management.

Electrical tests are performed using automated test equipment, and after measurement the data resides on UNIX boxes that control the equipment. The user initiates data loading by selecting the lot number and measurement stage. Data transfer over the factory LAN then takes place and the data is translated into the various tables.

Two reports are immediately generated once the data is loaded. The first is a table summarizing the data for the lot. This is generated in HTML format and is available on the factory Intranet for general viewing. The second is a box plot of test parameter against wafer number, as shown in figure 2. This gives a good graphical summary of the data; it shows the level of the data against specification limits and also the spread of the data within those limits. Many of the electrical test parameters are interrelated, so having them all graphed together helps the engineer to identify problems and initiate investigation to find the cause. The combination of these two reports allows a disposition to be made on the lot.

The remaining report functions are

designed to allow engineering analysis of the data to assist in yield improvement activities. Wafer mapping forms a key part of this procedure. However, with up to 80 000 die on a single wafer, the mapping facility is not trivial. Within SAS version 8 is the ability to generate contour plots (module SAS/GRAPH), which are used to generate wafer maps. Figure 3(a) shows a map for a 100% DC test, the blue die are pass die and the red ones fail die. The map does not allow individual die to be resolved, but clearly shows the pattern of failed die. The user may zoom in to a section of the wafer, the map will then revert from contour plot to a scatter plot, allowing individual die to be resolved and the 'probe' function to be used to look at data for individual die. Figure 3(b) shows a DC PCM test map for the same wafer. This is a map of just one test parameter, and because the number of data points is relatively small, a scatter plot covers the whole wafer. The correlation between the two plots in figure 3 is clearly evident, with low values (lighter yellow points) of the DC PCM test parameter corresponding with the pass die area. With this data in front of him, the engineer was able to make a conclusion about the cause of failure and implement a countermeasure.

Further reporting functions include SPC charts and capability plots. An SPC chart takes data from multiple device types, sorts it into test order by date, filters out outlying data and plots a normal mean standard deviation chart. This is used as an engineering tool to look at trends in data.

Capability reporting is used to look at longer-term trends in data. It is possible to plot histograms of each parameter at each test stage, with capability indices included as a legend, to plot a Pareto chart of capability indices for each test stage, and to make a monthly plot of Cp/Cpk trends for each parameter. An example of the latter chart is shown in figure 4. These charts help to highlight parameters with a low Cpk index and to target improvement activities. The improvement in capability indices over time indicates that the process is becoming more stable (the converse is also true!). The benefit of using the SAS data warehouse to generate such reports is the flexibility of data selection to populate the charts and the ease and speed at which they can be created.

For more in-depth statistical analysis of the data, SAS/INSIGHT provides a powerful statistical tool for analyzing, plotting and reporting the data – trends and patterns are easily spotted.

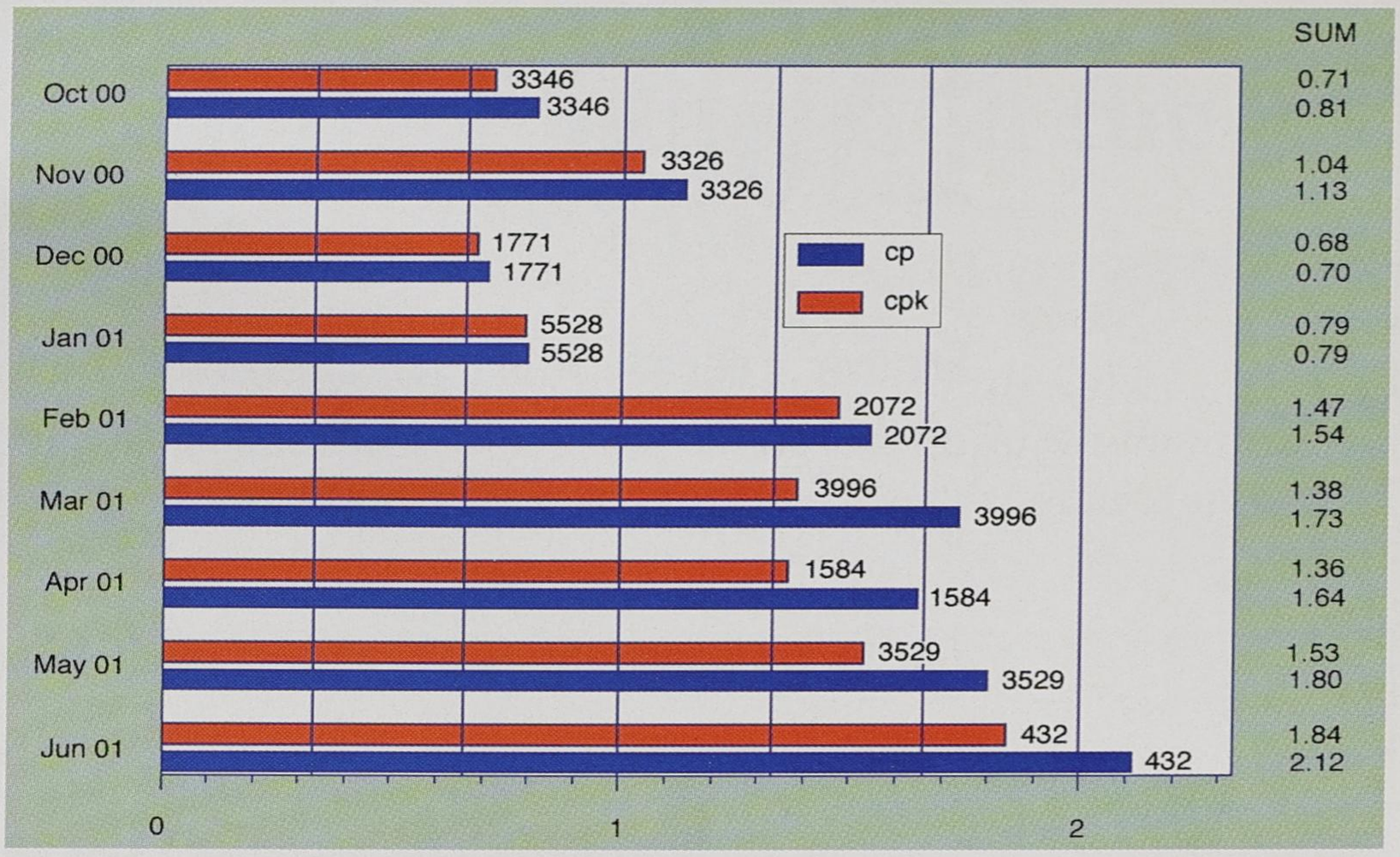


Fig. 4. Monthly capability index trend chart

One unanticipated benefit of the data warehouse has been the generation of electronic pass/fail maps for the assembly process. Typically in the semiconductor industry, failed dies are indicated by an ink spot. However, the process of inking wafers is costly and messy, it is also not a trivial task when the die size is down to 500 μm. The format of the data in the warehouse has made it relatively easy to generate an electronic map to supply to the assembly company.

[The data warehouse] is able to handle the large quantities of data generated by our complex manufacturing process and to convert this data into useful actionable information for our engineers.

Future plans for the database

The short-term goal for the data warehouse is to integrate test data from packaged parts. In the longer term, data from other sources needs to be added. The main source is the factory manufacturing execution system; as wafers are processed through the line, data is entered into this system at each measurement stage. Examples include linewidth measurements at photolithography stages, deposited layer thickness data and epitaxial layer characteristics – all physical parameters of the wafers. By adding this data to the warehouse, the existing reporting and analysis tools can be used to look at the data. More importantly, relationships can be established between the physical and electrical parameters of the wafers. This is the next key step in process characterization and yield improvement activities.

Conclusions

Filtronic made a strategic decision to implement a SAS-based data warehouse early in its total development process as part of its effort to deliver innovative products in the shortest possible time frame. This was considered essential to support a data-driven yield management strategy, seen as pre-requisite for successfully building market share and safeguarding customer commitments. SAS technology allowed us to build a scalable, modular solution that is able to handle the large quantities of data generated by our complex manufacturing process and to convert this data into useful actionable information for our engineers. The benefits of this investment have already been seen with reporting and analysis functions available to engineers at a very early stage in the life of the fab.

Paul Burgess is a senior engineer with Filtronic Compound Semiconductors Ltd, Newton Aycliffe, County Durham, UK. E-mail: pburgess@filcs.com.

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Incremental levels of automation in the compound semiconductor fab

In an effort to reduce cycle times and keep pace with changing market conditions, manufacturers of compound semiconductor devices are addressing the initial automation steps of WIP monitoring and management, writes ***Emmett Hughlett*** *of Karl Suss America.*

Producers of compound semiconductor devices are challenged to adapt production practices to an expanding market. The worldwide demand for compound semiconductors drives an accelerated market progression from low-volume, low-standardization products to high-volume, commodity-level products. Hence, economies of scale and best production practices play a critical role in the future viability of our industry's fabs and foundries. The jumbled-flow, job-shop production fab of the early 90s is now being superceded by connected/paced flow-line production.

The compound semiconductor producer's world of low-volume, high-price products is giving way to the primary goals of low-cost, high-volume products. This paper reaffirms the volume manufacturer's maxim that cycle time (CT) minimization supplants high equipment throughput/utilization, leading-edge processes, and frequent inspection as core competencies on the volume production line.

Factory automation is the means to CT control, but the production line must be dressed in the automation level that fits. Available automation technology is the result of the Darwinian evolution of automation driven by the silicon IC industry. The resultant automation technology is dauntingly visible as bookshelf-wide SEMI specifications, manufacturing execution systems, and automated material handling (AMH) hardware. The good news is that the trail to successful fab automation has been broken by our silicon siblings, so that compound semiconductor manufacturers can view available automation technology as a selectable menu for success. This paper details how the available incremental levels of automation are economically and rationally applied to the compound semiconductor producer's manufacturing technology roadmap.

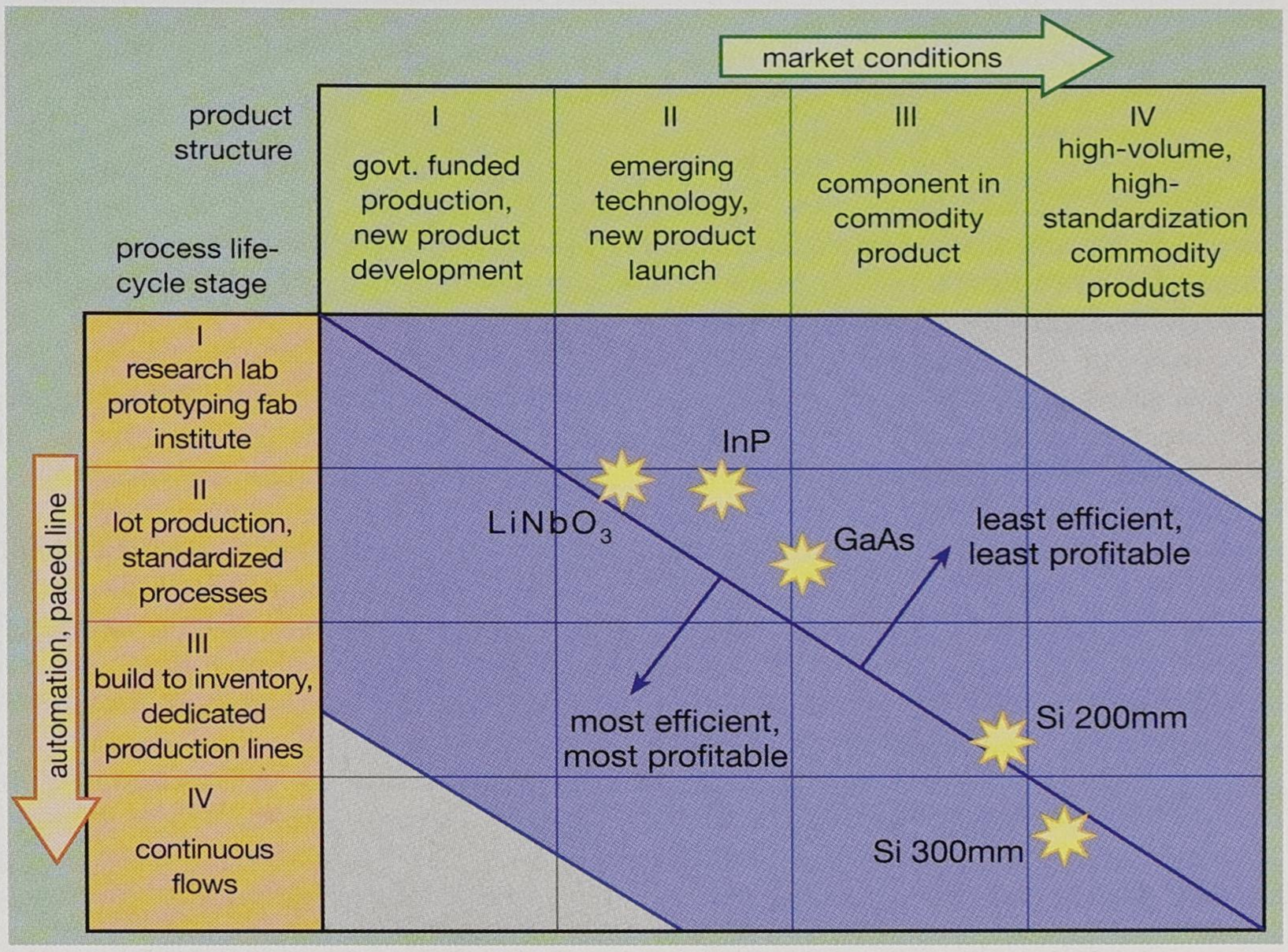


Fig. 1. The product–process matrix: production managers work to drive the process structure below the diagonal line.

The end of the job-shop model

In the mid 1990s, with total GaAs analog and digital IC shipments at about $250 million, commercial GaAs production surpassed military GaAs production for the first time. By the year 2000, total GaAs IC shipments reached $1.5 billion (Meyer). The same growth curve is seen for indium phosphide, lithium niobate, silicon germanium and other materials. Market conditions for emerging compound semiconductor technologies are rapidly changing, so that these products are starting to share the "big leagues" of commodity silicon-based products.

The successful compound semiconductor manufacturer will prosper by rapidly evolving manufacturing processes that respond to these forward-shifting market conditions. The requirement to match production methods to market conditions is illustrated in the product–process matrix of figure 1 (Hayes and Wheelwright).

Figure 1 merits close study. We see that compound semiconductors moved left to right, from product structure I to III, in less than five years. Producers efficiently responding to the demand increase will operate on or below the diagonal. In other words, they match the production process to the product structure. The silicon IC market is more mature. The Si 200 mm

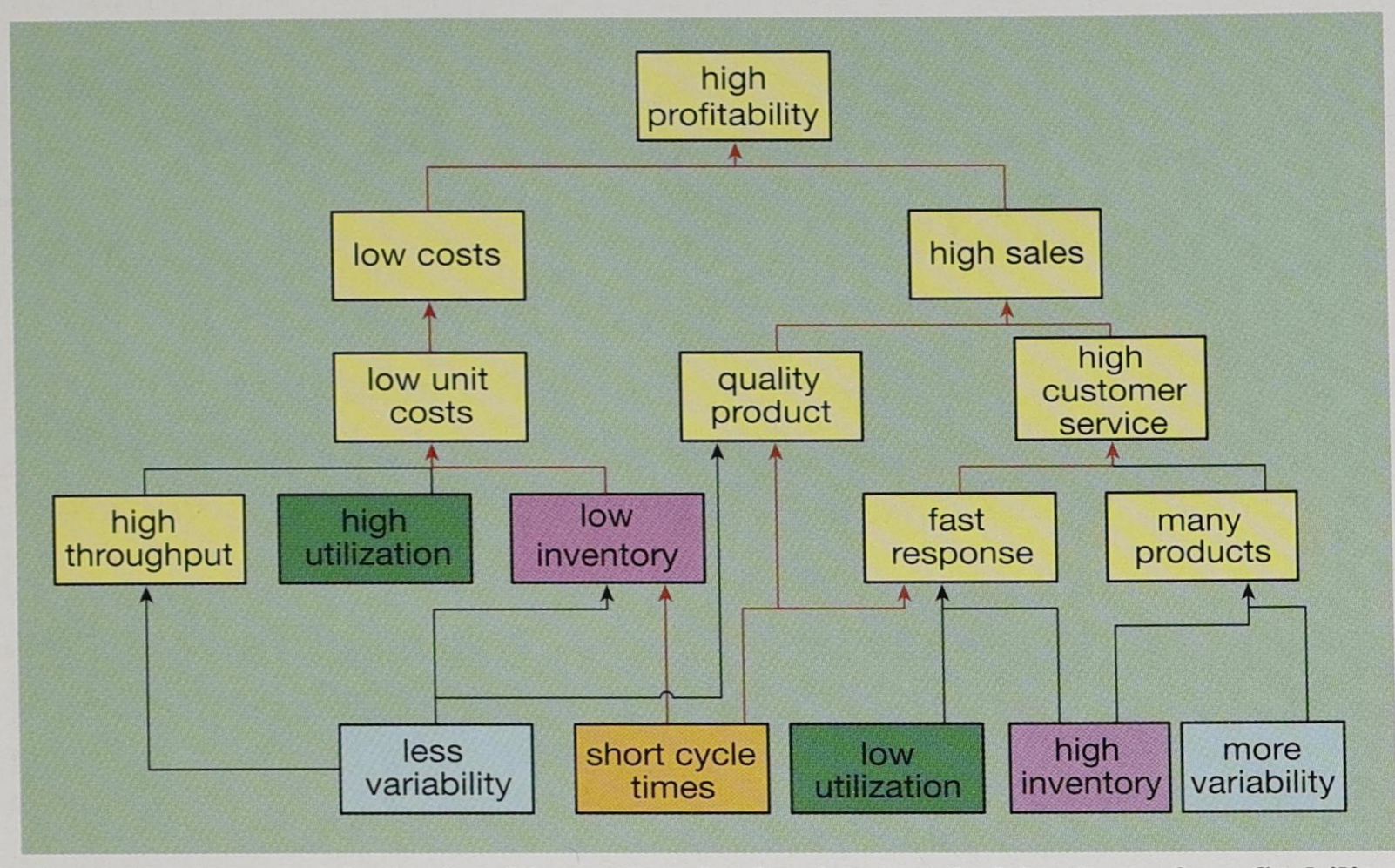


Fig. 2. In the manufacturing hierarchy, the fundamental objectives of profitability through cost control and high sales are standing on a number of subordinate objectives, including short cycle times.

process structure approximates an assembly line, a connected flow line with interbay AMH. Si 300 mm is characterized by intrabay AMH, approximating a continuous-flow conveyer belt. In our industry, GaAs leads the way with the highest demand and the most stable processes.

Cycle time reduction comes first

The compound semiconductor production manager works to drive the process structure below the diagonal of the product–process matrix shown in figure 1. Each step down the process structure axis is characterized by a step down in cycle time. Figure 2 illustrates the hierarchy of objectives common to every manufacturing organization (Hopp and Spearman). The fundamental objectives of profitability through cost control and high sales stand on a variety of subordinate objectives. Of all subordinate objectives, short CT uniquely services both low cost and high sales. The devil is in the details, and the details define the daily tactical decisions and commitments that consume the manager's time. Managing production is closer to combat than art. However, the successful compound semiconductor device manufacturer will treat cycle time reduction as the guiding principle behind almost every operational and process structure decision.

At any operational instant, Little's law (CT = WIP/TH) dictates that CT is the ratio of work in process (WIP) to throughput (TH). This relationship is true for an entire factory or a single process station. TH is a quasi-static attribute, strategically altered via capital equipment purchases or process requalification. WIP, however, is the dynamic attribute and is managed tactically. Figure 3 shows that work in process (e.g. a wafer lot) is either in process (P) or is waiting in a queue to be processed. In any fab (efficient or otherwise) a wafer's life is pretty boring, spending 50–98% of its time waiting (CTq), punctuated by exciting moments of value-added processing (CTp).

Controlling the queue time of work in process is the key to CT reduction. This concept is simple, but challenging to execute, because WIP is a function of abstractions, namely process variation and utilization. Variation is quantified as either variation in arrival time (Ca) or variation in process time (Cp). Ca and Cp are unitless coefficients of variation. Utilization (u) is less abstract, and is the proportion of time (also unitless) the process station is performing value-added work on the product. The concept of overall equipment effectiveness (OEE) defines the upper limit of u as a quality attribute of the equipment. Figure 4 shows the well-known factory operational curves illustrating the equation that quantifies the relationship between Ca, Cp, u and WIP.

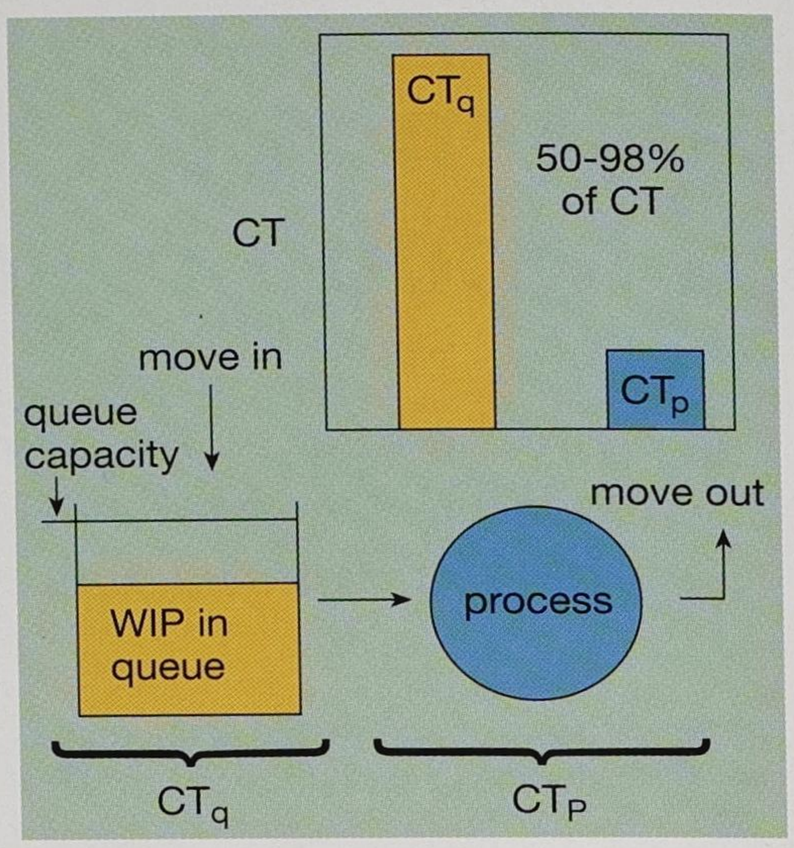


Fig. 3. At any process station, the wafer lot spends between 50% and 98% of the cycle time in a queue (CTq), with the remaining time spent in process (CTp).

The effect of variability on WIP is inconsequential if utilization is targeted at 30%. The effect of utilization on WIP is inconsequential if variability is less than 1. High volume production dictates the latter. The location of the operating point is a choice made by production management. For instance, Infineon considers variability between 0.75 and 1.33 to be moderate. Infineon targets variability at 0.4 with u = 0.8 for Si DRAM production (D Baur *et al.*).

Before progressing to the subject of automation, let us summarize to this point. CT reduction is the production manager's objective. WIP minimization (mainly WIP in queue) proportionally reduces CT. Variability and utilization give us WIP. Hence the position of the operating point on the operational curves indicates how, and how well, production is achieving the goal.

Incremental automation

In actual production, variability and utilization, hence WIP, are inherently unstable and change instantly. The location of the bottleneck process shifts rapidly in a high-utilization line. Tactically, the production line must be sensitized to these changes using instrumentation to raise the alarm. This is the job of monitoring. Production must respond to the change and take corrective (controlling) action immediately. Strategically, long-term factory performance (for lines, process stations etc) must be recorded to establish

a baseline for alarm thresholds and as a metric for continuous improvement.

The silicon industry, through trial and error, evolved progressive incremental levels of automation to instrument, monitor, and control production. The compound semiconductor manufacturer should view this technical legacy as a selectable menu of resources in the form of implementation studies (white papers), integration-ready manufacturing execution systems (MES), and software/network interface standards (SECS/GEM, CIM). SEMI (www.semi.org) and SEMATECH (www.sematech.org) are clearing houses for this information.

Figure 5 illustrates the fundamental increments of automation in a probable sequence of implementation. Before detailing each increment we note that few, if any, compound semiconductor manufacturers have progressed beyond the second step, WIP management. This is due, in the negative, to the high cost of entry for equipment interoperability and factory-wide automated production planning. It is also due, in the positive, to a high return on investment realized by implementing the two WIP management steps.

WIP monitoring

WIP monitoring is passive instrumentation that maps individual production lot status to process stations. Lot status is generally move-in, move-out, in-process, or hold. WIP queues and line WIP status is displayed. Lot status and location is keyed in (or bar-code scanned) at operator entry stations throughout the fab. Lot release data is input by production control. The data is maintained in a relational database, where the primary data is keyed on the lot-ID number.

The WIP monitoring system is the manufacturing execution system (MES). It is a shop-floor control system for semiconductor manufacturing. The real-time collection and display of WIP status allows for tactical lot release based on production status. Most importantly, it sensitizes the line to increases in variability. Once the steady state of the production line is empirically established based on long run data, out-of-control lines can be quickly diagnosed. WIP, hence CT, will not be allowed to explode. For example, WIP naturally accumulates in front of a process station that is introducing unacceptable variability. This unplanned bottleneck is quickly visible. Production control will dispatch a corrective action team to determine the root cause and fix it. In this way, Cp for the offending process station is brought under control.

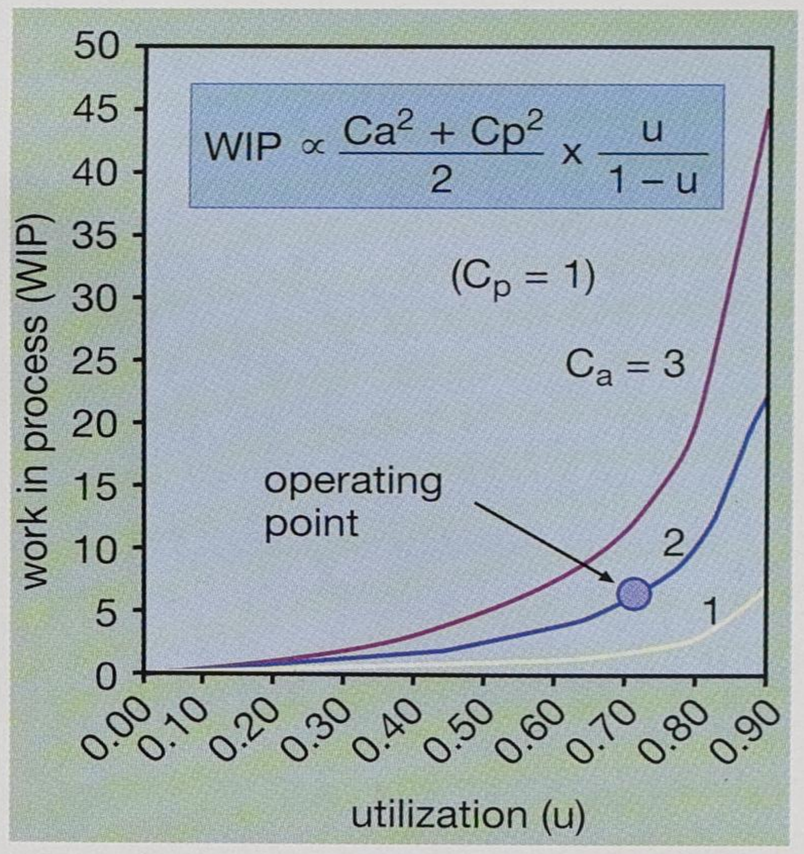


Fig. 4. Operation curves plotting the relationship between work in process (WIP), utilization (u), variation in arrival time (Ca) and variation in process time (Cp).

WIP management

WIP management is the second part of MES integration. The MES imposes rules on the handling, or movement, of lots through production. The complexity of the rules is proportional to the complexity of the production process. Two examples of process complexity common to compound semiconductors are time-limited moves, where a lot must begin the next process within a fixed time, and process iteration, where a lot will visit the same process repeatedly for each layer. However, the uniform motivation is to minimize WIP by reducing arrival time variability, Ca.

Movement rules may be global across the line: for instance, WIP caps (limits) may be set at each process station. If a process station has reached its cap of lots-in-queue, then no incoming lot moves will be allowed. This is a classic kanban implementation to control CT by WIP limiting. Rules may prioritize lots-in-queue at a process station. For instance, lots of the same layer (process program) as the lot-in-process will get priority. This minimizes variability introduced by equipment set-ups.

MES systems (bought or built) provide other capabilities, such as equipment maintenance schedules, periodic maintenance triggers based on wafer count, and report generation.

Equipment interoperability

Interoperable equipment is networked to a centralized host computer for the purpose of reporting detailed equipment-operating status. In the short term, real-time knowledge of process equipment status augments decision making when Cp moves out of control. In the long term, OEE for a particular process station is characterized. With OEE characterized, the upper utilization limit, or "equipment availability", is known. In both the short- and long-term cases, however, the primary focus is Cp control.

After years of work, the SECS/GEM equipment automation software standards were generated by SEMI. The standards cover the hardware, software, and documentation needs for production equipment and host communication. Most high-end MES suppliers provide an upgrade path to interface "SECS/GEM capable" equipment into the MES database.

Today, a small minority of process equipment in compound semiconductor factories is SECS/GEM capable. It is rarely specified in equipment buys, and most equipment for 6 inch and smaller wafers doesn't feature the standard. It will not be a common focus until MES implementations have matured.

Automated production planning

Shortly after successful MES integration, management will want to make the data available to the entire enterprise. The enterprise requirements planning (ERP) system will have at least read access to the MES database. This data, coupled with a model of the production line(s), enables automatic production planning. Production orders will be scheduled and dispatched based on the current WIP and equipment (line) status. Although not directly related to WIP control it is a form of CT minimization, since orders may be committed based on favorable capacity for a particular production line.

Automated material handling

AMH describes the automated movement of product from line to line or between process stations. Silicon production using 200 mm wafers saw implementations of interbay moves of wafer carriers among automated WIP queues, called stockers.

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The move to 300 mm Si production makes equipment-to-equipment intrabay AMH the big topic in the Si super-fabs. It is necessitated by ergonomics, since a boat of 300 mm wafers weighs 8 kg.

Integration of AMH capability into MES WIP control is theoretically an attractive way to control Ca. However, the cost of ownership of AMH is high. SEMATECH'S *International Technology Roadmap for Semiconductors*, 2000 edition, sets a goal for the cost of ownership of interbay AMH at 5% of total equipment cost, which is pretty expensive for a traditionally manual operation. The silicon industry waited for 200 mm DRAM production before implementing AMH, and compound semiconductor manufacturers will wait for similar production volumes before seeing a positive return on investment.

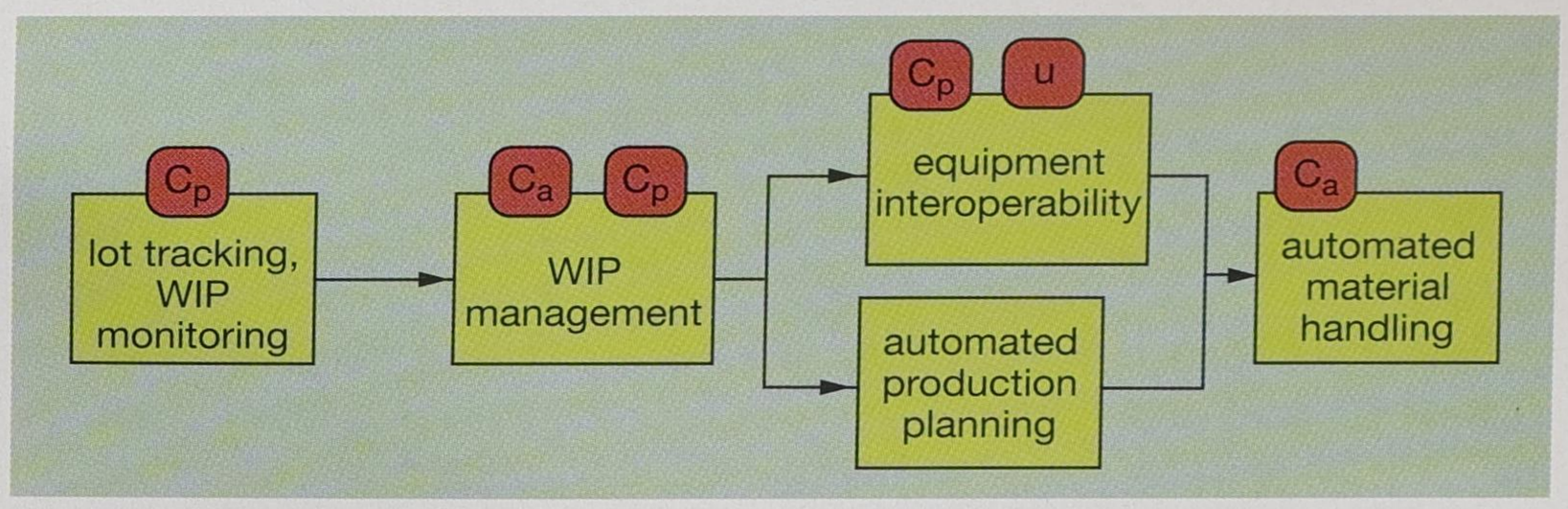


Fig. 5. Increments of automation. Few, if any, compound semiconductor manufacturers have progressed beyond the second step, WIP management.

Conclusions

Manufacturers of compound semiconductor devices must drive manufacturing CT down to keep pace with changing market conditions. Industry leaders are addressing this requirement by embracing the initial automation increments, focusing on WIP monitoring and management. WIP control gives CT reduction by exposing and minimizing production variability. The next steps of equipment interoperability and MES/ERP integration are still on the horizon. A fully automated compound semiconductor line may never require AMH, the final automation increment.

Further reading

D Baur, W Nagel and O Berger 2001 *Proc. Mantech conference.*
R Hayes and S Wheelwright 1979 *Harvard Business Review* Jan/Feb.
W Hopp and M Spearman 1996 *Factory Physics* Irwin Press.
M Meyer 1999 *Compound Semiconductor* Nov/Dec p26.

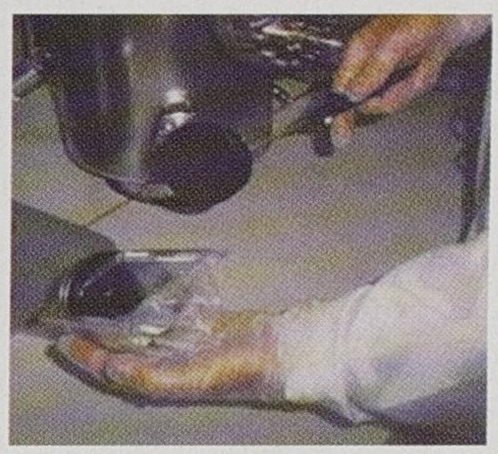
Emmett Hughlett is a director of applications engineering with Karl Suss America, Waterbury Center, VT, US. E-mail: ehughlet@suss.com. Web: www.suss.com. *This paper was presented at the Compound Semiconductor Manufacturing Expo (CS-MAX) held in Boston, MA, on July 9–11, 2001.*

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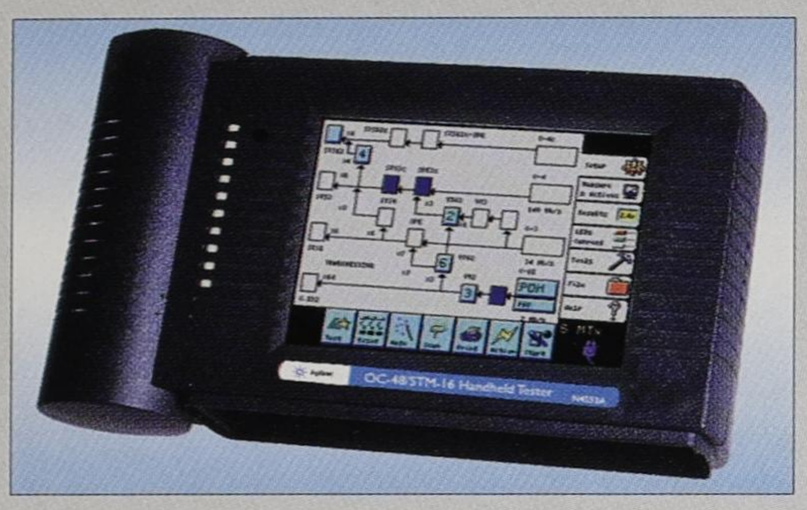
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Handheld evaluates 2.5 Gbit/s networks

Agilent Technologies has unveiled an OC-48/STM-16 handheld tester designed to evaluate SDH, SONET, PDH and T-Carrier network services and equipment at data rates up to 2.5 Gbit/s. The N4553A



can be applied to bit error rate analysis, error and alarm testing and automated network performance evaluation against numerous industry standards (e.g. G.821, G.826, M.2100 and M.2101).

Multiple built-in interfaces also allow for line and ring network topologies to be tested at 16 different electrical and optical line rates and framing standards.

Operating from either battery or mains, the company's tester weighs 5 pounds and can monitor up to 100 events simultaneously. It can also be operated in through-mode, mux/demux, OOS and ISM modes to test access network equipment prior to installation, or for passive monitoring.

Contact Sales, Agilent Technologies Test and Measurement, PO Box 4026, Englewood, CO 80155-4026, USA
Tel. +1 800 452 4844
Web www.agilent.com/comms

August offers Web-based support

August Technology has launched clickService, a Web-based technical support program that allows remote access to its wafer, die and bump inspection systems. Using the system, issues with software and hardware settings can be identified and corrected remotely by August service engineers, or interactively to assist the customer in resolving an issue.

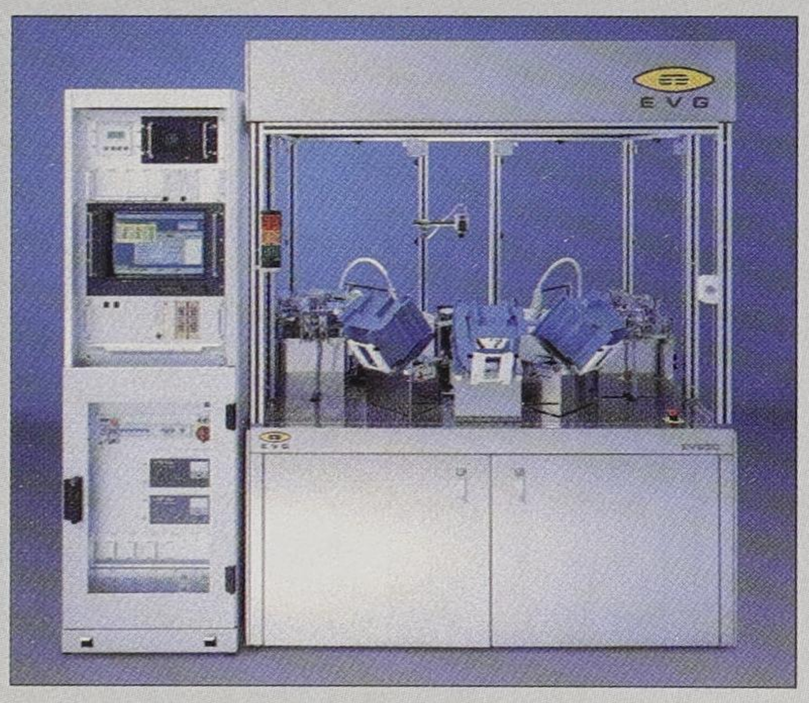
August's on-line program is available as part of a system warranty or can be purchased outside of warranty as a service contract option.

Contact Claus Nielsen, August Technology Corporation, 4900 West 78th Street, Bloomington, MN 55435, USA
Tel. +1 952 259 1613
Fax +1 952 820 0060
E-mail Claus.Nielsen@AugustTech.com

Robotic wax/spin-on bonder/debonder

EV Group (EVG) has introduced a fully-automated wax bonding, spin-on adhesive and adhesive film bonding and de-bonding system for compound semiconductor applications. The robotic system performs temporary bonding of fragile wafers on coated carriers; the latter can be completely processed and later de-bonded and removed.

The EV850 accommodates wafer diameters up to 6 inches, and can be configured for dry adhesive films or spin-on intermediate layers such as wax.

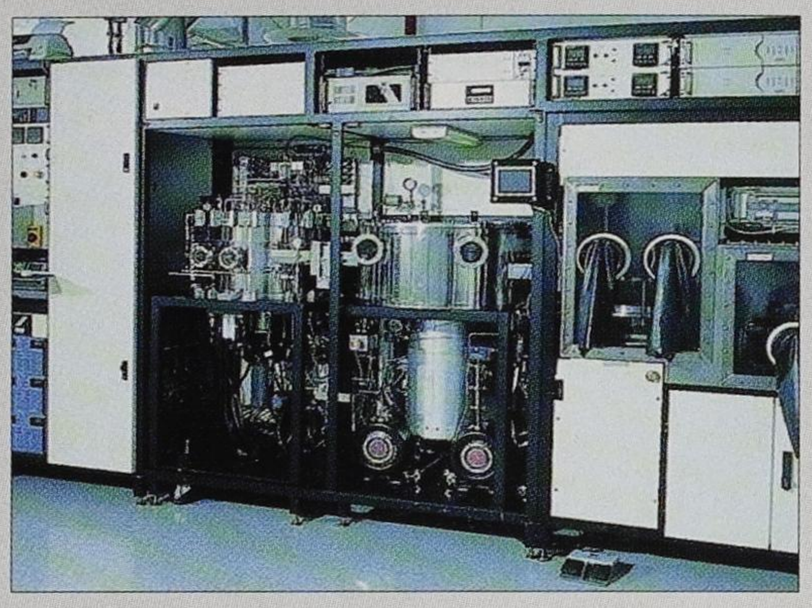


This approach provides a high level of uniformity for spin-on wax coating and bubble-free bonding in controlled atmospheres, while increasing throughput and eliminating wafer breakage.

Contact Rose Gismondi, EV Group, 1210 Pontiac Avenue, Cranston, Rhode Island 02920, USA
Tel. +1 401 784 0008
Fax +1 401 784 9933
E-mail r.gismondi@evgroup.com

New reactor series from Emcore

Emcore has expanded its range of Enterprise MOCVD reactors with the addition of the 300LDM and E450 series. Based on the company's existing TurboDisc vertical growth chamber



configuration, the 300LDM targets the growth of long wavelength, infrared and visible laser structures, and VCSELs. The E450 reactor is designed to grow HBT, PHEMT and LED epiwafers used in wireless and solid-state lighting applications.

"This expansion of our Enterprise reactor line also features our RealTemp optical control technology," said Paul Rotella, vice-president of the company's TurboDisc Tools Division. "This allows materials manufacturers to improve the quality of their materials, and facilitates a more efficient, accurate and cost-effective production process, while improving yield."

Contact Tom Miehe, Emcore Corporation, 145 Belmont Drive, Somerset, NJ 08773, USA
Tel. +1 732 271 9090
Fax +1 732 271 9686
E-mail info@emcore.com

Ansoft models foundry processes

Ansoft has released version 8.7 of Serenade, the company's latest circuit and communication system design software. Created with the needs of MMIC and RFIC designers in mind, the latest version takes into account design considerations

associated with foundry models.

Serenade 8.7 applies Monte Carlo analysis to both circuit and system simulation engines, and allows the user to directly view the overall or individual circuit/system response based on specified component tolerances. Enhanced post-processing is also possible and includes animated plots to visualize circuits and systems, including such phenomena as the distortion resulting from non-linear behavior.

Contact David DiOrio, Ansoft Corporation, 4 Station Square, Suite 200, Pittsburgh, PA 15219, USA
Tel. +1 412 261 3200
Fax +1 412 471 9427
E-mail diorio@ansoft.com

Cleaner flip-chip bonds and packages

Targeting flip-chip, optoelectronics and advanced high-reliability packages and assemblies, Austin American's Mega II system features a closed-loop solvent (or water) method that cleans electronic assemblies without producing waste streams.

The system is suited to precision cleaning for pre-wire bonding applications and pre-conformal coating, as well as tight-tolerance cleaning during flip-chip and post-ball attachment cleaning of ball-grid arrays. The system also includes wash and rinse cycles that incorporate a

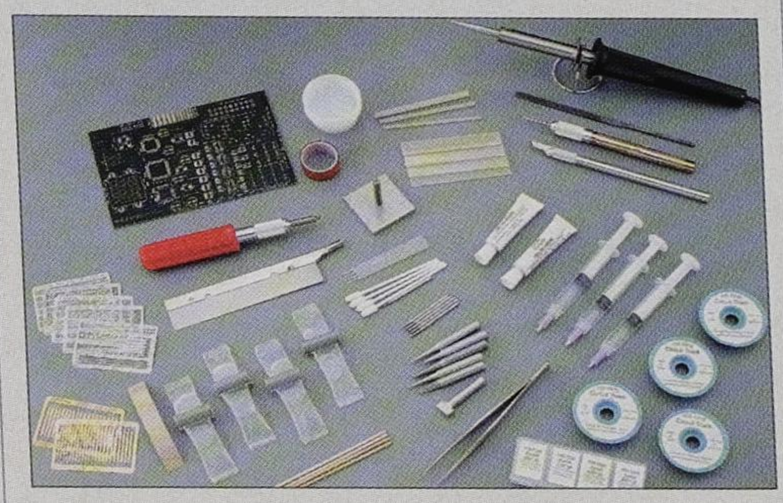


spray-under-immersion process. Agitation can be controlled to handle sensitive wire-bonded substrates or tight-tolerance flip-chip technology. An ultrasonic assist is available as an option for tough cleaning.

Contact Jon Phelps, Austin American Technology Corporation, 12201-160 Technology Blvd, Austin, TX 78727-6102, USA
Tel. +1 512 335 6400
Fax +1 512 335 5753
E-mail jrphelps@aat-corp.com

Repairs for damaged circuit boards

The Professional Repair Kit from Circuit Technology Center (CTC) is designed to repair circuits, surface mount pads and gold contacts. The package comes with materials to repair burns and defects in the baseboard and masks, and includes dry film, epoxy-backed circuit frames, and replacement circuits that require no liquid epoxy.

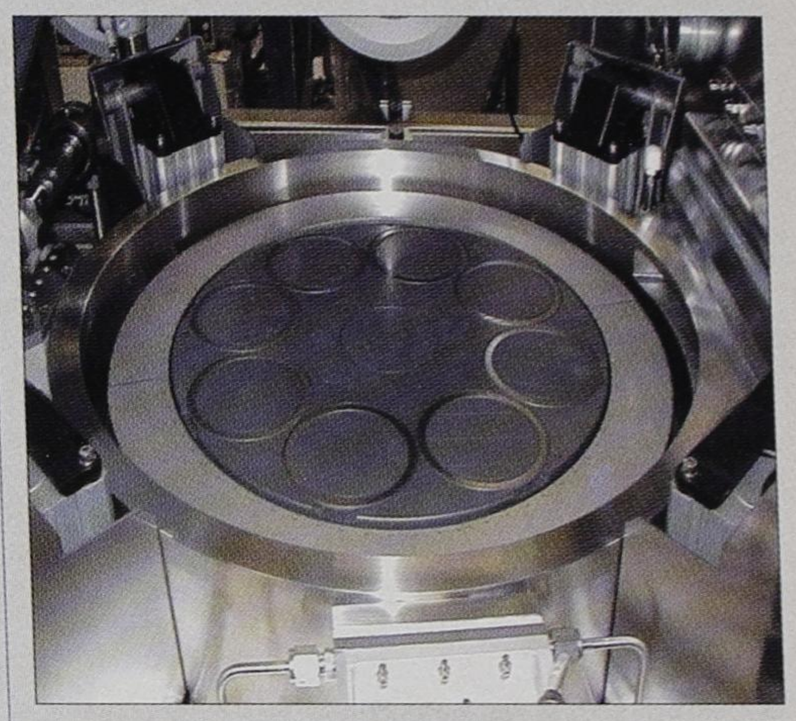


Also included are eyelets and setting tools for plated through-hole repair, circuit tracks to repair damaged circuits, epoxy and color agents for solder mask or baseboard repairs.

Contact Jeff Ferry, Circuit Technology Center, 45 Research Drive, Haverhill, MA 01832, USA
Tel. +1 978 374 5000
Fax +1 978 372 5700
E-mail jferry@circuittechctr.com

Aixtron upgrades reactor to 4 inch InP

Aixtron has unveiled an MOCVD system with a capacity for either 5 × 4 inch or 8 × 4 inch InP wafers. In common with the company's established AIX 2400/2600G3 Planetary reactors, the system features a cassette-to-cassette robot for direct loading/unloading, an RF heating unit



for fast cooling/heating cycles, and control of reactor boundary conditions.

"The compound semiconductor industry is preparing for the next generation of 40 Gbit/s ICs based on InP," said president Holger Juergensen. "Very soon, 4 inch [wafers] will dominate the market, as was the case earlier with GaAs, and we expect InP-based optoelectronics to move quickly from 3 to 4 inch wafers."

Contact Octavia Schirmer, Aixtron AG, Kackertstrasse 15-17, 52072 Aachen, Germany
Tel. +49 241 8909 474
Fax +49 241 8909 149
E-mail ocs@aixtron.com

Real time RF and microwave test

Cascade Microtech has released the Nucleus 2.1 Prober, a control software package that monitors and analyzes RF and microwave data in real time using wafer maps and histogram statistics. Nucleus 2.1 runs on the company's existing semi-automatic probe stations, and supports its RF motorized position systems to ensure accurate setup. The Nucleus 2.1 also provides complete graphical sub-site control and is compatible with NT 2000 operating systems. Control and monitoring of the thermal chuck temperature is also facilitated.

Contact Ellen Payne, Cascade Microtech, 2430 NW 206th Avenue, Beaverton, Oregon 97006, USA
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- vehicular, medical, fiber system IC's)
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Analyst community groping for bottoms

Are we seeing signs of the beginning of the end of the wireless slump? ***Marie Meyer*** *reports on the recent earnings announcements from RFMD, Alpha and others.*

During the wonderful run of the five-year bull market, many investors seemingly lost sight of the old adage that "what goes up must eventually come down", believing that share prices would continue to rise indefinitely. Evidence to the contrary is now all around us.

Happily, no one seems to have lost the hope that things will go up again. It is just a question of when. Hence one hears a great deal of talk about bottoms these days, as analysts search for indications that the current slump has reached its nadir. Only a few early earnings announcements were available when this issue went to press, and while they present a mixed outlook, one can see in them the first signs of the possibility of a recovery.

The reaction to Nokia's earnings announcement demonstrates just how mixed the current sentiment is. When the top mobile phone maker announced on July 19 that its sales had fallen just 8%, its share price jumped instantly from its 52-week low of $17 to over $20 – investors apparently believing that things could have been much, much worse. But over the next few days the share price began to slide back down, as "the glass is half empty" thinking seemed to take hold. It didn't help that analysts were disagreeing over whether Nokia's "guidance" for the next few quarters was good news or bad news. Basically, Nokia believes that the mobile phone industry will show little or no growth this year compared to last year, but did indicate that it expects to see a rebound in 2002. For anyone hoping for an immediate turnaround, this is disappointing news; for anyone who has already written off this year and is focusing on the future, Nokia's statements provided a confidence boost – supported by positive news from RFMD and Alpha.

Company	Symbol	Closing price July 20	52 week low–high	Market cap*	P/E ratio**
GaAs IC companies					
Alpha Industries	AHAA	34.80	13.0625–55.375	1.517B	73.65
Anadigics	ANAD	21.00	10.5000–43.3125	632.3M	78.92
Celeritek	CLTK	14.00	9.8125–53.3750	168.2M	N/A
Conexant	CNXT	8.82	6.9000–57.0625	2.179B	N/A
Endwave	ENWV	1.79	0.9000–20.6250	61.1M	N/A
RF Microdevices	RFMD	24.15	8.7500–48.3125	3.979B	N/A
Standford Microdevices	SMDI	10.62	4.2188–60.2500	310.5M	337.00
TriQuint	TQNT	20.46	10.2500–61.5625	1.646B	31.58
Vitesse	VTSS	17.94	15.1250–95.1875	3.289B	N/A
Opto companies					
Agilent	A	30.30	25.0000–80.9375	13.849B	20.91
Agere	AGRA	6.60	4.1000–9.5000	10.792B	N/A
Alcatel Optronics	ALAO	9.33	8.5300–71.7500	153.9M	8.37
Coherent	COHR	34.70	25.0000–93.5000	960.2M	12.10
Cree	CREE	24.14	12.2100–77.5000	1.755B	55.38
JDS Uniphase	JDSU	9.93	9.5500–140.5000	13.070B	N/A
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Tegal	TGAL	2.54	1.3125–8.0000	31.9M	51.00
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European shares (currency data in Euros)					
Aixtron	AIX	25.6	21.60–171.50	1.65B	40
Bede	BED	2.93	1.88–3.48	84.73	N/A
Filtronic	FTC	2.00	1.69–8.02	147.16	N/A
IQE	IQE	2.39	1.72–4.46	396.14	110
Picogiga	PICO NM	7.80	6.80–121.00	50.38M	N/A
Riber	RIBER	4.7	4.50–38.50	90.64M	N/A

**Market capitalization = # shares × current share price.*
***Price/Earnings ratio = current share price ÷ (income for the last 4 quarters ÷ # shares).*

RF Micro Devices

RFMD was one of the first companies to be battered by the slowdown in the wireless industry, and they now look like they are among the first to bounce back.

Revenues for the June quarter were $70.1 million, down 28% over the year-ago quarter but up 27% over the March quarter. This result was better than expected, as RFMD had been predicting sequential growth of approximately 20%.

Power amplifier (PA) module revenues increased 29% sequentially and represented 33% of revenues in the June quarter. Underscoring their commitment to module manufacturing, RFMD took special charges totaling $18.1 million in the quarter relating to obsolete chip inventory and MMIC testing equipment. The company also took a $4 million "asset impairment charge" as a result of its decision to out-

source all production packaging, and convert the current packaging line in North Carolina to an R&D facility.

Commenting on these activities, the CFO of RFMD, Dean Priddy, stated, "recent forecast analysis and customer inputs indicate a strengthening of our module business and continued strength in certain MMIC products but an overall excess of MMIC products in total...The shift in our business from MMICs to modules has happened rapidly, and we anticipate module revenue will represent approximately 50% of total revenue in the September quarter. The write-down of production packaging equipment reflects the growing industry trend to outsource non-core manufacturing. Our assembly partners have capacity and are working to reduce costs, so economically it now makes sense for us to outsource all packaging. However, based on customer input, we believe it's also a competitive advantage to maintain a strong packaging R&D group, which drove our decision to transition our packaging line to an all-R&D facility."

Excluding the effect of the special charges, net loss for the quarter would have been $7.5 million. With the one-time costs added in, the net loss for the quarter was pushed to $33.5 million.

Looking ahead, the company indicated that it is "fully booked to support approximately 10% sequential revenue growth in the September quarter". The company expects the loss to narrow to around $5 million in that quarter, with a return to profitability in the December quarter.

Commenting on the results and the overall outlook, David Norbury, president and CEO of RFMD, said, "We are very pleased to report better-than-forecasted sequential revenue growth particularly since the macro environment remains challenging...During the June quarter, the company experienced increased order activity and growth in backlog. Given these factors, and our ongoing communications with customers, we believe our visibility has improved into the September quarter. We continue to expect near-term revenue growth and market share gains, and we are optimistic about multiple opportunities in handset and non-handset markets."

Alpha Industries

Like RFMD, Alpha is heavily dependent on the wireless handset business, and they also had encouraging news to report. As expected, the results for the quarter were not stellar. Net sales were $32.2 million, down 50% from a year ago and down 40% from the previous quarter. The company reported a net loss of $3.9 million, compared with net income of $7.8 million from the year-ago quarter. But all of this was expected – company management had warned of a sharp drop-off in revenue six weeks ago.

What did come as a pleasant surprise was the assertion by president and CEO David Aldrich that the June quarter "represents the bottom in terms of inventory correction in the handset supply chain". In a conference call with investors he stated, "We've seen during the quarter and specifically in the latter half of the quarter, a significant reduction in the number of cancellation and order push outs. That had been a real problem for us at the end of [the March quarter] and into [the June quarter], and we've seen that abate by a lot recently. That's obviously a prerequisite to greater visibility and improvement going forward." He went on to say that Alpha anticipates a recovery in the September quarter, led by a 30% increase in revenue from the handset business. As for other areas, Aldrich predicted that recovery in the wireless infrastructure business would take hold later in the year. However, it is expected to lag behind the performance of the handset sector in the September quarter. He cautioned that visibility for Alpha's broadband business remains poor.

Alpha anticipates a recovery in the September quarter, lead by a 30% increase in the handset business.

Aldrich also said that "the excitement for us really begins in [the December quarter]", because at that time the company's recent PA module design wins will be entering volume production. He predicts that volume orders for GPRS (2.5G) phones will start in the December quarter and gain momentum in calendar 2002. He also predicted a return to profitability in the December quarter.

TriQuint/Sawtek

Not all the news from the RF sector was good. TriQuint Semiconductor had little to offer in the way of guidance for the next few quarters. The close of the June quarter represents the first time that TriQuint and Sawtek jointly reported their results since their merger was announced on May 15.

TriQuint reported revenues for the June quarter of $60.7 million, down 14% compared to $70.6 million for the same period last year. Net income, however, was off 86%, with $2.3 million reported for the June quarter compared to $16.4 million for the comparable quarter last year.

Sawtek has seen a much larger drop-off in sales. For the June quarter the company reported revenues of $18.8 million, down 57% compared to $44.1 million for the same period last year. Net income for the quarter was $2.4 million compared to $14.9 for the comparable quarter of 2000.

Commenting on the results, Kimon Anemogiannis, president of Sawtek, stated, "Our results for the [June quarter] reflect the slowdown that affected nearly every company in the wireless and communications markets. During this past quarter, we took numerous steps to place ourselves in a better position when the markets recover." Those measures included lay-offs in the company's plants in Orlando and Costa Rica, as well as disposing of an unprofitable sensor business.

The merger of the two companies is now complete and Sawtek shares have ceased to trade.

Stanford Microdevices

The mood was also downbeat in the earnings announcement for fabless RFIC manufacturer Stanford Microdevices. For the June quarter the company reported revenues of $5.4 million, compared with $7.9 million for the second quarter of 2000 and $7.8 million for the first quarter of 2001. The net loss was $1.5 million, compared with net income of $118 000 for the year-ago quarter and a net loss of $580 000 for the prior quarter.

"Despite recent encouraging signs from both direct customers and distribution channels, our near-term market visibility remains impaired," said Robert Van Buskirk, president and CEO of Stanford Microdevices. "The combination of the weak economy, inventory reductions and wireless network build-out deferments continues to impact component requirements and production plans for telecommunications equipment manufacturers worldwide." The company's revised outlook for 2001 includes total net revenues declining approximately 20–30% from the $34.6 million reported for 2000.

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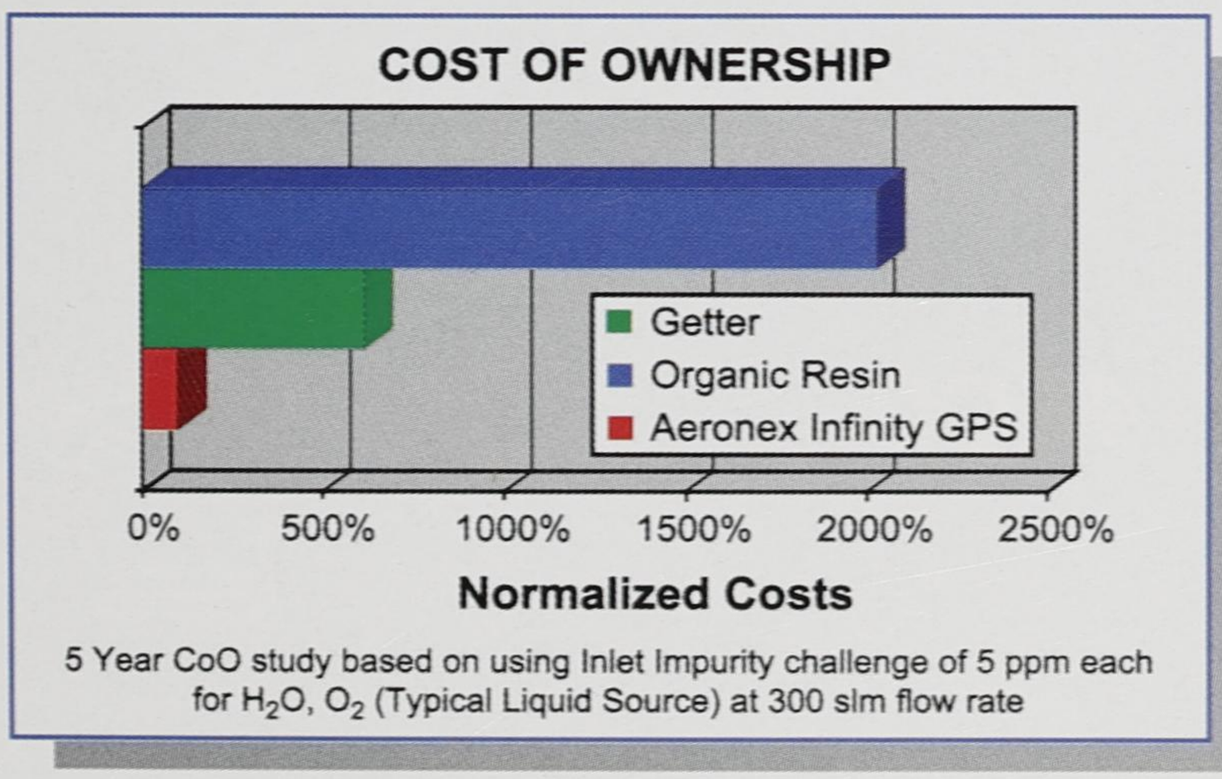
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