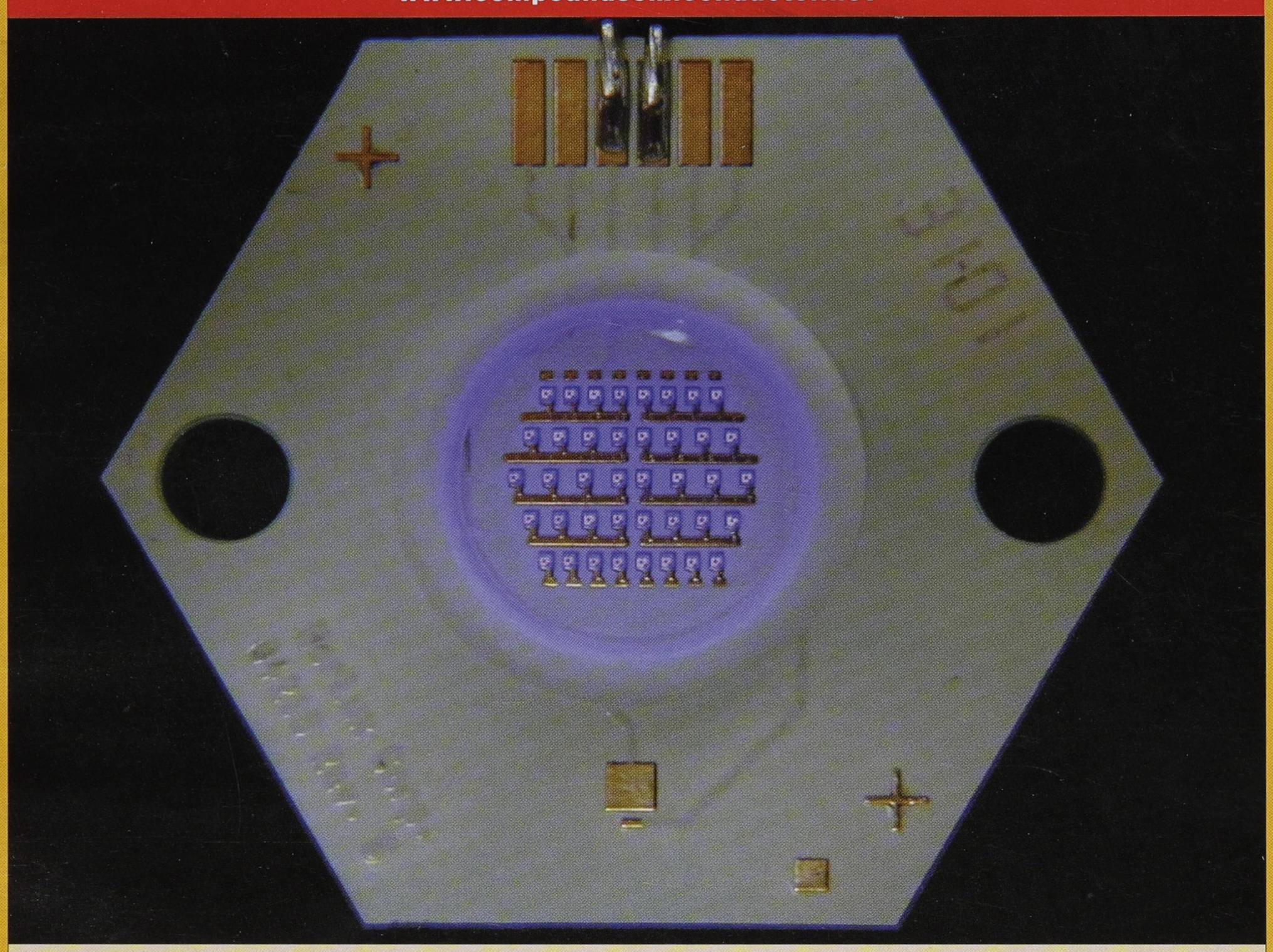
COMPOUND SEMICONDUCTOR

January/February 2002 Volume 8 Number 1

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Conexant in merger with Alpha	CMOS steals the show at IEDM	Nichia licenses white LEDs

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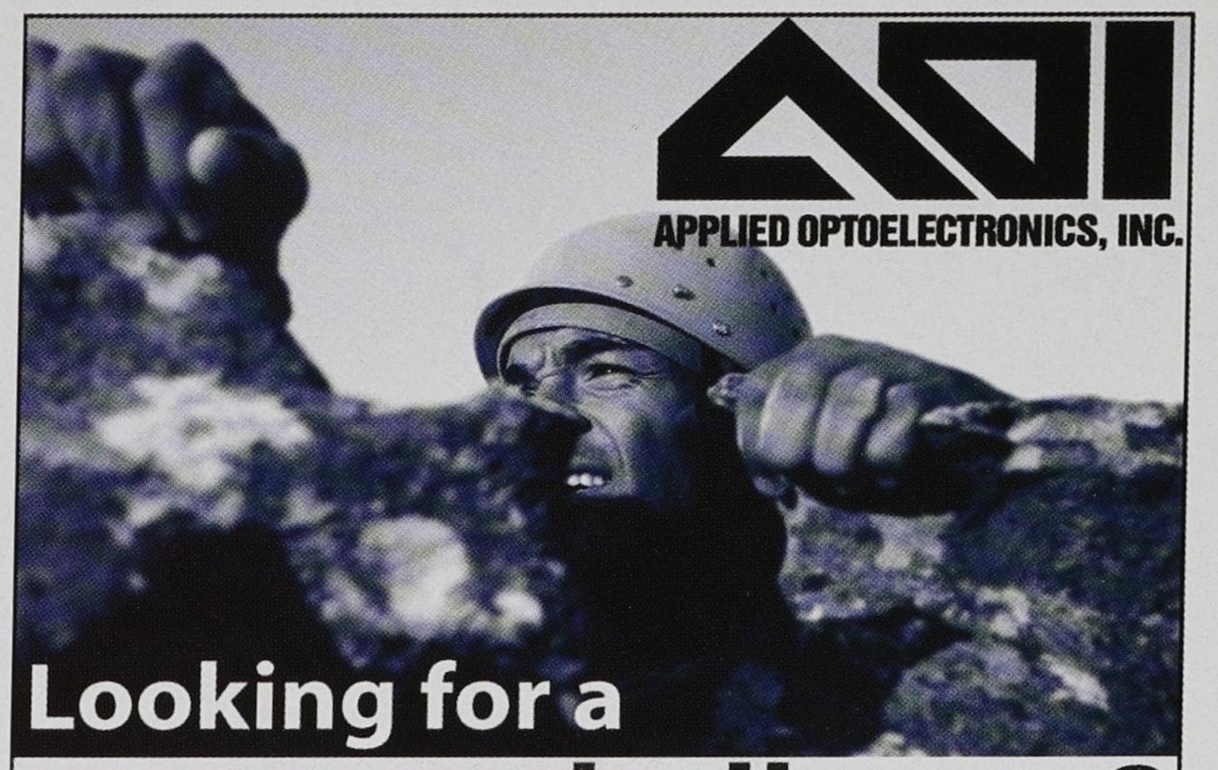
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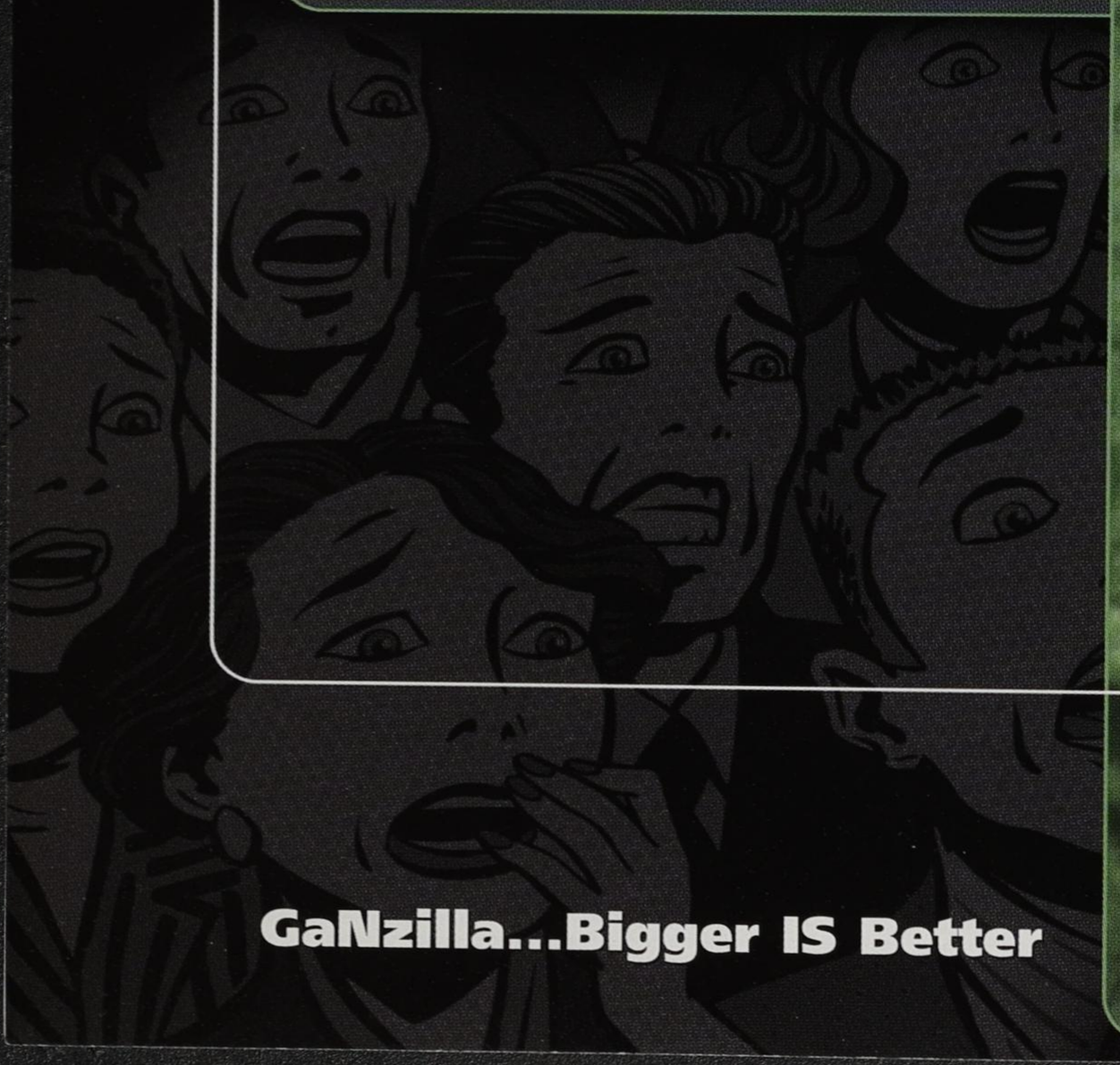
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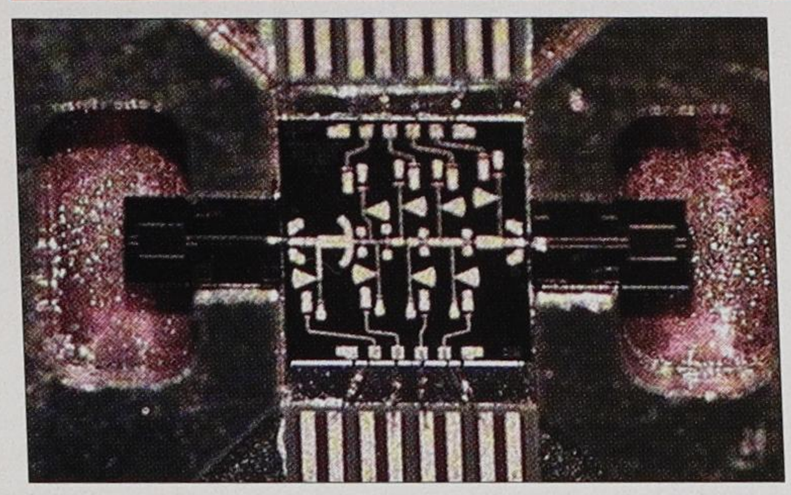
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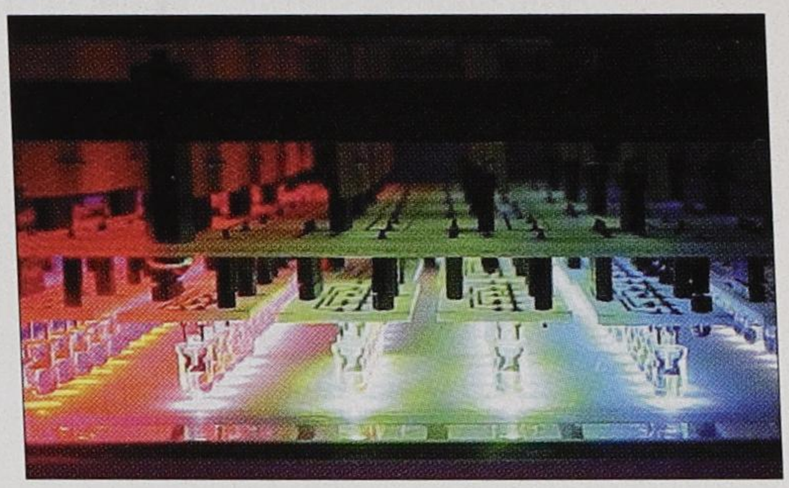
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Alpha and Conexant in wireless tie-up

By Marie Meyer and Tim Whitaker

In a major new deal announced on 17 December 2001, Conexant Systems will spin-off its wireless business and merge it with Alpha Industries to create a new company that is intended to be "the pure-play world leader in radio frequency and complete semiconductor system solutions for mobile communications applications".

The deal, which should be completed by June 2002, will proceed in four stages. Conexant will spin-off its wireless unit, and that business will immediately merge with Alpha to form a new company (with a new name that will be announced in the next few months). Then, the new company will buy Conexant's module manufacturing and test facility, located in Mexicali, Mexico, for $150 million in cash. Finally, the new company will be floated publicly. Alpha's shareholders will own approximately one-third and Conexant shareholders will own the remainder of the new company, which at today's prices would have a market capitalization of $3 billion. Dwight Decker, Conexant chairman and CEO, will serve as chairman of the board of directors for the new company; and David Aldrich, Alpha president and CEO, will be CEO of the new company. Alpha and Conexant will have equal representation on the board of directors of the new company.

Challenging RFMD

The new company will be the largest stand-alone supplier of RFICs. "For RF systems, this portfolio will include combination switch and filter products, multichip PA modules, and highly integrated transmit-and-receive devices for all major air-interface standards," said Aldrich. "For complete handset systems, the combined company will be able to deliver the world's most comprehensive 2.5G GSM/GPRS solution."

In a conference call with investors and analysts, management stressed that the new company would be able to offer all types of RFICs for all types of air-interface standards. But in reality the new company's particular strengths will lie in the areas of power amplifiers and switches. The new combination seems to be specifically aimed at challenging RFMD's dominance of the PA market and the rapidly emerging PA module market. According to analysts at Merrill Lynch, the new company won't have much competitive impact on TriQuint, as TriQuint's core competency lies in GaAs receiver products, an area where neither Alpha nor Conexant are particularly active.

The new company will be the largest stand-alone supplier of RFICs.

Conexant has traditionally been the top supplier of PAs for CDMA phones, with an estimated 80% market share, and customers including Samsung, Motorola, Ericsson and Nokia. Recently, however, Qualcomm has demonstrated a preference for RFMD's designs for CDMA PAs, and analysts believe that RFMD has been gaining market share over Conexant. The new company should be able to hasten the development of PA modules with integrated switches (Alpha's traditional strength), and thereby challenge RFMD's commanding lead in the PA module area. Management predicts that the new company will have around $300 million in annual revenues, which is comparable to RFMD and TriQuint, and roughly 50% higher than Alpha's current revenue level.

Facilities and technologies

Around 3100 of Conexant's current payroll of 6900 will be transferred to the new company, joining 900 former Alpha employees. Conexant will include its GaAs fab in Newbury Park, CA in the spin-off, while Alpha operates a fab in Woburn, MA together with the former Network Device Inc facility in Sunnyvale, CA. The new company will have in-house capability for several processes, including the AlGaAs HBT technology developed when Conexant was part of Rockwell, and the GaAs PHEMT and InGaP HBT processes commercialized by Alpha. In August 2001, Alpha announced the availability of an InP HBT process.

"The new company will have an expanded GaAs wafer manufacturing capability, including both PHEMT and InGaP HBT processes for RF switch and PA applications," said Dwight Decker. "The company will also own a high-volume, low-cost RF module assembly and test facility that has manufactured nearly 150 million PA modules to date. In addition, the company will have long-term assured access to Conexant's advanced SiGe and BiCMOS wafer manufacturing for integrated RF applications."

- Having completed the wireless spin-off, Conexant will be left with a broadband access business and an Internet infrastructure business. The latter unit, known as Mindspeed Technologies, will be separated into an independent publicly-traded company as soon as market conditions permit.

Bookham acquires Marconi Optical Components

By Jon Newey

Bookham Technology, Oxford, UK, has entered into an agreement with debt-heavy Marconi to purchase its Marconi Optical Components (MOC) division, which is located in Caswell, UK. The deal, expected to be concluded in late January, will see Bookham acquire MOC in exchange for nearly 13 million of its own shares, representing about 10% of Bookham's currently issued share capital. Based on the closing share price on 14 December 2001, this values the deal at £19.7 million ($28.4 million). As part of the agreement, Marconi will purchase components worth at least £30 million ($43.2 million) from Bookham over the next 18 months, both from its existing and new portfolios.

MOC has been in existence in its current form for little over a year. The division was formed by Marconi to shift the emphasis of activities at Caswell away from GaAs MMICs for wireless infrastructure towards components for optical networks (see *Compound Semiconductor* September 2001, p54). MOC's product portfolio includes InP-based fixed wavelength and tunable lasers, GaAs optical modulators and EDFAs, as well as GaAs MMICs. Though the wireless product range may be superfluous to Bookham's strategy of increasing the number of functions integrated into its optical network components, Giorgio Anania, CEO at Bookham, >>

said, "We expect to keep the wireless MMIC portfolio, where the Caswell people appear to have some world-class skills."

Actives and passives

Bookham's products use a proprietary silicon-based technology known as ASOC to fabricate passive devices such as multiplexers, demultiplexers, and variable optical attenuators (VOAs) on a single chip using well-established silicon processing technology. The acquisition of MOC is part of Bookham's strategy to provide its products with higher levels of functionality by integrating compound semiconductor-based active components with its silicon products.

"It has always been our strategy to improve the value of our integrated components by adding more III-V functionality onto our ASOC platform," said Steve Turley, Bookham's chief commercial officer. "While our MUX/VOA product is totally monolithic, others are using up to 11 chips to do the same thing." Bringing the two operations together will enable Bookham to integrate a large portion of the functionality that networks need onto its ASOC platform.

Marconi has been busy selling off non-core activities in recent months in an effort to reduce its huge debt burden, currently about £3.5 billion ($5.1 billion), and to concentrate on the provision of communication networks, which it sees as its main business. While the sale of MOC will not raise any cash for Marconi, it does remove a significant overhead to the business. In results for the year ending 31 March 2001, MOC reported a loss of £18.7 million on a turnover of £11.1 million. Though Bookham would not comment on the asset value of the acquisition relative to the value of the share transaction, this looks like a good deal for Bookham, which will acquire a significant patent portfolio in addition to MOC's physical assets.

The acquisition is part of Bookham's strategy to provide higher levels of functionality by integrating active components with its silicon products.

Marconi has made significant capital investment in the Caswell facility in the last few years, so Bookham's short-term investment obligations will be minimal. Marconi's investment program included the installation of the 6 inch GaAs line. This enables the cost of production for large-area devices such as optical modulators to be lowered relative to production on 3 or 4 inch process lines. Bookham's CFO Steve Abely would not comment on staffing levels, but stated that "Marconi is currently consulting with the workforce."

JDS Uniphase gains optical transceiver business from IBM

JDS Uniphase has acquired IBM's optical transceiver business in a cash and stock deal worth $340 million. The acquisition moves JDSU, which has previously concentrated on products for long-haul networks, into the short-reach datacom market. IBM's products include small-form-factor transceivers for storage and local-area networks using the Gigabit Ethernet and Fibre Channel standards. Short-wavelength 850 nm transceivers utilize VCSELs, while 1310 nm products use Fabry–Perot lasers. The purchase also gives JDSU access to technology and expertise in CMOS and SiGe IC design. Until recently, JDSU sold VCSEL-based modules manufactured by Emcore, but sales and marketing responsibility for these products has now reverted to Emcore (see *Compound Semiconductor* November 2001, p15).

"With this unit's innovative packaging and strategic design capabilities, we believe we can offer enterprises the same value-added proposition for data communications as we do in telecommunications, i.e. improved network flexibility, capacity, reach, reliability and cost, through advanced fiber-optic components and modules," said Jozef Straus, JDSU's co-chairman, president and CEO. JDSU will pay $100 million in cash and transfer 29.6 million JDSU shares to IBM. An additional payment of $85 million in cash or stock may be made in 2003 depending on the profits of the purchased business. IBM said that employees working for the division in Rochester, MN, who total about 100, will be offered jobs by JDS Uniphase.

RF Micro Devices buys GPS business unit from IBM

RF Micro Devices is to expand its product range into GPS chipsets after agreeing to buy IBM's GPS development operation. IBM was the first company to introduce SiGe technology into GPS components and the acquisition will increase RFMD's activity in silicon and SiGe technology. The agreement includes the transfer of IBM's intellectual property in the area, for which RFMD is already planning patent protection. The unit's existing GPS chipsets include LNAs, signal processors and RFICs for in-car, marine and handheld navigation devices.

William Pratt, RFMD's chairman and CTO said, "This acquisition immediately establishes a strong presence in the GPS market for us, while strengthening our extensive module and silicon system development efforts. We anticipate that our combined expertise will help to accelerate the commercialization of next-generation solutions currently in development, such as GPS on a single chip."

RFMD will utilize the GPS technology in its products for mobile-phone manufacturers, with the technology expected to appear in CDMA-based systems within a year. This will enable the accurate location of callers to the emergency services to be determined, as well as allowing navigation services to be provided to subscribers. The early provision of GPS capability in mobile phones also pre-empts the possible introduction of regulatory mandates.

Although the terms of the deal were not disclosed, analysts who follow RFMD are estimating the purchase price to be between $25–35 million, with the division capable of generating revenues of $20 million in 2002. Market researchers estimate that the global market for GPS ICs will grow from approximately $270 million in 2000 to around $1.2 billion in 2005, with nearly half of the latter forecast figure relating to GPS products in mobile handsets.

CS-MAX – the Compound Semiconductor Manufacturing Expo – will be held on 11–13 November 2002 in San Jose, California.

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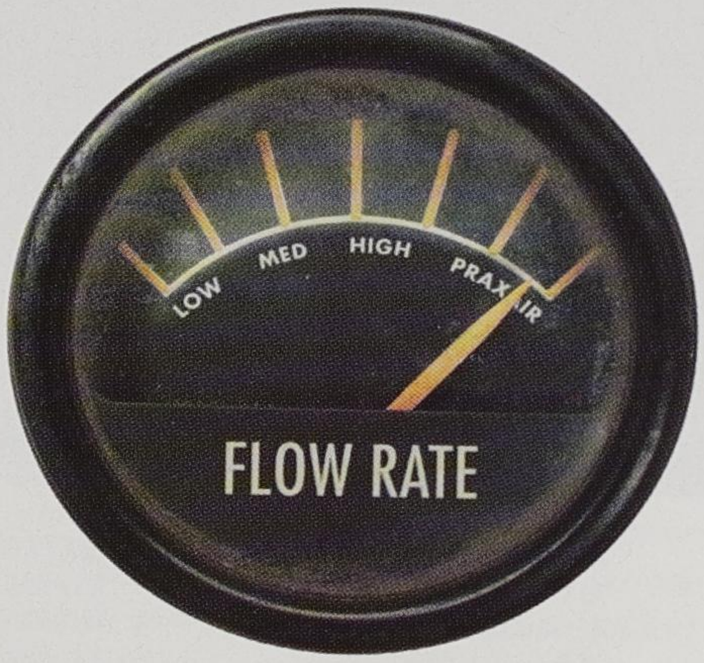
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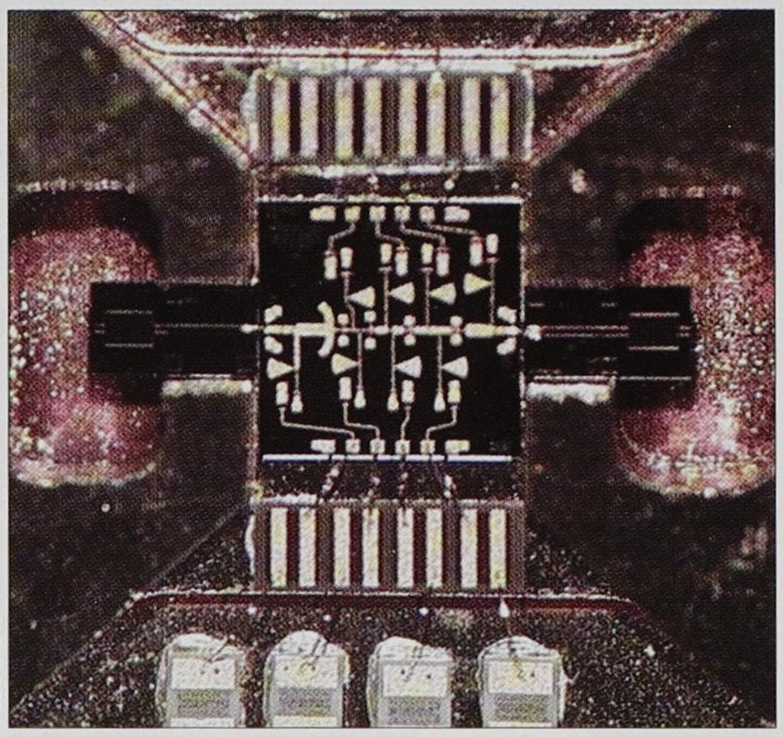
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CSIRO telescope uses InP circuits

Velocium and Australia's national research body, CSIRO, have formed a strategic alliance to develop GaAs and InP components for radio-astronomy, millimeter-wave sensors and telecommunications systems. Velocium recently supplied the InP LNAs and digital receiver circuits used in an upgrade of CSIRO's Australia Telescope. Operating up to 100 GHz, the circuits were designed by CSIRO engineers and fabricated by Velocium at its 4 inch InP fab in California. The upgraded system can now make detailed observations of the nearest galaxy harboring a super-massive black hole.

"The Australia Telescope is a demanding test bed for our InP chips," said Velocium's president, Dwight Streit. "Velocium's InP chips are helping to improve the science of astronomy now, and will soon be helping to improve the performance of other sensor and telecommunication systems."



VELOCIUM



Velocium has supplied 100 GHz InP ICs (left) for the Australia Telescope (right).

CSIRO started working with TRW in 1993, and in 1999 gained early access to TRW's InP technology for exploratory research, which helped expedite its development. Research performed under the new strategic alliance will have applications in areas ranging from vehicle guidance to the detection of concealed weapons and contraband, says the company.

TriQuint lowers business outlook

At the close of business on 18 December 2001 TriQuint announced that it was lowering its outlook for the December and March quarters. The company's revenue estimate for the quarter ending 31 December 2001 has been lowered from $75 million to approximately $65 million. The March 2002 quarter is expected to be comparable to the December 2001 quarter. The company has also said it will be taking a one-time only charge of $100 million in the December quarter.

TriQuint's announcement seems tied primarily to a downturn in the company's optical and satellite, rather than wireless, businesses. The signs from Alpha, Anadigics and RFMD indicate that the bottom has been reached in the wireless business and orders are beginning to pick up in that sector. TriQuint CEO Stephen Sharp gave a variety of reasons for the new fourth-quarter forecast. "Reduced revenue and earnings per share is the result of delayed shipments of products at the request of certain customers, continued softness in our optical networking business, and a slowdown in satellite and microwave businesses coupled with flat revenue in our wireless phone business," he said.

However, some analysts believe that TriQuint is also hurting in part due to the loss of market share to RFMD. In particular, TriQuint is believed to have lost some sockets in the heavily promoted Nokia model 3360 phone. Nokia accounts for 13–15% of TriQuint's total revenues.

Alpha wins Ericsson orders for GaAs ICs

Alpha Industries has received orders from a leading European wireless handset OEM, which is believed to be Ericsson, and is ramping production of GaAs ICs and other components for several new handsets targeting the Americas. The phones feature between two and four Alpha products per handset, based on TDMA and CDMA air-interface standards. Orders are expected to generate $5–10 million in additional sales in 2002.

"Our products for these applications include ultra-linear MMIC switches and control circuits based on multiple-gate PHEMTs," said Liam Griffin, Alpha's vice-president of sales and marketing. "These products are part of the new generation of 0–2.75 V positive voltage circuits based on Alpha's PHEMT technology. These ICs are able to handle high power with high linearity and extremely low insertion loss."

Alpha sees strong growth in wireless LAN sector

Alpha Industries has reported strong order growth in the wireless local area networking (WLAN) sector. The company says its ultra-linear GaAs switches are being designed into 802.11b chipsets, which are used to connect PCs and wireless devices at 2.4 GHz in small office, enterprise and home applications up to a couple of hundred feet apart. In recent months, Alpha has received orders exceeding three million units from a number of companies, including the industry's top provider of 802.11b chipsets. In addition, Alpha has recently introduced a new 5.8 GHz transceiver chipset that contains a PA, LNA and GaAs switch and targets 802.11a applications.

"Recent industry data identifies WLAN for business, small office and home applications as among the communications industry's hottest segments," said Liam Griffin, Alpha's VP of sales and marketing. "The orders we are receiving today are in production, and we expect to see accelerating revenue from this market beginning in 2002. These products provide the mobility and versatility that consumers are looking for, delivering low-cost wireless access while maintaining data rates up to 11 Mbit/s."

Anadigics samples new module

Anadigics is sampling new integrated RF modules for dual-band GSM/DCS wireless handsets. The AWT6200 PowerPlexer combines the company's InGaP HBT PA and GaAs PHEMT multi-throw RF antenna switch with integrated passives and analog control circuits, and delivers class-12 GPRS performance.

A $12 \times 12 \times 1.5$ mm^3 SMT module package houses two PAs with low-pass harmonic filters, a high-linearity integrated PHEMT antenna switch and a CMOS controller. In addition, Anadigics says it has developed an integrated passive process that lowers the discrete component count and reduces the size and cost of the module.

"Traditionally, wireless handset OEMs spend a considerable amount of time and engineering resources to optimize the interface between the PA module and the antenna switch," said Ali Khatibzadeh, VP of wireless products. "The PowerPlexer simplifies the handset design process by providing a single RF transmit module with the optimum interface built-in. This enables a significant cost and size reduction as well as a time-to-market advantage for customers, as they use the same reference design across multiple platforms with minimum re-engineering."

PA orders from Ericsson

In more news, Anadigics is shipping production volumes of a PA chipset for Ericsson's new WAP-enabled T60d handset. Employed in TDMA networks, the new handset will be powered by two Anadigics GaAs PAs and one PA driver. The T60d is the latest dual-band, tri-mode phone from Ericsson, which recently ordered Anadigics' PA chipsets for use in its new R300d handset (see *Compound Semiconductor* December 2001, p8).

Motorola shrinks quad-band module

Motorola has reduced the size of GSM power amplifier modules using a new design that provides 50 Ω impedance matching without the need for additional passive components. Called the High Impedance Integrated Power Amplifier (HIIPA), the new module achieves a 50 Ω output by integrating capacitors onto the die, while inductors are implemented by wire bonds of variable lengths. The tolerance of the capacitor values, together with the precision of the wire bonding process, allow a matching impedance value with less design variance than can be achieved with passive components on a traditional radio board, says the company.

The first product is expected to be a quad-band PA module, which covers either European triple-band GSM/GPRS or dual or triple-band GSM/GPRS in the US. This module also uses Motorola's enhancement-mode HFET GaAs technology, which eliminates the negative voltage supply (see *Compound Semiconductor* February 2001, p74).

"The HIIPA concept creates a cost-effective solution for radio designers by combining high-performance E-mode GaAs technology with highly innovative circuit and package design techniques," said Behrooz Abdi, VP of Motorola's Radio Products Division. "[This provides] a 50 Ω solution at a more competitive price than is possible with modules using traditional passive components for matching."

The MMM5062 quad-band module is encased in a 7×7 mm^2 package with a thickness of less than 1.11 mm, and volume production is planned for the first half of 2002.

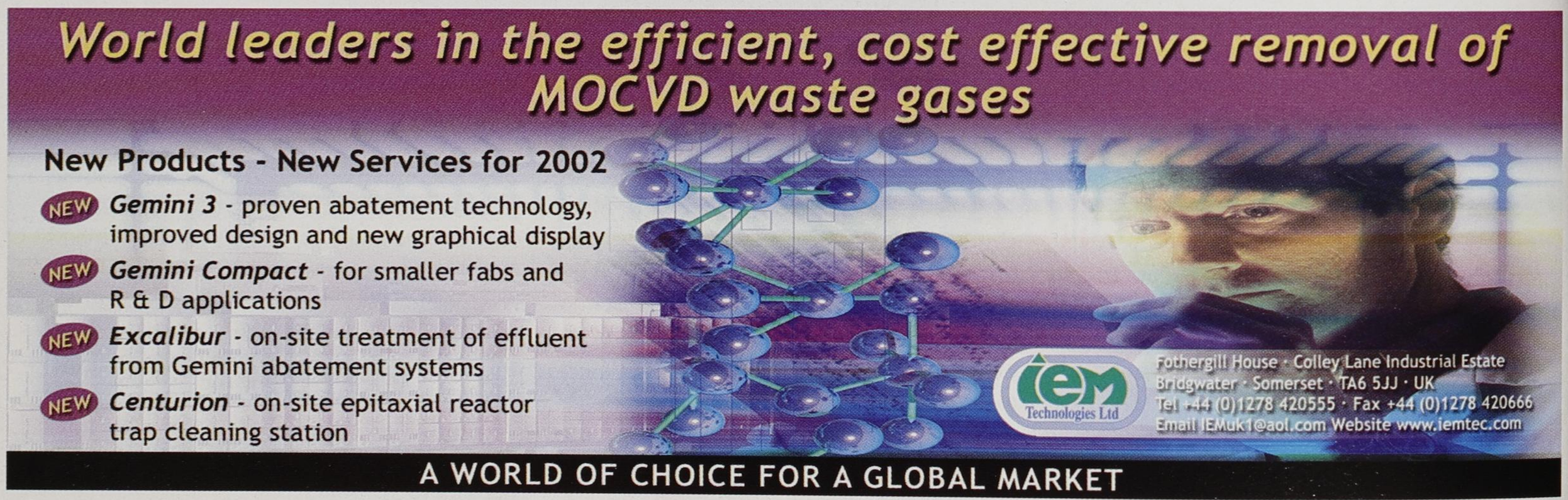
In brief...

RFMD extends sales and support base into Taiwan

RF Micro Devices will open a sales and customer support office in Taipei, Taiwan. The office includes a customer development lab for WLAN and GSM handset development employing RFMD's chipsets and reference designs. "The opening of our new Taiwan office underscores our belief that this region will continue to have tremendous growth potential, especially in cellular handset and wireless LAN manufacturing," said David Norbury, president and CEO.

TriQuint to supply GaAs MMICs for jet fighter

TriQuint's Texas division will supply Northrop Grumman Electronic Systems with GaAs MMICs as part of the US Department of Defense development program for the Joint Strike Fighter. TriQuint has a long history of supplying GaAs circuits for many of Northrop Grumman's activities, such as the previous generation F-22 jet-fighter program, which included GaAs chips for transmit/receive modules used in phased array radar.



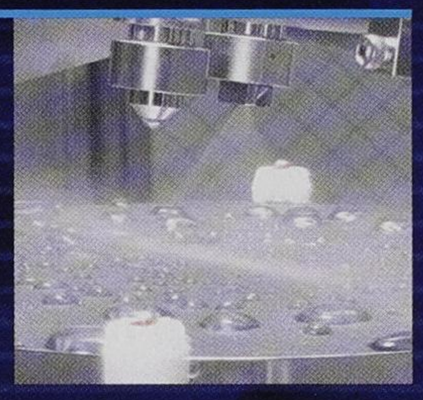
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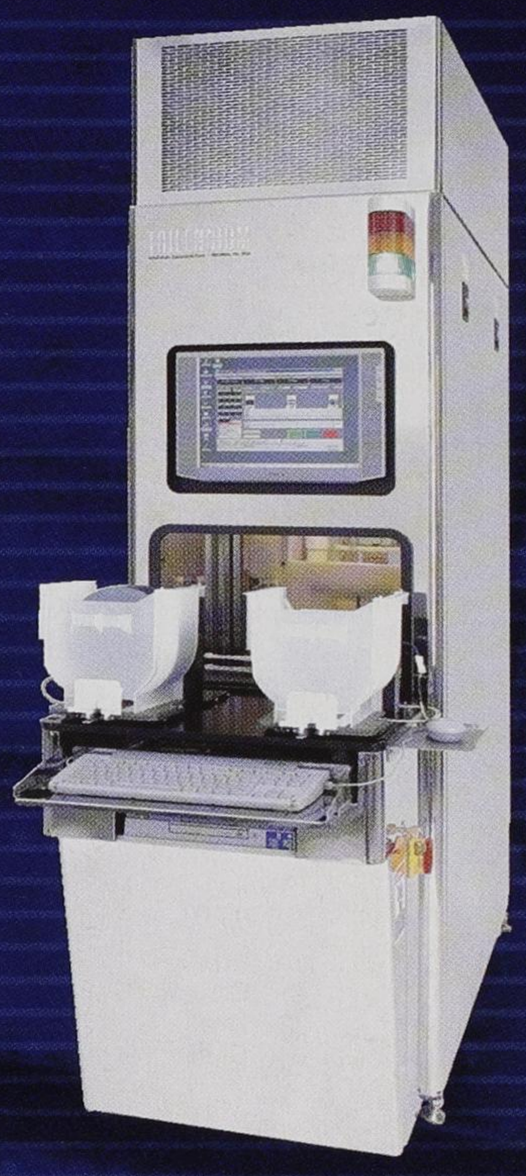
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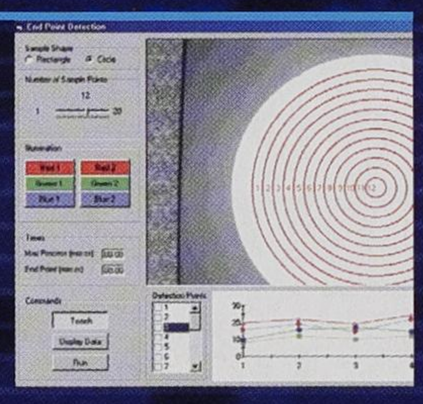


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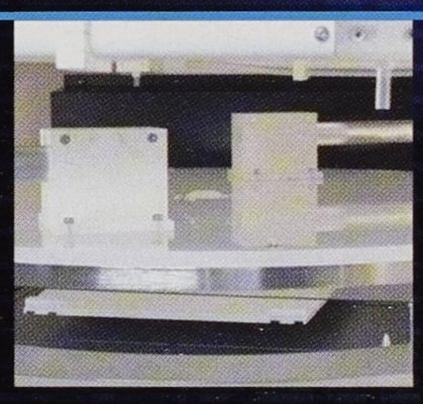


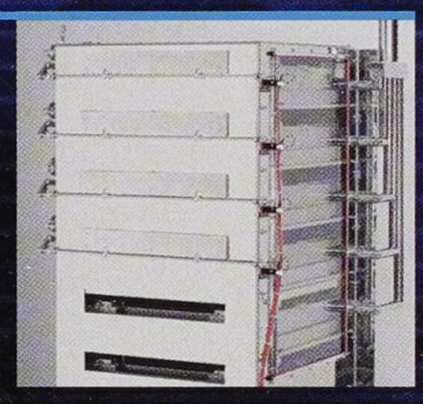




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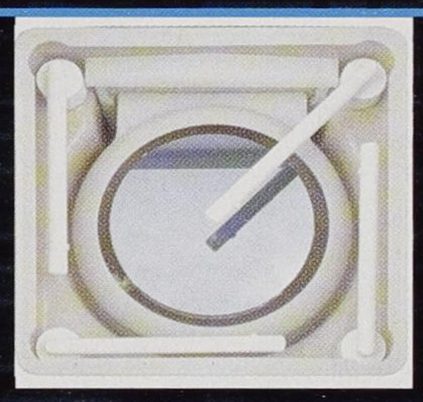


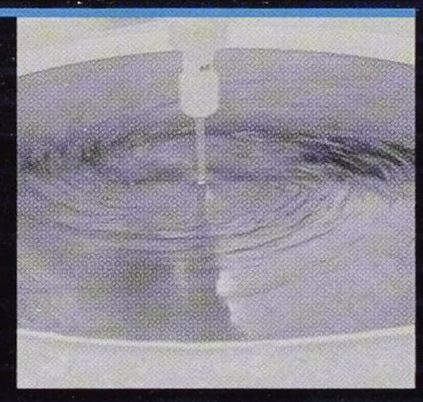


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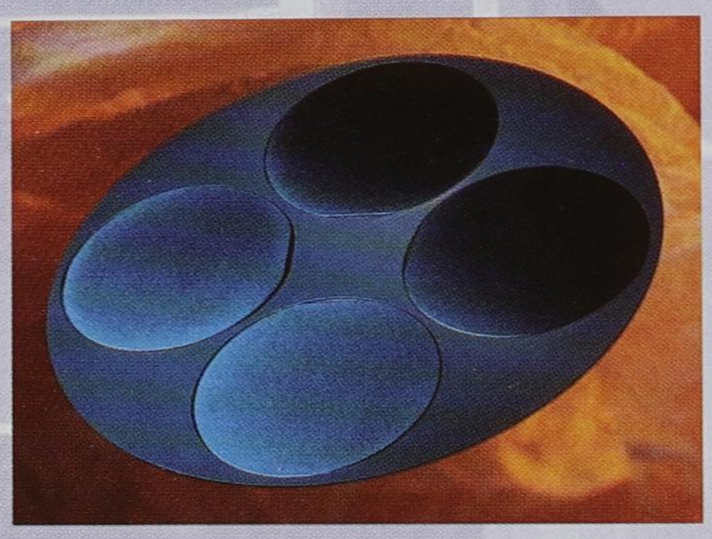
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Nichia and Citizen in white LED tie-up

Nichia Corporation and Citizen Electronics have formed an alliance to produce and sell white LEDs. Citizen, one of the world's largest LED manufacturers, will purchase production quantities of blue InGaN LED chips from Nichia and will manufacture white LEDs using technology licensed from Nichia.

The agreement marks two significant changes in strategy for Nichia, which has previously only sold packaged devices. More significantly, Nichia has consistently stated that it would not license its extensive intellectual property portfolio in the field of nitride LEDs.

"The sale of unpackaged die and the licensing of technology are firsts for Nichia, so this alliance was not rushed into," said Noboru Tazaki, MD and general manager of Nichia's Optoelectronics Products Division. "In Citizen we found a partner that could take our technology to a broader market in a high-quality package, and that made the difference."

LEDs fight jet lag and fatigue

An innovative handheld device uses white LEDs to combat the effects of jet lag, fatigue and even bulimia, according to its manufacturers. The Litebook Company, based in Medicine Hat, Canada, has incorporated 72 white LEDs supplied by Nichia into its handheld light supplement devices (see photo). With the Litebook model, users are provided with "a heightened sense of alertness and well-being by bathing in the light for 15–20 minutes per day", says CEO Larry Pederson. The Time Traveler model combats jet lag, which causes the disruption of more than 50 physiological and psychological rhythms. "The human body clock can be safely shifted to up to 12 time zones in two days with a precisely timed exposure to a sufficiently bright light," explains Pederson. The device's program indicates the appropriate times to seek and avoid light.

Nichia's white LEDs consist of blue LED devices combined with phosphors emitting in the yellow region. Pederson claims that the Litebook products exhibit shorter supplement times than other devices because the blue wavelengths are the most effective at suppressing melatonin, the hormone which is linked to sleep disorders.



LITEBOOK

The Litebook Time Traveller has 72 white LEDs and combats jet lag and fatigue.

Sun powers white LED streetlight

Two Japanese companies have developed a solar-powered LED streetlight that can operate in isolated areas away from power lines. The streetlight uses 90 white LEDs inside a specially formed glass cover, and provides a brightness of 3 lux at a height of 3.2 m, or 1 lux at a height of 10 m. The light operates from –30 °C to 80 °C and the LEDs are claimed to have a service life of 70 000 hours, which is equivalent to 20 years if the streetlight is operated for 10 hours each day. A small battery, charged by solar cells, can act as a back-up and power the streetlight for seven days without the need for sunlight.

Lawsuit against Cree dismissed

The Tokyo District Court has dismissed a lawsuit that was filed in April 2000 by Nichia against Sumitomo, one of Cree's distributors in Japan. Nichia alleged that certain Cree LED products had infringed Japanese patent no. 2 778 405 and sought an injunction to prevent Sumitomo from selling the LEDs in Japan. Cree argued successfully that its LEDs utilized a structure that was fundamentally different from the invention claimed in the patent. Sumitomo, which currently sells Cree's LEDs in Japan at a rate of about 15 million per month, said it hoped to expand sales following the ruling.

Uniroyal faces financial crisis

On 7 January Uniroyal Technology Corporation (UTC) announced the lay-off of 90 of its 400 employees and the sale of its Coated Fabrics division to raise money for the company's LED operation and other compound semiconductor-related activities. This announcement comes hard on the heels of Uniroyal's annual report, which reveals that the company's auditors have doubts about whether UTC is viable as a going concern.

Since 1998, UTC management has been trying to reposition the company away from mature, industrial-based activities and into the high-growth compound semiconductor industry. In February of that year Uniroyal formed a joint venture with Emcore to manufacture HB-LED wafers and package-ready dies. However, Emcore pulled out of the deal in August 2001. UTC has spent $54 million building a 77 000 sq. ft fab in Tampa, Florida.

UTC is facing a liquidity crisis. Cash on hand dwindled to $2 million from $36.6 million a year ago. The company has reported a loss in each of the last three years, and is forecasting negative cash flow in 2002. While the company's compound semiconductor activities are described as the way forward, this operation had an accumulated deficit of more than $60.4 million as of 30 September 2001. It incurred net losses of around $46.5 million in 2001, $27 million in 2000 and in the September quarter it generated a loss of $19 million on sales of $1.7 million.

UTC is also facing an $8 million lawsuit for allegedly reneging on its agreement for a new facility for its recently acquired Sterling Semiconductor subsidiary. Uniroyal's stock price has fluctuated widely – over the last 24 months the company hit a high of $36.44, but is currently trading at less than $1. UTC has lost half its value since the full extent of the crisis was revealed in the annual report.

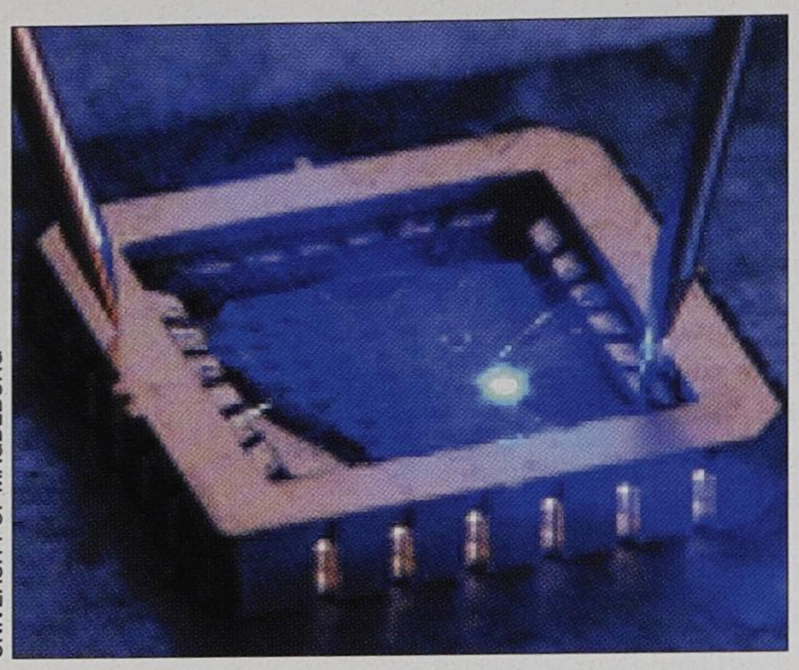
Silicon substrates benefit GaN LEDs

By Richard Dixon

Nitronex is not alone in its investigation of the properties of silicon substrates for the growth of GaN devices (see *Compound Semiconductor* September 2001, p63). Both Sanken Electric and the University of Magdeburg have also reported making considerable advances in the fabrication of blue LEDs.

While most GaN devices are currently grown on sapphire or SiC substrates, silicon offers advantages such as much lower cost and larger size. Added to this is the ability to use both front and back contacts due to the conducting nature of the silicon substrate (SiC is also conducting). In contrast, the non-conducting sapphire substrates require two front contacts, which necessitates etching down through the structure.

Together, these factors add up to considerable cost savings, although silicon has the disadvantage that it absorbs visible light. GaN-on-silicon LEDs could, however, be of interest in producing low-power emitters for signaling or illumination, and it may also be possible to integrate such light emitters with silicon electronics.



UNIVERSITY OF MAGDEBURG

GaN-on-Si blue LEDs have sufficient light emission for indicator applications.

Sanken estimates that using silicon wafers lowers the cost of producing blue LEDs by at least 90%.

Sanken targets indoor applications

Sanken Electric of Saitama, Japan, already supplies a wide range of LEDs, including 470 nm blue InGaN/GaN devices. The company began investigating blue emitters on silicon early in 1995 in collaboration with Kogakuin University and more recently Nagoya Institute of Technology, and is growing GaN-on-Si by MOVPE.

Sanken uses a hydrogen-terminated Si(111) surface for growth, which is obtained by etching away the oxidized Si layer. This provides a smooth surface suitable for high-quality crystalline growth of low-temperature buffers directly on the surface. These AlN/GaN buffer layers offset the large mismatches in lattice constants and thermal expansion coefficients between the substrate and epilayers. Using this approach, crack-free GaN layers can be grown up to 1.5 μm thick.

It is probably because Sanken has filed 23 patents on its device technology that details are scant concerning the exact LED structure. However, the company has revealed that the QWs are grown in the thick GaN layer about 0.7 μm above the silicon substrate. The device features a forward voltage of 4.1 V, and is said to achieve emission characteristics equivalent to those of the standard low-brightness blue and green LEDs used in indoor applications. The company says that by the spring of 2002 it aims to have increased the power efficiency by reducing the forward voltage to the 3.0 V level demonstrated by commercial LEDs, and also to further increase the brightness.

Sanken is also looking at using high-quality GaN-on-Si thin films for the power devices used in power supply applications. This could offer significant advantages over conventional power devices in terms of cost and performance. Overall, the company estimates that using silicon wafers lowers the cost of producing blue LEDs by at least 90% compared with devices on sapphire or SiC substrates.

Magdeburg demonstrates GaN on Si

Researchers at the University of Magdeburg in Germany have also developed crack-free InGaN/GaN LEDs on Si(111) substrates. To overcome the mismatch problems, Armin Dadgar and colleagues have employed silicon nitride masks to reduce the dislocation density in thick GaN films, and added low-temperature AlN layers to compensate for stress in the resultant thick LED structure.

"Our growth process on the planar silicon substrate is very simple, since we do not need any pretreatment except for a simple chemical etch," says Dadgar. "These LEDs could therefore be suitable as inexpensive emitters such as indicator lights."

The devices are grown by MOCVD and begin with GaN on an etched and hydrogen-terminated Si(111) surface. A silicon-doped AlN seed layer is followed by a GaN buffer and low-temperature AlN/GaN/AlN layers. GaN is then deposited prior to the Si_xN_y mask, which is grown *in situ*. The mask contains windows up to $300 \times 300\ \mu m^2$ in size. To achieve coalescence of the GaN below its critical thickness on Si, the mask is made relatively thick and coalescence is encouraged using high ammonia flow rates. Cracks in the subsequent layer are thus confined to well-defined regions bounded by the mask, which results in crack-free GaN.

The active layers of the device contain five $In_{0.15}Ga_{0.85}N$/GaN QWs, above which is a Mg-doped AlGaN blocking layer and a GaN cap. In this manner, a 2 inch wafer was grown entirely crack-free. X-ray data confirmed that the level of stress in the wafer was low and that the material was of a similar quality to GaN grown on sapphire. Compared with growth of GaN on AlN buffers alone, the importance of the masks was confirmed by the five-fold increase in electroluminescence intensity.

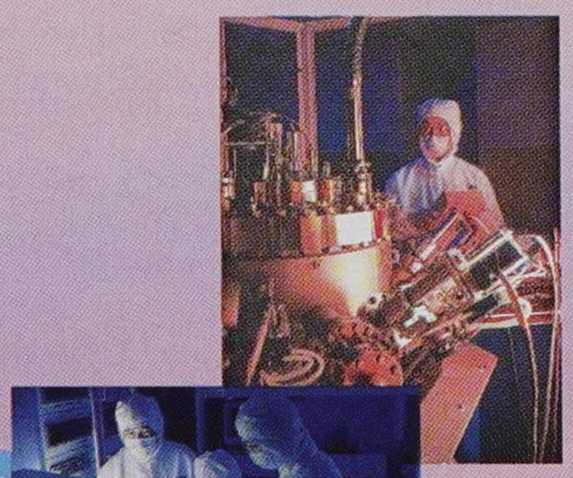
Devices with vertical contacts were electrically characterized on-wafer and power measurements were obtained by mounting $1 \times 1\ mm^2$ chips into epoxy LED housings. Optical measurements revealed blue emission at around 455 nm, with around 150 μW radiant flux at 20 mA, and a turn-on voltage of 2.8 V. This level of performance is sufficient for indicator applications.

Dadgar says the devices currently suffer from a high series resistance (55 Ω) compared with commercial devices, which stems from the p-type contact and the AlN:Si layers. Future LEDs will target 20 Ω. In addition, these AlN layers generate new dislocations that are not reduced over the average thickness of subsequent device growth, and the silicon nitride masks are helpful in removing these threaders and improving the performance of the device.

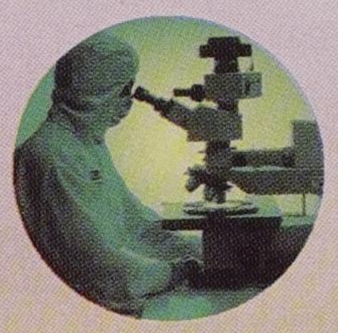
Although the series resistance prevented successful operation at higher drive currents, reducing the absorption losses from the Si substrate and InGaN layers could significantly increase the brightness. This is largely because no side facets are etched and the devices are not separated from each other.

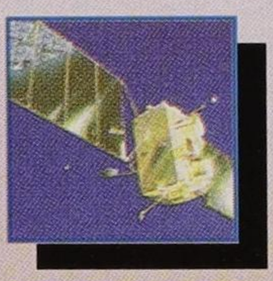
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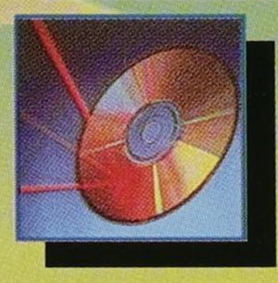


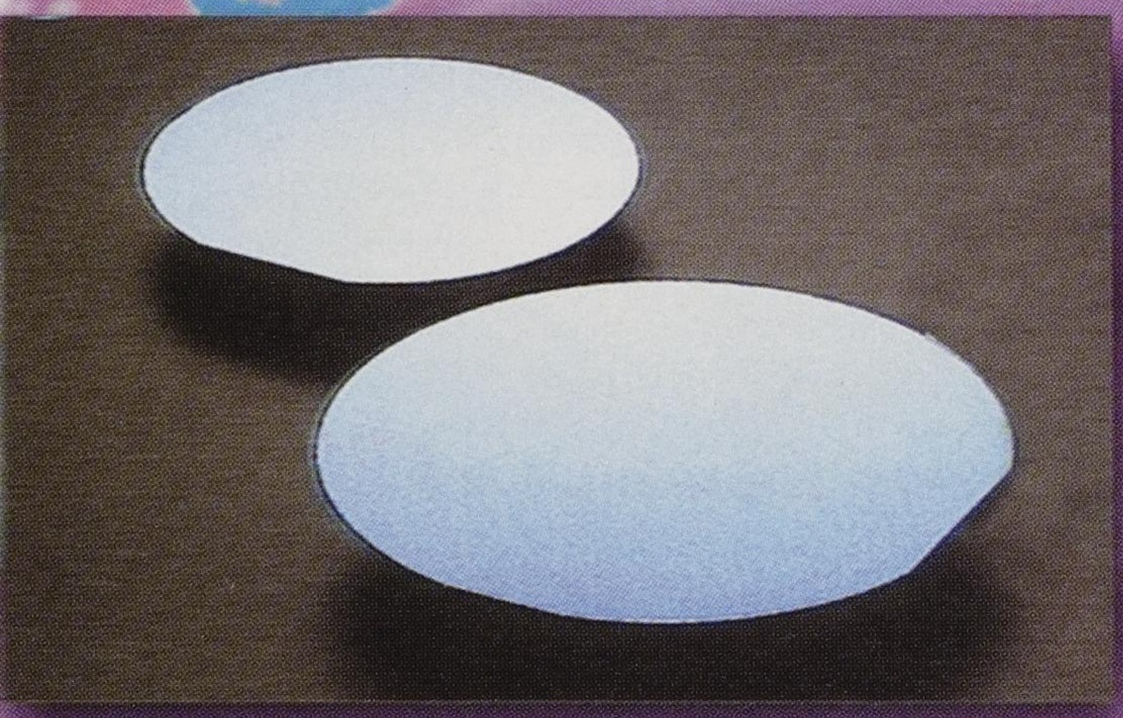












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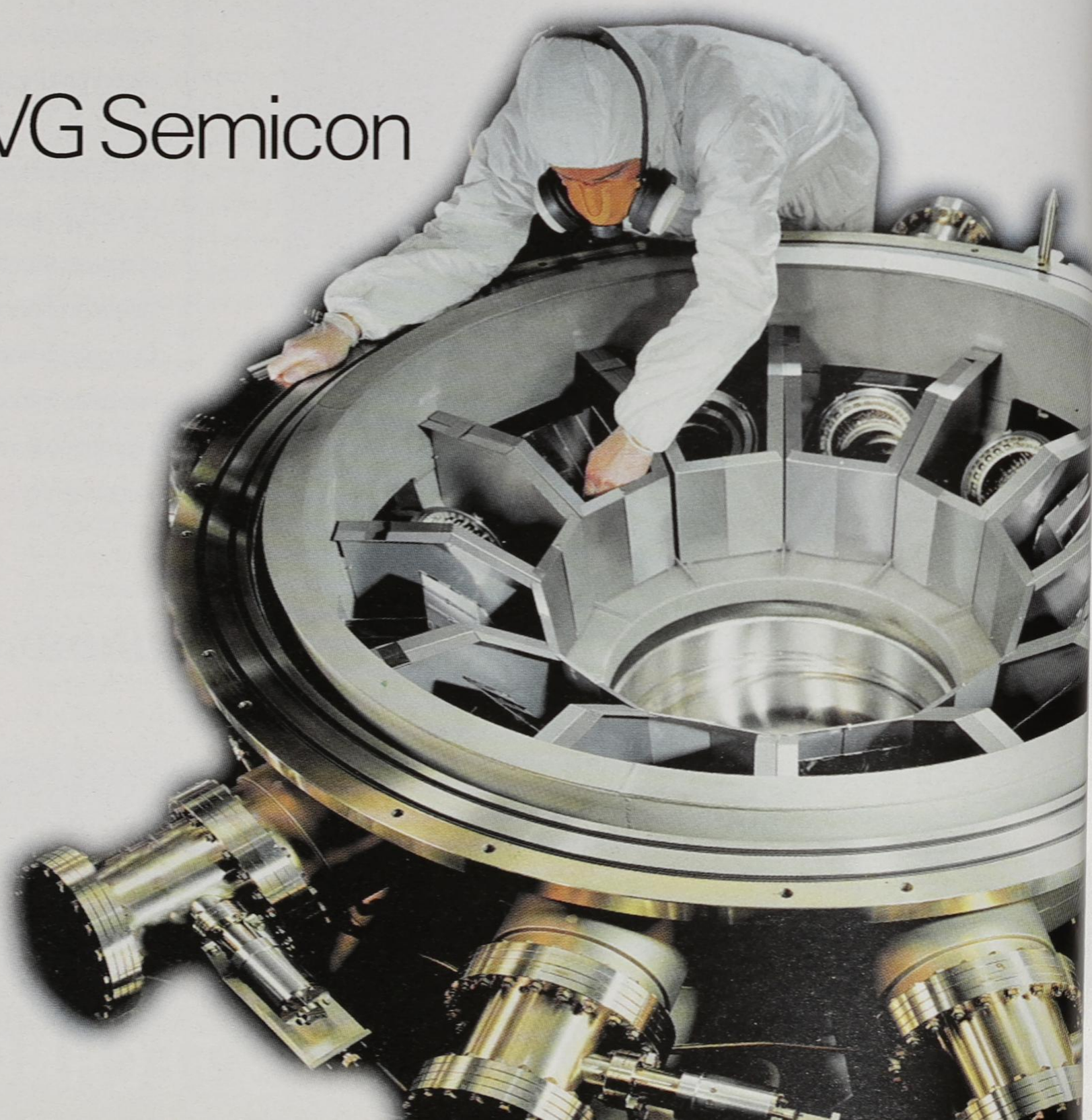
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IC vendors eye OC-768 applications

Despite the current downturn in the optical networking sector and reduced capital spending by network carriers, several vendors have recently introduced high-frequency ICs and processes for 40 Gbit/s applications, in anticipation of new network designs and the build-out of future higher capacity optical networks.

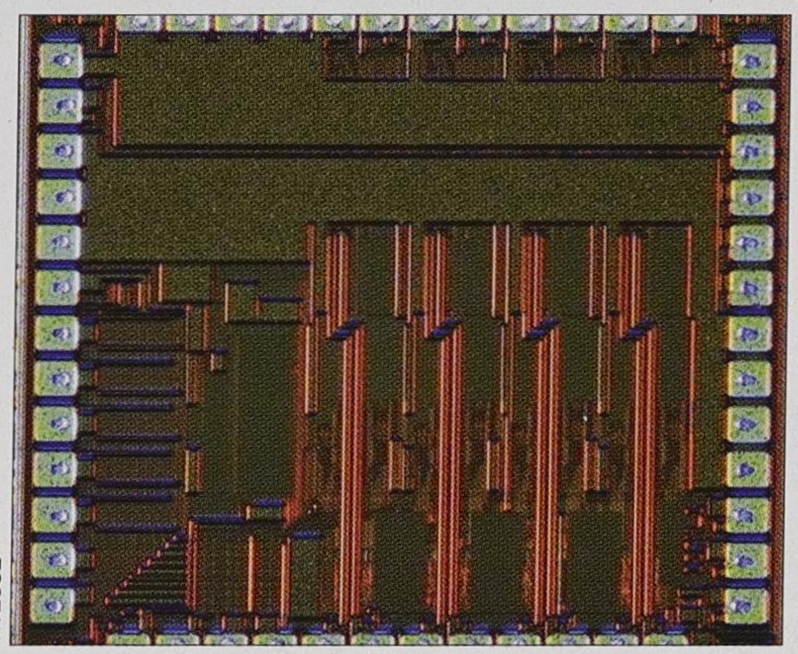
Vitesse demos 40 Gbit/s InP ICs

Vitesse has developed all of the key circuits needed to construct an OC-768 physical layer chipset, using the 0.8 μm InP HBT process developed at its 4 inch wafer fab in Camarillo, CA (see *Compound Semiconductor* July 2001, p7). The initial 40 Gbit/s products include transimpedance amplifiers (TIAs), post/limiting amplifiers, *pin* photodiodes, and 2:1 and 4:1 MUX ICs together with the corresponding DEMUX circuits. The new components are available either as evaluation kits in MMIC-style packages or as bare die. Operation has been demonstrated at greater than 56 Gbit/s, with high yield and manufacturability. More highly integrated OC-768 chipsets are said to be in progress for introduction during 2002.

Vitesse has also launched two InP-based 10 Gbit/s products, namely a *pin* detector and a monolithically integrated *pin* and TIA. The latter part is the first in a series of optoelectronic and photonic ICs that will lead to the monolithic integration of the receive side of an OC-768 transponder. "The monolithic integration of optoelectronic integrated circuits is essential to reduce system costs at both the circuit and the module level," said Alan Huelsman, director of the company's InP program. "The inclusion of a 16:1 monolithically integrated transponder allows all data rates in excess of 2.5 Gbit/s to be contained on the IC, instead of propagating on the circuit board."

MHEMTs used for Raytheon TIAs

Rather than developing an InP process, Raytheon's RF Components Division has commercialized a metamorphic HEMT process that uses 4 inch GaAs wafers (see *Compound Semiconductor* October 2001, p11). The company's first product is a high-speed TIA designed for 40 Gbit/s applications. Available as a $3.71 \times 1.70\ mm^2$ chip, the device has a bandwidth of 40 GHz and power dissipation of 450 mW. According to Raytheon, the advantage of the metamorphic HEMT process is its ability to achieve the high electron velocity normally only found in InP HEMTs, without the additional expense of InP substrates and manufacturing issues associated with InP-based devices.



VITESSE

Vitesse's 4:1 MUX IC operates up to 43 Gbit/s and is fabricated using an indium phosphide HBT process.

"The metamorphic growth of high indium content HEMT devices on GaAs substrates opens the high-frequency spectrum and the optical-to-electrical signal conversion space to traditional GaAs fabs," said Colin Whelan, a senior scientist at Raytheon. "This technology has matured to the point where it is transitioning from development to manufacturing lines to realize the cost advantages of large-diameter substrates."

Yokogawa uses InGaP HBTs

Yokogawa Electric has chosen InGaP HBTs for its 40 Gbit/s modules, which include modulator drivers and logic circuit modules for multiplexer, demultiplexer and flip-flop functions (see *Compound Semiconductor* May 2001, p11). The company is using InGaP HBT epiwafers from Kopin. ICs have demonstrated f_t and f_{max} values of 190 and 230 GHz, respectively. "The InGaP HBT delivers superior output power and jitter characteristics, allowing our circuit modules to deliver excellent performance at a competitive cost," said Akira Miura, general manager of Yokogawa's Development Project Center.

GCS unveils double HBT process

For applications requiring high breakdown voltages, foundry service provider Global Communication Semiconductors of Torrance, CA, has added an InP double HBT process to its single HBT process. The SHBT process has f_t and f_{max} values of 160 and 180 GHz, respectively, with a BV_{CEO} of 3 V. The DHBT process, which is more suitable for power amplifiers and modulator drivers, has a BV_{CEO} of over 8 V with an f_t value above 150 GHz at a current density of $1\ mA/\mu m^2$.

GCS also announced a new InGaAs mesa *pin* photodiode process on 4 inch InP wafers. "Conventional planar InP-based photodiode processes with Zn-diffused p-contacts typically deal with 2 inch wafers, and are limited in speed performance due to inherent parasitic capacitance," said Samuel Wang, VP of Optoelectronics. "Our mesa approach offers the advantages of 4 inch wafer processing as well as higher speed performance, and is the result of successful passivation of the exposed small-bandgap intrinsic layer in the device's mesa structure." The diode's responsivity exceeds 0.9 A/W at 1310 nm, while the –3 dB bandwidth, measured with a 50 Ω input impedance TIA, reaches 19 and 23 GHz for 24 and 18 μm diameter diodes, respectively.

In brief...

Fuji Xerox mass-produces low-cost VCSELs

Fuji Xerox Co is to become the first Japanese company to mass-produce VCSELs. The company plans to ship 850 nm AlGaAs/GaAs devices with oxide current confinement. Production volume will be 100 000 devices per month, rising to 500 000 per month. Fuji Xerox says that its devices will have simpler control circuits than those of its competitors, allowing the price to be ¥1000 ($8).

Qusion Technologies launches InP modulator

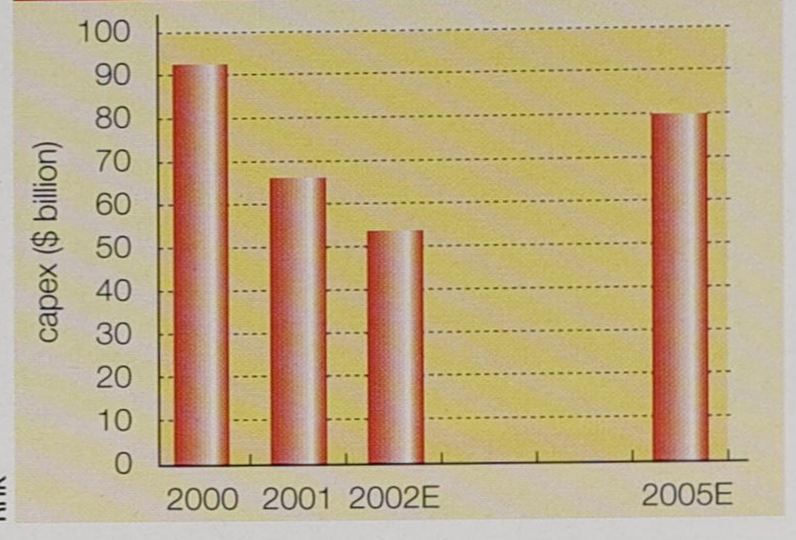
Qusion Technologies of North Brunswick, NJ, has unveiled its first InP device – a wide optical bandwidth electroabsorption modulator spanning the C-band. The device is for operation with 10 Gbit/s tunable lasers in metro optical networks. Power dissipation is under 10 mW and a 3 Vp-p modulator driver is required. The extinction ratio is over 20 dB and the propagation loss is 0.5 dB/mm.

Service provider capex set to recover in 2003

According to RHK, North American wireline service provider capital expenditures (capex) will continue to decline in 2002, but will rebound in late 2002 or early 2003, reaching approximately $80 billion by 2005. From a record $92 billion in 2000, capex declined by 28% to roughly $66 billion in 2001, and a further 20% decrease to approximately $53 billion is predicted for 2002.

RHK says that the 2001–2002 drop in capex is the after-effect of an unsustainable $50 billion capex bubble in 1999–2000. The market had simply became flooded with too many providers offering cut-price services. However, spending is expected to increase in 2003 due to service providers' improved operating cash flow, more robust balance sheets, and the efforts that are being made to meet growing IP traffic demands.

Service provider capex



Bandwidth Semiconductor stops VCSEL development program

Stratos Lightwave has announced that it has delayed the VCSEL development program at its wholly-owned subsidiary, Bandwidth Semiconductor, and expects to incur a special charge of approximately $1.2 million in Q3. Stratos manufactures a wide range of optical transceivers for fiber communications, many of which use VCSELs as the transmission source. The company has decided to use external suppliers to deliver VCSELs for transceivers in the 1–2 Gbit/s range, but it is continuing to develop next-generation 10 Gbit/s devices, as well as concentrating on its epiwafer business.

"At this time there is extensive market availability of high-quality lasers in the merchant market, and we maintain strong relationships with those suppliers," David Slack, CFO of Stratos Lightwave, told *Compound Semiconductor*. "While we have qualified several of the devices from the Bandwidth program, the economics argued strongly in favor of taking advantage of the current supply situation and putting that effort on hold."

Bandwidth Semiconductor was formed in December 1999 when Stratos Lightwave acquired Spire Corporation's Optoelectronics Division. Slack said that Bandwidth will continue its materials science, manufacturing and testing activities. "We will retain the technical capability to re-launch device development in the future if we see an opportunity and the economics make sense," he added.

Bandwidth moves to new facility

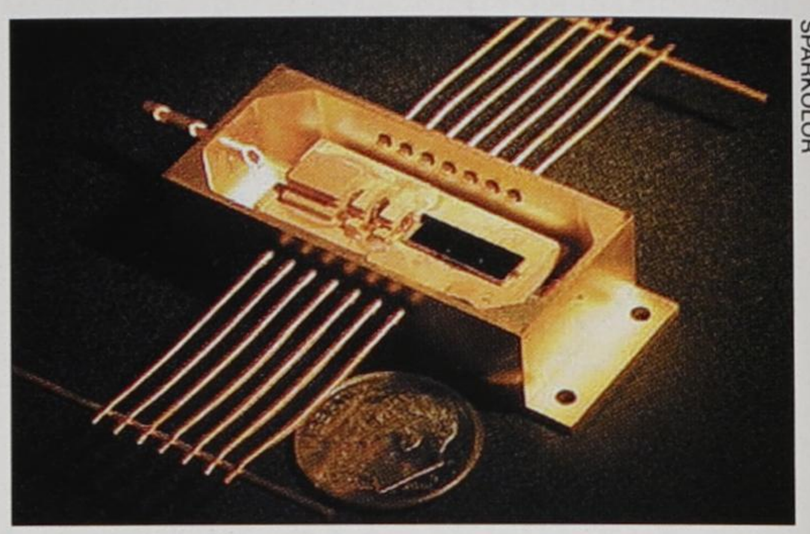
In a move unrelated to the restructuring of its business activities, Bandwidth Semiconductor has expanded its operations and moved into a new 13 500 sq. ft state-of-the-art foundry housed in a 50 000 sq. ft building in Hudson, NH. The new facility, which has an additional 40 000 sq. ft for expansion, replaces the 4000 sq. ft fab in Bedford, MA.

In the new facility, Bandwidth operates a complete compound semiconductor growth and device fabrication line in class 100/1000 clean rooms. A new multiwafer MOCVD reactor has been purchased for the growth of GaAs- and InP-based materials, providing outstanding wafer reproducibility and uniformity on up to 4 inch diameter wafers.

Bandwidth's MOCVD engineers, initially from Spire, have been developing and growing III-V optoelectronic, RF and microwave structures for more than 20 years. The company sells epiwafers, OEM devices – including lasers and detectors – and also offers foundry services, including processing, on-wafer and device test, die separation and prototype packaging.

New laser tunes at 25 GHz spacing

Sparkolor Corporation has demonstrated a tunable laser for DWDM applications with 25 GHz channel spacing. Currently, most long-haul systems operate at 50 or 100 GHz spacing, and manufacturers will probably migrate to 25 GHz channel spacing in the next few years. Sparkolor, located in Santa Clara, CA, employs a hybrid integration approach to manufacture tunable DBR lasers (see photo below). Fabry–Perot lasers, purchased externally, are mounted on a silicon optical bench containing a tunable grating section made from deposited silica. The laser is bonded to the bench using a proprietary process.


SPARKOLOR

Sparkolor's tunable laser is assembled by mounting optical components (at left inside the package) onto a silicon optical bench (visible as the dark rectangle at right).

"The ability to tune to 25 GHz shows that these lasers have the precision-tuning characteristics to obsolete most fixed-wavelength DWDM source lasers by 2005," said Steffen Koehler, Sparkolor's VP of marketing.

Bandwidth9 tests fixed λ VCSELs

Bandwidth9 is sampling fixed wavelength 1550 and 1600 nm versions of its tunable VCSELs. To date, the company has concentrated on tunable products, but says that as a result of higher production yields, its new fixed VCSELs will be able to compete on price with conventional DFB lasers. Bandwidth9 uses MBE to grow long-wavelength VCSELs on InP. The new fixed transmitters operate up to 2.5 Gbit/s and target short- and intermediate-range applications from 2 to 20 km, where single-mode transmission is required. Bandwidth9's fab in Fremont, CA has a capacity of 100 000 devices per month.



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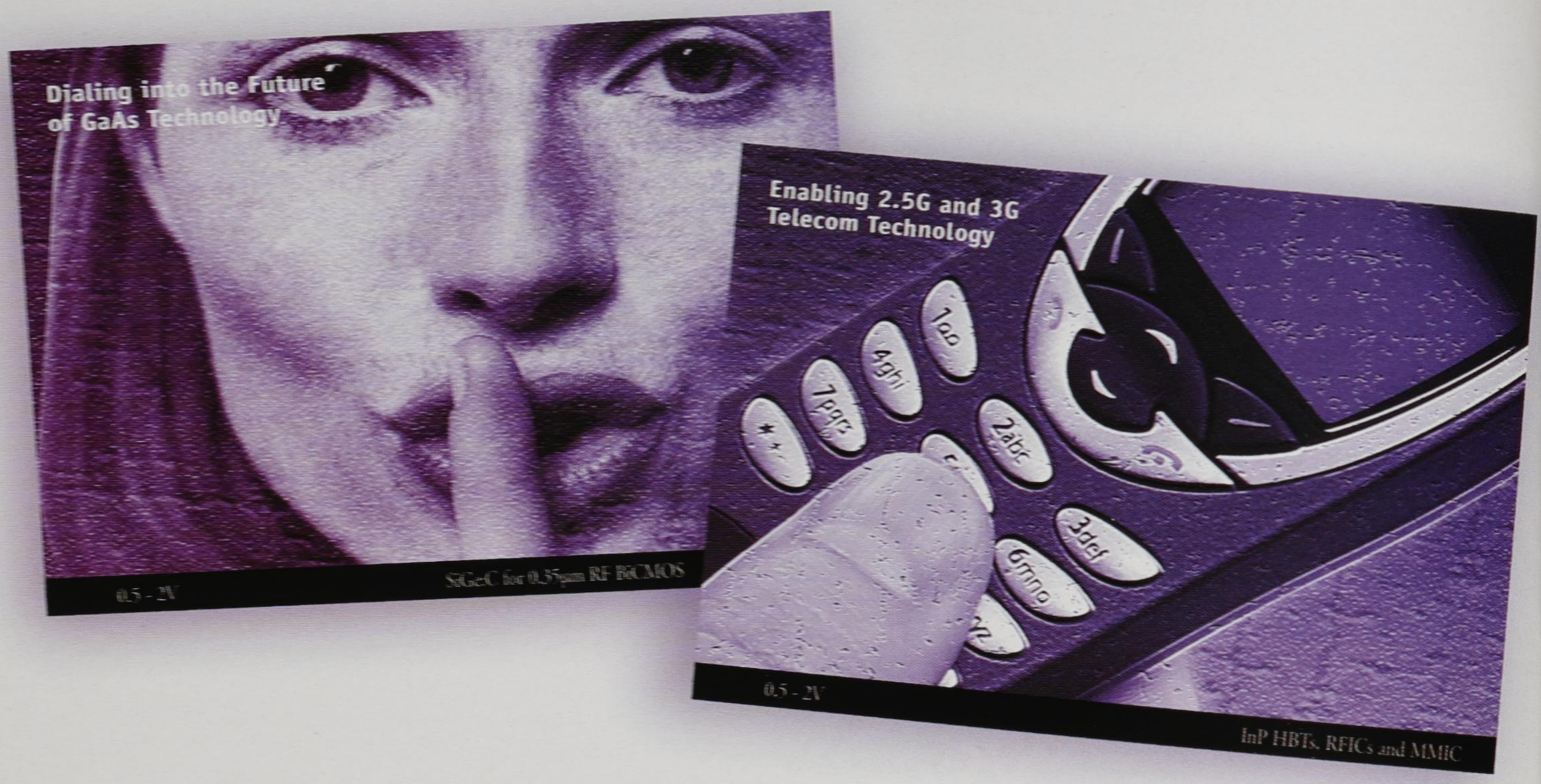
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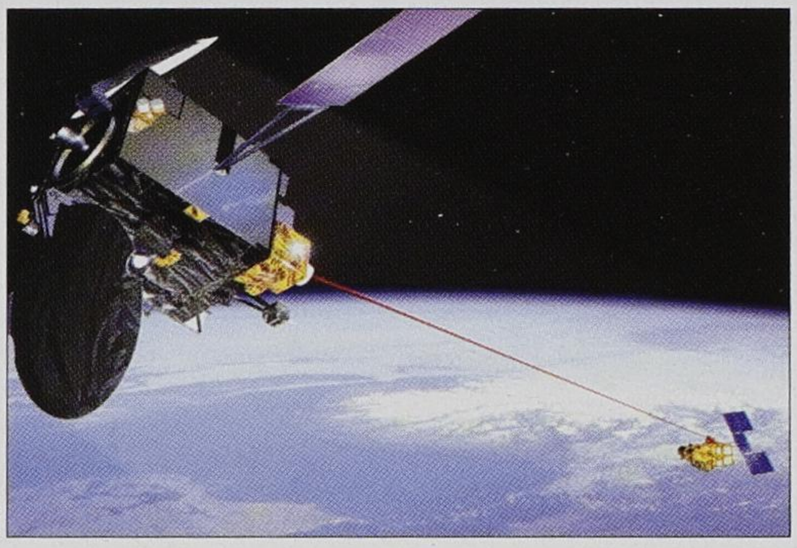
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AlGaAs laser links satellites in orbit

A semiconductor laser has been used in an experiment to make the first optical data link between two satellites in orbit. Data from the French Space Agency's Earth observation satellite, SPOT-4, were transmitted to a second satellite, Artemis, in a higher orbit approximately 30 000 km away. Using the data link, images from SPOT-4 were transmitted to a ground station via Artemis in real time, removing the delay between acquisition of the images and transmission to the ground station.

During the experiment the link was established four times in four successive orbits for up to 20 minutes. Data were transmitted at a rate of 50 Mbit/s with a bit-error rate of less than 10^{-9}. Each satellite has a laser transmit and a receive terminal containing an AlGaAs/GaAs laser diode.



ESA

An AlGaAs/GaAs laser operating in the 800–850 nm range has transmitted data at 50 Mbit/s across 30 000 km.

The diodes operate within the 800–850 nm range with a peak optical power of 120 mW. The average operating power during the link was 60 mW. The lasers were manufactured by SDL, which is now part of JDS Uniphase (see *Compound Semiconductor* October 1998, p19).

GaAs cells propel Nuna to victory

The 2001 World Solar Challenge, a 3010 km race across Australia for solar-powered cars, has been won by a team from the Technical University of Delft, The Netherlands. The winning vehicle "Nuna" was fitted with 36 solar panels made of dual and triple-junction GaAs solar cells developed by the European Space Agency. Road tests showed the cells to be 24% efficient. The vehicle had a top speed of 100 mph and completed the race at an average speed of 57 mph.

CST wins $5 million investment package from Intel and others

A Scottish optoelectronic foundry and technology-transfer company, Compound Semiconductor Technologies (CST), has secured a $5 million second-round funding package. The money has come from a consortium of venture capitalists including European Digital Partners and Intel Capital, the strategic investment arm of Intel.

The funds will be used to improve further the manufacturing capabilities that CST offers its customers. CST derives 60% of its income from its foundry services, whose customers are mainly US start-ups. It also has a role as an incubator, helping start-ups develop prototypes and get sample products out to customers. Notable successes include Kamelian and Intense Photonics – both companies started life with CST but now occupy their own premises elsewhere.

Intel Capital has made many investments in optoelectronic-based start-ups as part of its stated mission to "drive Internet growth and advance the computing platform". Other companies that have been backed by Intel include Princeton Optronics, Avalon Photonics and Nova Crystals.

Unique Mode set to expand following new funding round

Unique Mode, a spin-off from the Fraunhoffer Institute based in Jenna, Germany, has secured second-round funding to enable it to expand into new production and clean-room facilities in the first quarter of 2002. The exact sum has not been disclosed, but has come from a variety of sources including a venture-capital company and government grants and loans.

The company was set up in February 2000 to commercialize an optical system that improves the brightness of laser diodes. Diode stripe lasers effectively provide a line source. Most applications ideally need a symmetrical spot to use the laser light efficiently, for example when coupling the light into fibers. Unique Mode's micro-optical system transforms the widespread line emitter into a virtual stack of line emitters of much less width. Therefore the emitter is transformed into a square source yielding a symmetrical spot.

Unique Mode manufactures compact laser modules containing a semiconductor laser and the micro-optical assembly for pumping solid-state and fiber lasers. The semiconductor lasers are supplied to Unique Mode by a variety of companies including JDS Uniphase, Sony and LDI. Products include 975 and 915 nm pumps for erbium-doped fiber lasers and amplifiers. These are available at powers of up to 5.2 W.

Terahertz Photonics adapts to stay afloat

Scottish start-up Terahertz Photonics is looking for a buyer for its optical coatings business in a bid to stay afloat. Terahertz's problems stem from its second funding round which is due in January, though at a reduced level from the $14.5 million originally hoped for. In early December the company cut its staff from 36 to 23 and halted its optical coatings unit and semiconductor devices division which includes semiconductor optical amplifiers and tunable filters. Terahertz will now focus on planar lightwave circuits as this part of the business shows the most promise.

Mitsubishi boosts CD and DVD drives

Mitsubishi Electric has developed a range of lasers that allow high-speed recording in CD and DVD drives. The lasers have a unique structure that makes it easy to narrow the beam spot and are also designed to prevent deformation caused by heating. Mitsubishi has introduced a 90 mW laser operating at 650 nm, which is suitable for 4× DVD-R drives, and 180 and 200 mW lasers with a wavelength of 780 nm for 32–40× CD-R drives. Conventional 2× DVD-R lasers have an output of 70 mW, while 24× CD-R drives generally use 160 mW lasers.

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Kodak and Sanyo form OLED company

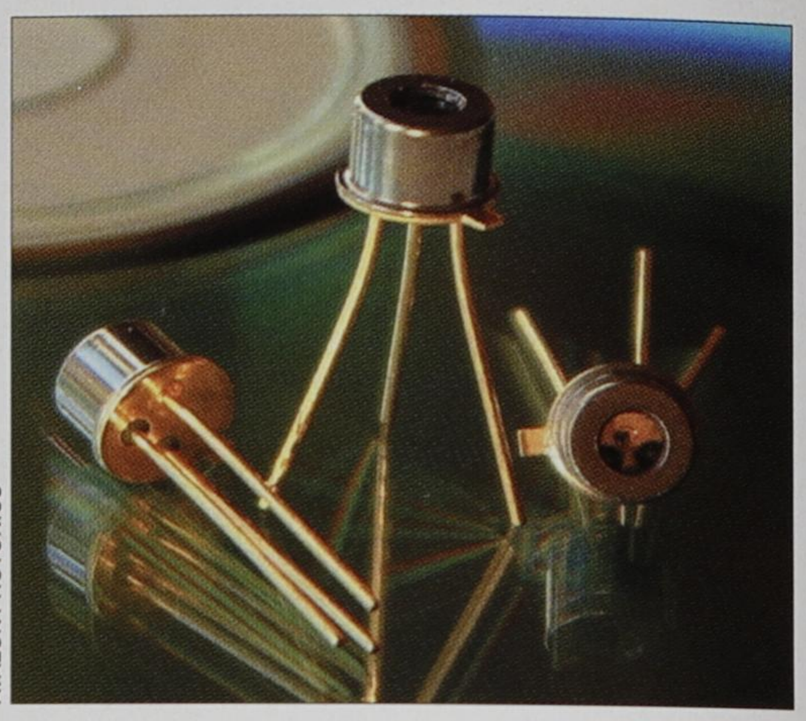
Japan's third-largest consumer electronics manufacturer Sanyo Electric and photo-film giant Eastman Kodak have formed a joint venture business called SK Display to manufacture OLED displays. Beginning with a pilot facility in early 2002 and graduating to a full production facility in 2003, SK Display will have one of the first manufacturing facilities dedicated to full-color, active-matrix OLED displays.

As part of the agreement, Kodak holds a 34% stake in SK Display and will provide its OLED manufacturing technology and a strong patent portfolio, in addition to committing $125 million to the venture. Sanyo holds the remaining share and will invest $225 million, and provide its expertise in the manufacture of low-temperature polysilicon thin-film transistors. The technologies from both companies will be brought together at the new plant in Japan. Each company will take responsibility for selling and marketing the displays.

Singlemode VCSELs from Avalon

Avalon Photonics has launched a family of singlemode VCSELs with wavelengths in the 759–766, 790–794 and 850–855 nm ranges. The VCSELs are designed for absorption spectroscopy, and the emitters combine fundamental longitudinal-mode operation and a wide mode hop-free tuning range. Based in Zürich, Switzerland, Avalon is a spin-off from CSEM (the Swiss Center for Electronics and Microtechnology) that is targeting the short-reach high-bandwidth datacom market (see *Compound Semiconductor* Dec 2000/Jan 2001, p34).

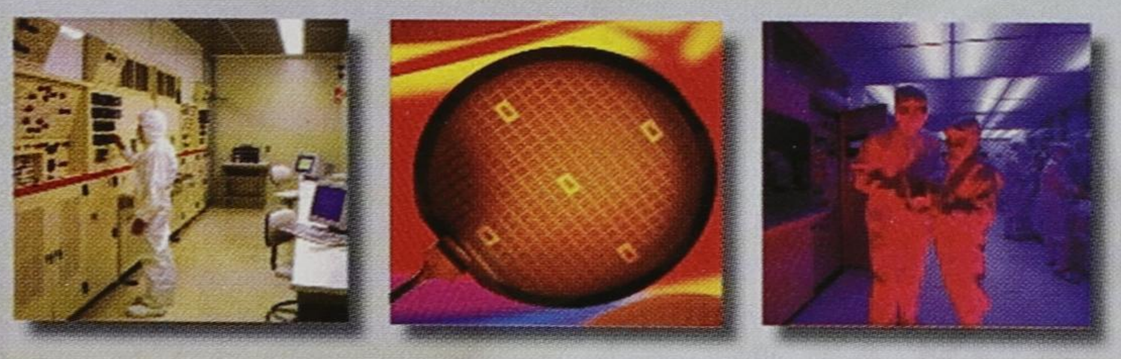
Avalon says that its VCSELs contain an active region which is just one wavelength thick, which ensures that only one axial mode is supported in the cavity. This allows for operation in the fundamental longitudinal mode, which is desirable for spectroscopy applications. Depending on the required wavelength regime, the active layer in the devices contains one or more quantum wells of GaAs, AlGaAs or InGaAs. Avalon's devices are packaged in TO-46 or TO-510 cans with peltier and thermistor elements for temperature control.



AVALON PHOTONICS

Avalon's new singlemode VCSELs are designed for absorption spectroscopy. The company also targets the short-reach datacom markets with 1 x 4 and 1 x 12 VCSEL arrays operating at 850 nm.

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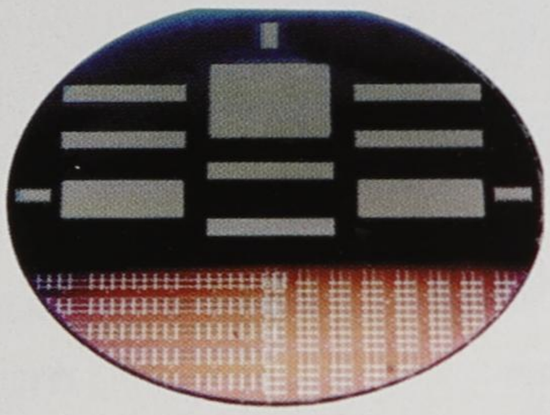
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Three companies open new facilities

Three equipment manufacturers – Thermo VG Semicon, Philips Analytical and Bede – have opened new facilities. MBE system maker Thermo VG Semicon has relocated to a new production facility close to its original factory in East Grinstead, UK. The company says that the building incorporates improvements in all sectors of instrument build and test procedures, leading to a three-fold increase in production capacity. The facilities include a large clean room for UHV component testing, a single large assembly and a test hall for instrument assembly. Thermo VG Semicon is viewed as a flagship business unit by its parent company Thermo Electron Corp, which has invested heavily to upgrade the production capability of its subsidiary.

Philips Analytical has recently opened a new 25 000 sq. ft facility in Waterloo, Canada, dedicated to compound semiconductor applications. The new site includes production, demonstration and office facilities, and it follows the opening of a similar 10 000 sq. ft facility in Arizona. "The move will help us to meet our growing orders from compound semiconductor and SiGe customers worldwide," said Huub Smit, general manager. "The new building is a stone's throw away from the old facility, which helped us to make the move smoothly and without loss in production." The Waterloo facility designs and manufactures characterization instruments that use the complementary techniques of photoluminescence and X-ray diffraction.

Bede, which also manufactures X-ray diffraction equipment, has moved into new custom-built premises. The 27 000 sq. ft facility is located on Belmont Business Park on the outskirts of Durham in the UK. The new building incorporates expanded clean production facilities (including class 100 clean room assembly areas), demonstration and application laboratories, plus meeting and office space. Neil Loxley, Bede's chief executive, said, "I am delighted that we have been able to move to better facilities, and remove previous capacity constraints on our business. The new building will allow us to cope with the increased demand for our products, and an expanded workforce as a result of heavy recruitment throughout 2001."

Equipment sales

● **Arima Optoelectronics** has placed orders for **Aixtron** AIX 2000HT and 2400G3HT reactors to expand its production of nitride-based blue and green high-brightness LEDs.

Arima Optoelectronics was established in 1998 as a subsidiary of the Arima Group with facilities in Dashi, Taiwan and an R&D center in the UK. "We are successfully producing GaN-based LED structures that use our patented structure, and have more than 20 patents for several LED epitaxial structures," said Andy Huang, director of Arima Optoelectronics.

● **RF Micro Devices** (RFMD) has purchased a Rapid PL Mapping system and DIVA Dynamic I(V) Analyzer from **Accent Optical Technologies**.

The tools will be used for epiwafer characterization, device modeling and process optimization at RFMD's facility in Greensboro, NC.

In more news, **Accent** has signed a distribution contract with **Seki Technotron** of Japan to sell its DIVA analyzer. A major distributor of communications test equipment, Seki Technotron will promote Accent's pulsed current voltage measurement instrument, which distinguishes dynamic high-speed or RF characteristics from static DC properties in microelectronic circuits, lasers and photodetectors.

Chinese company uses Thomas Swan systems for GaN growth

Jiangxi Fangda Focus Information Materials Co Ltd (JFFIM) has ordered five production reactors from Thomas Swan Scientific Equipment. The purchase is for two 6 × 2 inch and three 19 × 2 inch systems for the manufacture of GaN-based optoelectronic devices, including blue and violet LEDs. Due for delivery in the spring and fall of 2002, the new reactors add to the existing Thomas Swan system at JFFIM's facility at the High-Tech Industry Development Zone in Nanchang, China. According to JFFIM's general manager Yu Guoan, the company has made Thomas Swan its exclusive supplier for GaN MOCVD reactors. JFFIM is a joint venture between several industrial and academic organizations, including the China Fanged Group, the Shines-based Industrial Group, the Enterprise Group of Nanchang University, the Optronics Company of Nanchang University, the Jiangnan Materials Company, and the Hong Kong Junjia Group. The company was granted "Research Center" status for LEDs by the Chinese Education Department in May 2001.

IntelliEPI unveils InP HBT epiwafers

IntelliEPI has introduced InP HBT epiwafers designed to address 40 Gbit/s applications and 3G wireless handsets. The company says the new epiwafer process allows carbon doping levels up to 1×10^{20} cm^{-3}. Single HBT devices have so far demonstrated f_t and f_{max} values of 200 GHz with a uniformity of less than 0.5% in resistivity variation both across the epiwafer and wafer-to-wafer.

IntelliEPI is also supplying beryllium-doped epiwafers in production volumes. According to sales and marketing director Jim Fang, customers have consistently reported devices exhibiting f_t and f_{max} values of 150 and 160 GHz, in devices based on the company's InP single HBT epiwafer structures.

"We have been working on 4 inch InP HBT epiwafers since the first half of 2000 using multi-wafer production MBE systems," said IntelliEPI's president and CEO Yung-Chung Kao. "We began supplying carbon-doped InP HBT wafers to our strategic customers in March of this year [2001], and are working closely with several domestic and foreign customers on their OC-768 and other wireless communication applications."

Correction – UMS

In our November issue we published an incorrect Web address for United Monolithic Semiconductors (UMS). The correct address is www.ums-gaas.com.

wt

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Aixtron opens Japanese unit

Aixtron has opened a customer support base in Tokyo called Aixtron KK. Together with its partner Moritani, the new subsidiary will be offering customer service, spare parts and process support for the Aixtron product group, which includes Thomas Swan and Epigress MOCVD systems. Future sales of the company's reactors will continue to be handled by Moritani, with the technical support supplied by Aixtron KK.

Furukawa begins GaAs recycling

Furukawa, the world's leading supplier of high-purity metal arsenic, is set to begin recovering arsenic from GaAs wafer scraps. The company plans to recycle about one ton of metallic arsenic each month at its factory in Iwashi, Fukushima Prefecture, commencing in April 2002.

Patent awarded for package design

StratEdge has received a patent for its high-frequency pass band microelectronics package. The patent covers a family of ceramic packages that have been designed for DC to 23 GHz devices and which protect GaAs MMICs from thermal and mechanical shock and from electromagnetic interference.

PEOPLE NEWS

Pioneers win Kyoto Prize

The 2001 Kyoto Prize for Advanced Technology was awarded to three scientists who have made "pioneering contributions to the development of optoelectronics…with the achievement of continuous-wave operation of semiconductor lasers at room temperature". The recipients of the Kyoto Prize were Zhores Alferov of Russia, Izuo Hayashi of Japan and Morton Panish of the USA.

Zhores Alferov is the director of the Ioffe Institute of Physics and Technology and was a recipient of the 2000 Nobel Prize for Physics. Morton Panish was at Bell Laboratories from 1964 to 1992, and worked for several years with Izuo Hayashi, who joined NEC in 1971 where he became director of the Optoelectronics Technology Research Laboratory in Tsukuba. The Kyoto Prizes are presented annually by the Inamori Foundation in the categories of Advanced Technology, Basic Sciences, and Arts and Philosophy. Laureates receive Kyoto Prize medals and ¥50 million ($375 000) in prize money.

Lasing in semiconductor diodes was achieved in 1962, using liquid nitrogen for cooling. However, the current density necessary for lasing was too high to be generated by conventional semiconductor devices, and laser diodes were abandoned as impractical outside of a laboratory. It was not until 1970 that Alferov, Hayashi and Panish overcame this problem, reporting continuous operation of semiconductor lasers at room temperature.

The semiconductor lasers they developed featured a double heterostructure with a GaAs active layer sandwiched between two AlGaAs layers. The threshold current density was substantially reduced by the dual effects of confining the electrons and holes in the active region and using this region, with its higher index of refraction, as a waveguide.

Working at Bell Labs, Hayashi theoretically proved the applicability of the double heterostructure to semiconductor lasers, and Panish developed a method of growing the epitaxial layers – the slide-board method – which enabled the creation of the double heterostructure. Several months earlier, Alferov had also achieved continuous-wave operation at room temperature, employing a method similar to the one used at Bell Labs.

The breakthrough of achieving CW operation at room temperature paved the way for many commercial applications of laser diodes, including fiber-optic communications, CD and DVD players, and laser printers. The high luminous efficiency of laser diodes coupled with compactness and low cost opened up a far broader range of applications than could be addressed by solid-state or gas lasers.

Rank Prize honors VCSEL pioneers

The 2002 Rank Prize for Optoelectronics has been awarded to Robert Burnham, Kenichi Iga and Donald Scifres for the invention of VCSELs. In 1979, at the Tokyo Institute of Technology, Iga demonstrated a laser which emitted coherent light through the surface of the wafer (see *Japanese J. Appl. Phys.* 1979 **18** 2329). A vertical cavity was formed by depositing metallic mirrors on the top and bottom surfaces of the wafer.

Independently, and also in 1979, Burnham, Scifres and the late William Streifer filed US patent no. 4 309 670 describing structures containing Fabry–Perot optical cavities transverse to the plane of the wafer. One embodiment described the use of alternating semiconductor layers to form distributed Bragg reflector structures which act as high-reflectivity mirrors.

Appointments

BOC Coating Technology has appointed **Jim Golden** as president of Temescal, the supplier of thin-film deposition systems.

Aeronex has selected **Xiaosong Jiang** to head its new marketing department to focus on market opportunities in semiconductor processes which are sensitive to molecular contaminants.

Novalux has appointed **Ian Jenks** as its president and CEO, replacing Malcolm Thompson, who will continue to serve on the company's technical advisory board. Jenks was formerly president of Uniphase Lasers and Fiber Optics.

TriQuint has announced the resignation of **Kimon Anemogiannis** as president of its Sawtek subsidiary, and has named three officers to the interim office of president.

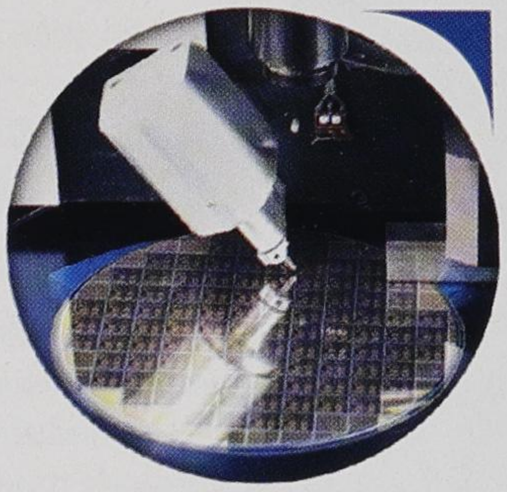
Fiber-optic market research firm **RHK** has named **Marc Litvinoff**, formerly of Gartner, as its next CEO.

Fitel Technologies has appointed **Jun Goto** as director of sales for active and passive optoelectronic components.

Nicholas Nee has been appointed Asia Pacific sales manager for **MRSI**.

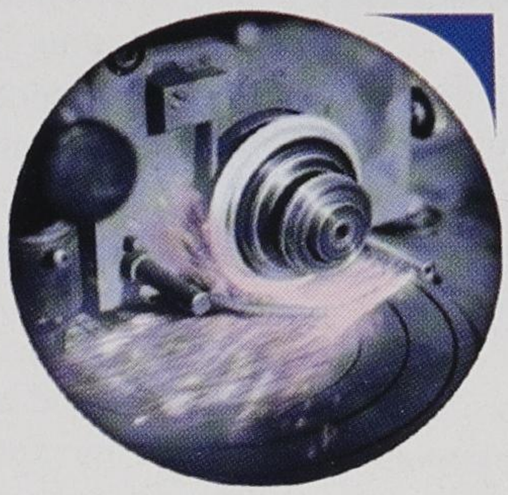
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OPTO PRODUCTS



New solid-state relays from NEC

Santa Clara, CA NEC's new solid-state relays suit AC/DC switching in air conditioning, heating and other industrial controls. Available now from US subsidiary CEL, the PS710B-1A range is housed in 6 pin DIP packages and includes a low on resistance (R_{ON}) of 50 μΩ, and a large continuous load current of 2.5 A, in addition to a drive current of 2 mA. Other parameters include a turn on/off time of 3 ms and 1500 V_{rms} isolation voltage.

The company's relays employ GaAs LEDs on the input side and two MOSFETs on the output side. The PS710B-1A is available now in bulk or on tape and reel.
www.cel.com

LumiLeds offers new LED options

San Jose, CA LumiLeds Lighting has expanded its Luxeon LED family of linear, ring, star and flood-mounted configurations to include individual Luxeon emitters.

The new devices are available in high volume as production-suitable reels, as well as 50 unit evaluation kits. Device types include GaN-based white, green, blue, royal blue and cyan LEDs, as well as AlInGaP-based red, red-orange and amber devices. Each kit includes 50 unmounted emitters and a design guide to assist developers in circuit design and heat management.
www.lumileds.com

FIBER PRODUCTS

Fitel debuts coaxial uncooled lasers

Clinton, NJ Fitel Technologies has introduced a series of uncooled coaxial DFB and Fabry–Perot laser diode modules for intermediate and long-haul networks. The design enables extremely low power consumption and small mounting size due to the absence of a thermoelectric cooler.

The suite of four DFB modules and one Fabry–Perot module, which vary in power from 0.05 to 1.6 mW, are available in three package designs: an MF pigtail module, and RC and LC modules. All are compliant with Telcordia reliability tests.

The M1 and M2 series are available in 1310, 1510 and 1550 nm wavelengths, and are designed for intermediate and long-haul use. The MX series is designed for CWDM systems, and is available from 1470 to 1610 nm. All DFB modules operate at speeds up to 2.5 Gbit/s. The 1310 nm Fabry–Perot laser diode module is intended for intermediate use and supports SONET/SDH and fiber-in-the-loop links for speeds up to 622 Mbit/s.
www.fitel.com

Laser includes integral driver

Durham, NC The SLM1113, supplied by ExceLight Communications, is a 10 Gbit/s directly modulated uncooled laser diode module for the short-haul telecom market. The company says the key differentiator is the high-speed laser driver within the miniature package.

Complementing ExceLight's laser product portfolio, the new laser employs Sumitomo Electric's Fabry–Perot InP laser chip and laser driver devices integrated into a 19 pin butterfly package.

Sample quantities of the 1310 nm integrated laser module are available now, with production quantities available in the first quarter of 2002.
www.excelight.com

WIRELESS PRODUCTS

UMS launches new multiplier MMIC

Orsay, France United Monolithic Semiconductors has unveiled a new GaAs MMIC

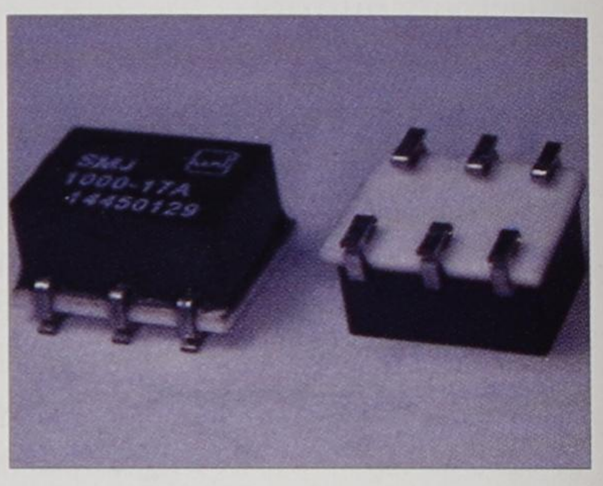


designed for microwave and millimeter-wave applications. The CHX2089 is a two-stage monolithic frequency multiplier and buffer amplifier designed with an input frequency rejection of 20 dBc and low power consumption from a 3.5 V and 65 mA bias supply.

Offering an input frequency range of 8–11.5 GHz and output range of 16–23 GHz, the device is available in die form and is based on the company's PH25 process. The output power level is 15 dBm at 12 dBm input.
www.ums-gaas.com

WJ introduces two 3G wireless mixers

San Jose, CA WJ Communications has released two low-cost passive GaAs MESFET mixer MMICs for 3G UMTS wireless

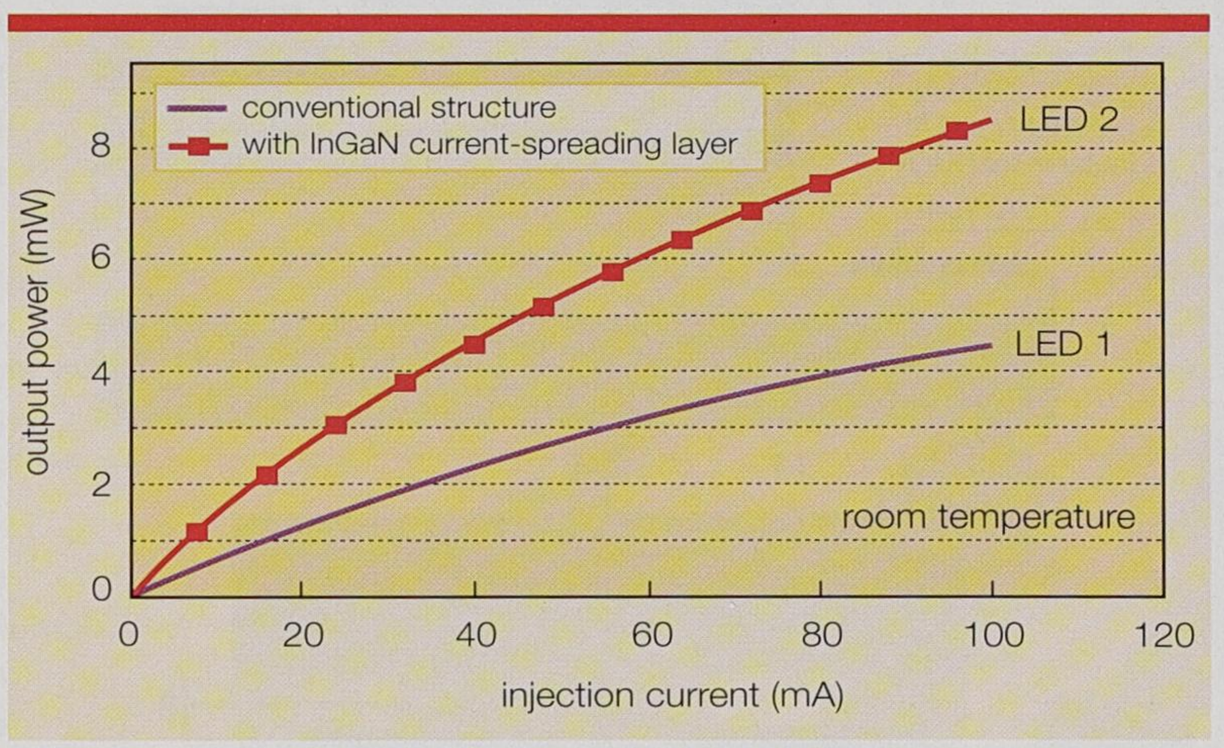


infrastructure equipment. The MH101 and MH102 provide high dynamic range with an IP3 value of +30 dBm and input P1 dB of 16 dBm across the UMTS band (1.9–2.2 GHz).

The company has also introduced a single supply GaAs FET amplifier for base stations and wireless infrastructures. The AH201 offers 1 W and is designed to operate from 250 MHz to 3.0 GHz (i.e. covering cellular, PCS, NMT and UMTS bands). Housed in a 6 × 6 mm^2 surface-mount package, the device features an enhanced thermal design that allows the unit to achieve +49 dBm IP3 performance at a mounting temperature of +85 °C. The AH201 also offers 13 dB of gain and +30 dBm output P1 dB.
www.wj.com

Taiwanese group uses novel layers to boost GaN-based LED performance

A collaborative effort between researchers from Epistar, National Central University and National Cheng-Kung University, Taiwan, has resulted in two papers which report improvements to the efficiency of GaN-based LEDs. The first paper describes the use of an InGaN/GaN short period superlattice (SPS) as a tunneling contact layer (*Electron Dev. Lett.* 2001 **22(10)** 460). The ability to lower the operating voltage and improve the spread of injected current across the active area of GaN-based LEDs is limited by the high resistivity of the Mg-doped GaN contact layer. Using a semi-transparent electrode deposited across the entire contact area can enhance current spreading. However, the operating voltage is still limited by the high contact resistance between the p-type GaN and the metal contact. Solutions to this problem have included using a buried tunnel-junction (see *Compound Semiconductor* September 2001, p41), and an AlGaN/GaN superlattice as the contact layer.



NATIONAL CENTRAL UNIVERSITY

The output power of InGaN/GaN LEDs as a function of the injection current for devices with and without the current-spreading layer.

The Taiwanese team used a Si-doped n^+-$In_{0.23}Ga_{0.77}N$/GaN SPS as a contact layer between the metal electrode and the p-type GaN contact layer. This formed a low-voltage drop contact, reducing the operating voltage compared with conventional devices. The operating characteristics of the SPS contact-layer LED and a conventional InGaN/GaN LED were compared. Both gave a turn-on voltage of 2.5 V at 10 μA. At 20 mA, forward voltage was 3.8 V for the conventional structure and 2.95 V for the SPS contact-layer device. The SPS device also gave lower series resistance due to improved current spreading by the top SPS contact. As high series resistance leads to heating and the accelerated degradation of electrodes, devices incorporating the SPS contact layer should have improved lifetimes.

In the second paper (*Phot. Tech. Lett.* 2001 **13(11)** 1164) the group report results for a GaN-based LED using a Si-doped InGaN current-spreading layer to improve electron-hole recombination efficiency. Due to the large lattice mismatch between the InGaN and GaN layers commonly used in MQW active regions, the piezoelectric field-induced quantum-confined Stark effect (QCSE) results in the spatial separation of electrons and holes, reducing LED efficiency. The group compared two GaN-based LEDs: LED 1 had a conventional structure with a three-period InGaN/GaN QW active region, and LED 2 contained a 15 nm thick Si-doped $In_{0.18}Ga_{0.82}N$ current-spreading layer between the GaN buffer and the MQW active region. A thin (3 nm) Si-doped GaN layer acted as a tunneling barrier between the active region and the current-spreading layer. Electrons are able to tunnel through into the active region, but holes are blocked from penetrating out of the active region into the current-spreading layer. The external quantum efficiency at 20 mA injection current and 470 nm emission was 2.37% (1.25 mW) and 4.93% (2.6 mW) for LED 1 and LED 2, respectively (see figure). The emission was observed to be more spatially uniform as the layer reduced current crowding below the metal contacts. The reduction in current crowding also led to a decrease in operating voltage.

Record powers from AlGaAs DBR red VCSELs

Andrea Knigge and colleagues from the Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH) in Berlin, Germany, have made major improvements to the performance of red VCSELs with wavelengths between 645 and 657 nm (*Elec. Lett.* 2001 **37(20)** 1222). VCSELs operating in this range could find applications in data communication, high-resolution printing and optical data storage. Previously reported VCSELs at this wavelength had powers up to 2 mW, but did not contain all-semiconductor DBRs and failed during CW operation over 25 °C. The best reported power for a 650 nm VCSEL with all-semiconductor DBRs is 0.4 mW.

The MOVPE-grown layer structure featured three InGaP QWs embedded in $(Al_{0.67}Ga_{0.33})_{0.52}In_{0.48}P$ barrier and $(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$ cavity layers, surrounded by all-semiconductor AlGaAs DBRs. Devices with large current apertures defined by selective oxidation showed pulsed threshold current densities of less than 3.0 kA/cm^2 for wavelengths between 641 and 658 nm. At 650 nm the minimum threshold current density was 1.7 kA/cm^2.

At room temperature the FBH group's devices with 13 μm wide oxide apertures showed a maximum output power of 2.1 mW at 647 nm, 3.1 mW at 650 nm and more than 4 mW at 654 nm. These are record values for VCSELs with all-semiconductor DBRs. With operating voltages below 3 V the peak wall-plug efficiency reached values up to 16%.

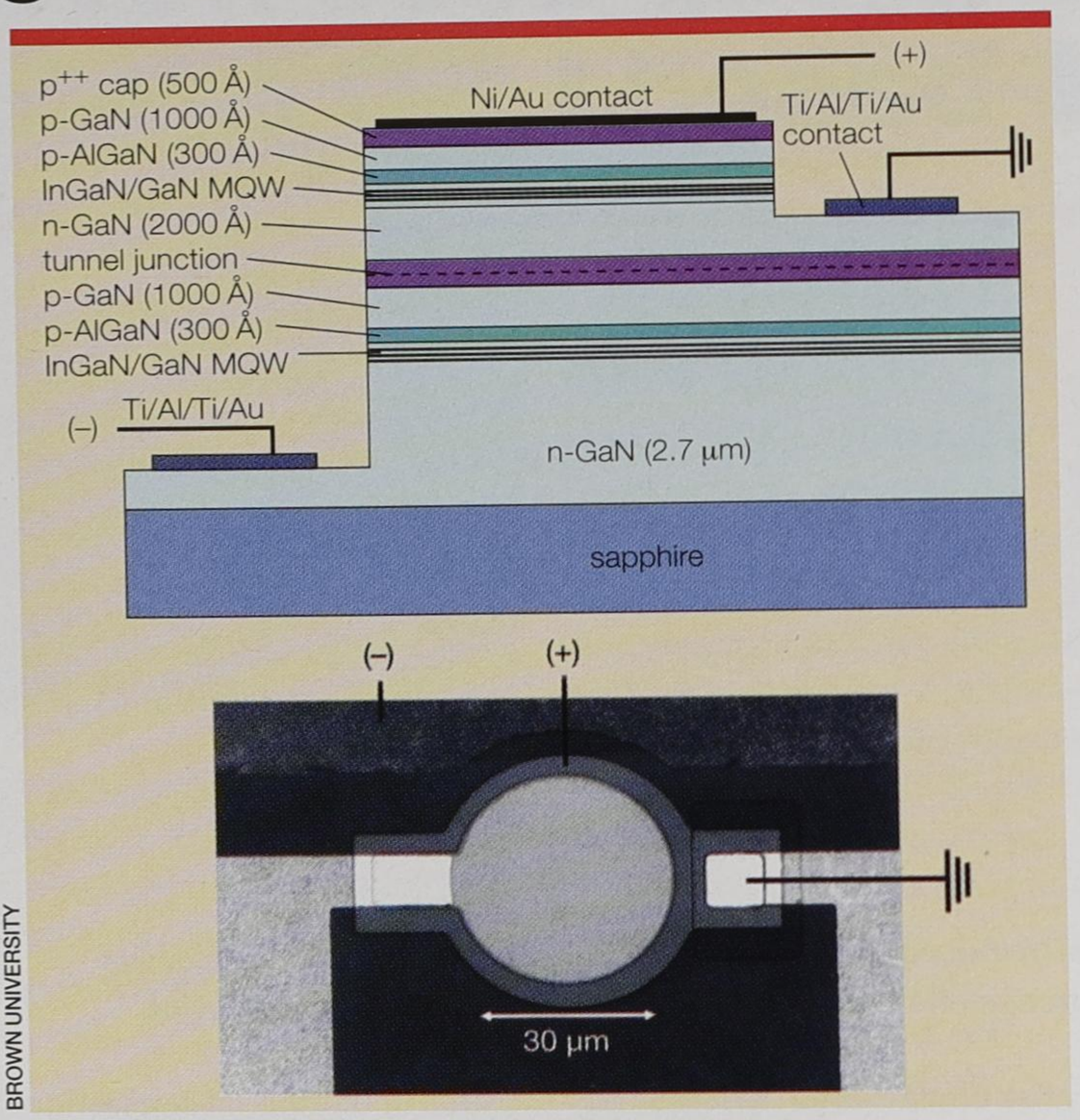
The FBH group also reported improved performance as a function of operating temperature. Due to the low band offsets in the AlGaInP material system, red VCSELs tend to have poor temperature stability. However, at 650 nm FBH's devices with a 13 μm wide aperture gave 0.4 mW output power at 35 °C. Devices with smaller apertures at 657 nm showed laser emission up to 60 °C.

The group expects there to be further increases in output power at elevated temperatures as the aperture size is optimized and heat removal is improved.

Dual-wavelength LEDs aid fluorescence labeling

Monolithically grown structures containing two LEDs that can be switched at high frequencies are potentially useful for display applications. Ozden *et al.* from Brown University, Agilent and LumiLeds have successfully designed a prototype dual-wavelength blue-green InGaN-based LED, separated by a p^{++}/n^{++} tunnel junction, for biological systems that use fluorescence labeling (*Appl. Phys. Lett.* 2001 **79(16)** 2532).

The tunnel junction acts as a means for electrically sectioning the nitride heterostructure into two independent LEDs, in addition to providing lateral current spreading for the bottom LED device. While tunnel junctions have been demonstrated in infrared LEDs, their use in nitride structures has been limited by the difficulties associated with growing a thin, heavily doped p^{++} layer of GaN.



BROWN UNIVERSITY

Schematic (top) of the three-terminal blue-green (470/535 nm) LED structure, and plan view image (bottom) of the processed device.

The three-terminal device operated at 470 and 535 nm, and employed an active region made up of four InGaN/GaN QWs for both emitters, in addition to $Al_{0.07}Ga_{0.93}N$ electron blocking layers (see figure). Emission was through the bottom of the sapphire substrate, and the device was processed using standard etching techniques into a circular emitter with a 30 μm diameter aperture. The tunnel junction increased series resistance and added 1 V to the forward voltage compared with the typical single-wavelength LEDs operating at these wavelengths.

The authors believe that further optimization could lead to the development of dual-wavelength LEDs with applications in fluorescent dye detection at high speeds (i.e. up to 100 MHz switching). This could then lead to the replacement of the more expensive combination of spectrometer and CCD detector.

Vertical-cavity LED with DBR and tunnel junction

A paper from Brown University, Agilent, LumiLeds and Sandia National Laboratories has reported a vertical-cavity violet LED with a monolithic AlGaN/GaN bottom DBR mirror structure (*Appl. Phys. Lett.* 2001 **79(22)** 3720). The device employs the same tunnel junction as described above and improves lateral hole-current spreading. The emitter also features a high-reflectivity top-dielectric SiO_2/HfO_2 reflector, which is grown *ex situ*.

The LED was grown by MOCVD on sapphire and featured a 60-pair, quarter-wavelength $GaN/Al_{0.25}Ga_{0.75}N$ stack. The stack was engineered to reduce stress, allowing 5 μm thick crack-free mirrors over several square centimeters. The active region consisted of seven 4 nm thick $In_{0.08}Ga_{0.92}N$ layers, 6 nm GaN barriers and AlGaN current-blocking/carrier-confinement regions. Doped GaN was used for cladding. Following the p^{++}/n^{++} InGaN/GaN bilayer tunnel region, the cavity was capped with a multilayer quarter-wavelength dielectric stack (99.5% reflectivity) which was deposited *ex situ* by reactive ion-beam sputtering.

The device was processed, using standard techniques, into a circular LED with a 20 μm aperture, and emitted with a dominant mode of 413 nm and FWHM of 0.6 nm. At high injection current densities (~1 kA/cm^2), the additional series resistance added by the tunnel junction became evident. At the lower levels more typical of LED operation (~0.1 kA/cm^2), around 1 V was added to the typical forward voltage of the violet LED, compared to simpler structures without the tunnel junction. The tunnel junction was, however, successful in spreading the light emission from the device uniformly. The LED demonstrated improved performance compared to a violet LED without the cavity. Fabrication-related challenges remain to be solved, including those related to the appearance of additional "ghost modes" caused by secondary vertical cavities in the structure.

Short-wavelength AlGaN LEDs struggle for power

Short-wavelength emitters are required for the efficient pumping and down-conversion of YAG phosphors used in white-light LEDs. A research group from Texas University has recently demonstrated a 321 nm AlGaN/AlGaN LED grown by MOCVD (*Elec. Lett.* 2001 **37(19)** 1188). Wong *et al.* describe the operation of diodes designed to be mounted p-side down in order to emit through the transparent sapphire substrate, which provides a better heatsink for high-power operation. While GaN-based UV devices have been previously reported at 333 nm, no output powers were quoted. The peak emission wavelength of the current device is 321 nm, which the authors believe places it among the shortest wavelength LEDs yet reported.

The double-heterojunction emitter was grown on a 2 inch sapphire substrate and consisted of a 700 nm window layer and a thin 45 nm grading layer, both of which were grown with AlGaN:Si. The active region was composed of a single $Al_{0.23}Ga_{0.77}N$ layer with p- and n-type $Al_{0.45}Ga_{0.55}N$ cladding regions. The active area was fully strained relative to the thicker $Al_{0.49}Ga_{0.51}N$ p and n cladding regions. The device was processed using standard techniques and produced 39 nW output power at a current of 35 mA without coatings. High series resistance led to heating effects that limited light output above 35 mA.

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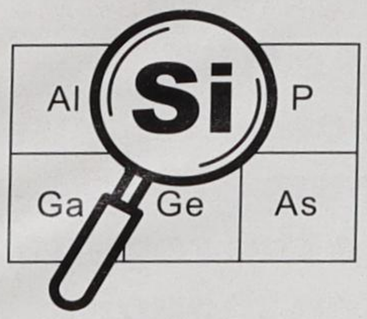
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WITH BOB METZGER

CMOS devices steal show

While SiGe bipolar work often grabs the headlines at IEDM, the most significant and exciting results reported at this year's annual device showcase were those relating to CMOS devices.



Many of these advanced CMOS processes have the capability to eliminate the need for SiGe bipolar technology.

The annual International Electron Devices Meeting (IEDM) is the premier conference for presenting the best silicon device results. In recent years it has been the venue for reporting on the latest improvements in SiGe bipolar transistors, and this year was no exception. However, while SiGe bipolar work usually receives the headlines, based on the perception that it is competing head-to-head with III-V devices, this year's highlights and greatest leaps forward were clearly CMOS devices.

Bipolar breakthroughs

The main thrust of the bipolar work presented at the IEDM was the ever-improving RF performance. This emphasis is driven by the commercially important 1–5 GHz market and competition with III-V devices. This year's achievements demonstrated that SiGe bipolar work has broken through the 100 GHz barrier (for both f_t and f_{max}) and is closing in on the 200 GHz regime.

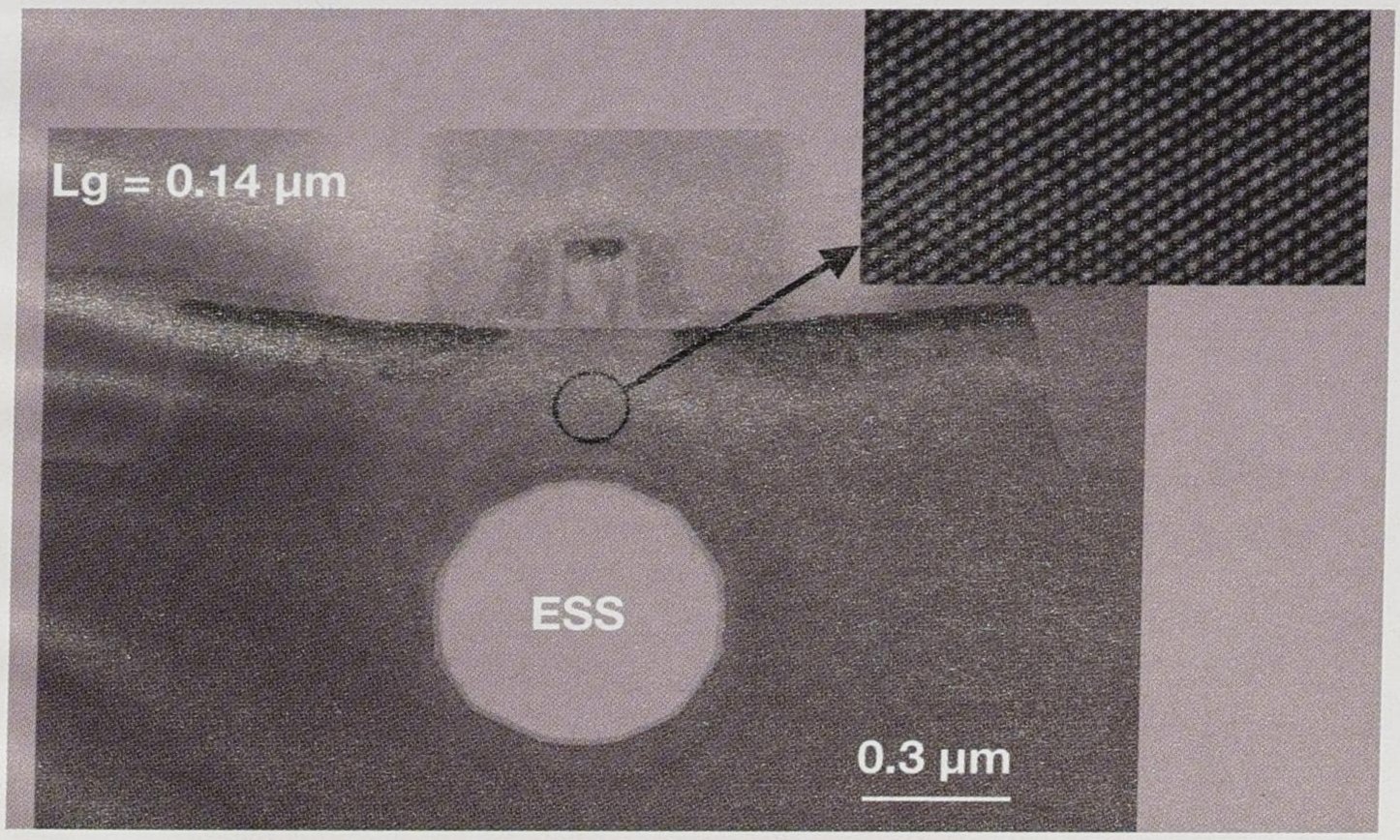
SiGe bipolar transistors possess sufficient performance to make them well-suited for applications in the emerging 40 Gbit/s optical networking arena. However, like all Si-based bipolar devices, they suffer from relatively low breakdown voltages compared with III-V HBTs. In a novel approach to address this issue, researchers at Philips included an additional layer of SiGe (10 nm with 20% Ge content) in the highly doped part of the emitter, thereby inducing greater Auger recombination which in turn enhances base current without affecting I_c and f_t. This increase in base current reduces the gain of the device, which reduces the onset of avalanche breakdown. In essence, this trades gain (β) against breakdown voltage, where in this case β is reduced from 2100 to approximately 400 (more than adequate for most applications). As a result breakdown is increased from 2.0 to 2.6 V, representing an improvement of 30%, although this is still much less than can be achieved with GaAs HBTs.

In an attempt to lessen the impact of HBT processing on CMOS fabrication in a BiCMOS process, researchers at IHP in Germany used an "HBT before CMOS" integration scheme. Fabricating the HBT prior to the CMOS portion lessens the thermal budget on the CMOS (in this case a 0.125 μm process), which allows tighter control over source/drain implantation profiles; this in turn improves CMOS performance. However, because this approach increases the thermal load that the HBT experiences during processing, a C-doped base, which is less susceptible to diffusion, is used. The HBTs deliver f_t and f_{max} values of 80 and 90 GHz, respectively, with a breakdown of 2.5 V.

Carbon doping in SiGe

Hitachi researchers used small amounts of carbon (up to 0.4%) in the base to compensate for the lattice strain induced by the inclusion of Ge. This reduction in strain reduces B out-diffusion, resulting in sharper doping profiles. The device with 0.4% carbon had f_t and f_{max} values of 124 and 174 GHz, respectively, and a breakdown voltage of 2.3 V, compared with 1.7 V without carbon. In similar work, researchers at Infineon Technologies in Germany used a SiGe:C approach to implement an HBT with f_t and f_{max} values of 106 and 145 GHz, and a breakdown voltage of 2.3 V. IHP has also used carbon in the base to produce devices with f_t and f_{max} values of 100 and 130 GHz, and a breakdown voltage of 2.5 V. The IHP process is relatively simple and does not require an epitaxially buried sub-collector or deep trench isolation, making it attractive for commercial applications.

While carbon incorporation has improved SiGe bipolar device performance, simple scaling and reduction of parasitics results in substantial performance improvements. For example, Conexant demonstrated a 0.15 μm emitter design exhibiting f_t and f_{max} values of 170 and 160 GHz, with a breakdown voltage of 2.0 V. This SiGe bipolar process has been merged with a 0.18 μm CMOS process that uses six layers of metal.



TOSHIBA

Fig. 1. A cross-sectional TEM of Toshiba's "silicon on nothing" MOSFET, showing an "empty space in silicon" (ESS) region which has been formed by trench transformation on hydrogen annealing. The inset TEM shows the crystalline perfection of the silicon-on-nothing region.

Even though many of these results are not reflective of the SiGe bipolar devices in commercial production, such devices continue to show performance improvements. IBM's latest commercial SiGe BiCMOS process uses a 0.2 μm emitter and exhibits f_t and f_{max} values of 117 and 100 GHz, with impressive noise figures of 0.4 dB at 3 GHz and 0.6 dB at 10 GHz. These bipolars are merged with a 0.18 μm CMOS process in which the NMOS exhibits an f_t of 80 GHz.

CMOS makes SiGe obsolete

It is often stated that a BiCMOS process utilizing SiGe bipolar technology for high-speed RF requirements, coupled with CMOS for large-scale digital ICs, offers the full range of characteristics required for almost any desired circuit application, and opens the way for system-on-chip applications. However, based on the improvements in the speed and RF capabilities of CMOS reported at IEDM, through aggressive scaling and a wide range of novel processing developments, many of these advanced CMOS processes could eliminate the need for a SiGe bipolar component.

Using a 70 nm cobalt silicide gate, coupled with a body-tied partially-depleted SOI CMOS process featuring dual offset-implanted source-drains to minimize parasitics, researchers at Mitsubishi have developed a CMOS process with RF characteristics that rival those of the SiGe bipolars presented at this year's IEDM. The Mitsubishi devices exhibited f_t and f_{max} values of 114 and 135 GHz, and a gain of 11 dB at 40 GHz.

An SOI approach certainly improves RF characteristics through the reduction of parasitic capacitive coupling to the lossy Si substrate. However, the buried oxide impedes thermal dissipation through the conducting Si substrate, which can be a limitation for power RF applications. With that consideration, researchers at Philips have addressed RF improvements not through the reduction of substrate capacitive coupling using an SOI substrate, but through the reduction of gate resistance. Based on a commercial 0.18 μm CMOS process with a conventional Si substrate, the unit cell uses a novel folded RF-NMOS layout that significantly reduces gate resistance, while the shared drains in the device reduce junction capacitance. In addition, p^+ guard rings are used to suppress the pick-up and injection of substrate noise. The resulting gate resistance is a relatively low 4 Ω/square, producing an NMOS device that exhibits f_t and f_{max} values of 70 and 150 GHz, and a noise figure of less than 1.0 dB for frequencies up to 8 GHz. What makes these characteristics so remarkable is that the devices are fabricated with a conventional CMOS process (using commercially available geometries) and are able to deliver SiGe bipolar-like performance.

By combining a parasitic-reducing SOI substrate, reduction in gate resistance using an Al overlay gate approach, and a small gate length of 80 nm, researchers at Fujitsu were able to see even greater improvements in RF performance. The resulting metal overlay gate

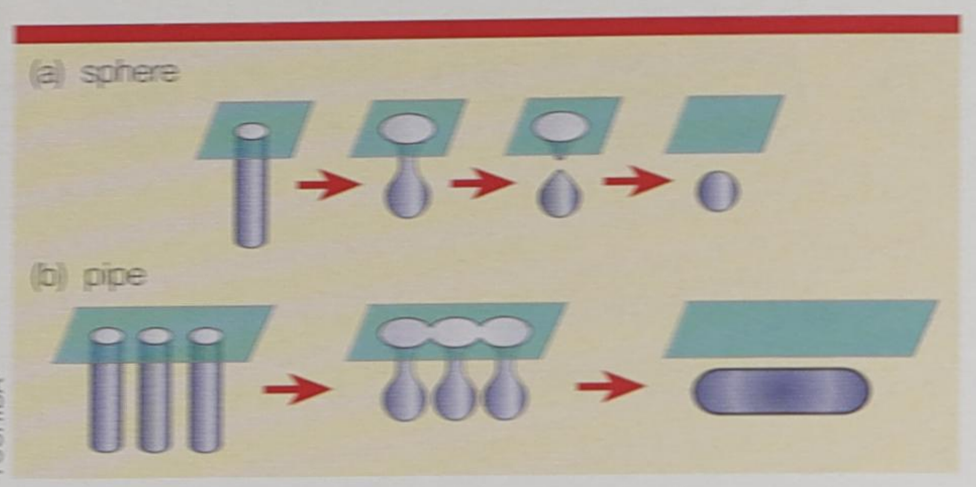


Fig. 2. A schematic showing the formation of voids in silicon. Toshiba's "empty space in silicon" (ESS) process uses hydrogen annealing to close trenches that have been formed by RIE.

had a sheet resistance of only 0.02 Ω/square, allowing this device to exhibit f_t and f_{max} values of 120 and 185 GHz, and a noise figure of 0.8 dB at 10 GHz (lower than the Philips results due to the much lower gate resistance). Such performance not only rivals the best results reported for SiGe bipolar processes, but exceeds most GaAs HBT processes and enters the regime that is often thought to be reserved for InP HBTs.

Rather than relying on a metal overlay gate approach, researchers at IBM used very small gate lengths of 40 nm, SOI substrates and aggressive gate oxide scaling (using a gate oxide of only 1.9 nm) in order to improve CMOS performance. The device exhibited f_t and f_{max} values of 178 and 193 GHz – better results than the best SiGe bipolar results presented this year. If this process were combined with the metal overlay gate approach, it is anticipated that such CMOS devices could be pushed through the 200 GHz barrier.

More tricks for CMOS

While aggressive device scaling, SOI substrates, sophisticated gate layouts and source-drain implant profiles, and reductions in gate resistance have produced greatly improved performance, all these approaches should still be considered fairly conventional process refinements. So it is no surprise that CMOS process engineers are looking beyond these approaches to even more radical fabrication techniques to further enhance performance.

In the last year, both IBM and Amberwave have announced the use of SiGe buffer layers in combination with chemical–mechanical planarization (CMP) approaches that permit the growth of strained Si CMOS devices exhibiting enhanced device mobility. Following a similar approach, Hitachi revealed a SiGe virtual substrate process (using a Ge content in the buffer of 30%), which exhibited an extremely low surface roughness after CMP processing of only 0.4 nm (rms). The resulting devices with gate lengths of 0.24 μm showed large increases in mobility of 120% and 42% for electrons and holes, respectively, which translated into improvements in current drives of both NMOS and PMOS devices of 70% and 51%.

Wanting to take advantage of the parasitic reducing capabilities of an SOI approach, while at the same time

Such performance not only rivals the best results reported for SiGe bipolar processes, but exceeds most GaAs HBT processes, and brings CMOS into the regime often thought to be reserved for InP HBTs.

IBM's CMOS device exhibited f_t and f_{max} values of 178 and 193 GHz – better results than the best SiGe bipolar results presented this year.

eliminating the poor thermal behavior, researchers at the Singapore Institute of Microelectronics reported a process to produce a partial SOI platform on a conventional Si substrate. Reactive ion etching (RIE) was used to form a sequence of narrow and deep trenches, in which the upper part of the trenches was passivated by a thin SiO_2/SiN layer. The lower portion of the trench was then oxidized by conventional thermal oxidation to form a buried thermal oxide under single crystal silicon regions. This produces regions of SOI structures adjacent to Si-only regions that act as high thermal conductivity pathways to the substrate. Compared with a pure Si bulk process, devices fabricated over the buried oxide regions showed a 56% reduction in output capacitance, a 37% increase in output power for a 2 GHz LDMOS amplifier, and an order of magnitude reduction in drain current. In addition, inductors fabricated over the buried oxide regions exhibited a high Q-factor of 15 at 3 GHz operation.

Silicon on nothing

The most novel approach to the reduction of parasitic coupling to the substrate was that reported by Toshiba in the development of a "silicon-on-nothing" (SON) MOSFET using "empty space in silicon" (ESS) technology (see figure 1). The ideal solution to reduce parasitic coupling is not to have a substrate at all, which can be achieved by substrate removal or lift-off. However, in those cases the resulting self-heating and floating body effects of devices fabricated on such membranes render these approaches impractical. Such devices are typically bonded to transfer substrates and then face the same parasitic coupling issues as in conventional device fabrication.

Instead, Toshiba has developed a process to fabricate empty spaces in a conventional Si substrate above which devices can be fabricated. The ESS approach is illustrated in figure 2. Conventional RIE and SiO_2 masking techniques are used to fabricate deep trenches. These trenches can be transformed into buried spheres, pipes and plates by H_2 annealing at 1100 °C for 3 minutes. During the high-temperature annealing, the trenches close at the surface and form voids beneath. Figure 1 shows a cross-sectional TEM of a fabricated MOS structure above an ESS sphere, where a high degree of crystalline perfection is obtained. This approach should be applicable to any CMOS application, and has the potential of delivering SOI-like device characteristics, while maintaining the high thermal conductivity characteristics of bulk Si wafers.



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Nitride LED makers strive to enhance efficiency and power

Manufacturers of high-brightness LEDs continue to make significant advances in the output power of nitride-based emitters, targeting a range of applications, writes **Richard Dixon**.

New applications continue to be found for high-brightness LEDs, which have established a niche in the automotive sector as brake lights, and dashboard and interior lighting, in addition to their use in outdoor displays and traffic lights. Signaling and indicator applications continue to benefit from device and package improvements, and allow compact, efficient emitters to be employed in other markets such as cellphone backlights. However, the big market for LEDs still lies in general illumination, which despite some recent success in areas such as spot lighting, is thought to be some 5–10 years away.

The requirements placed on devices used in indicator or signaling applications and in illumination are very different. Several manufacturers are looking at larger area chips to house higher drive currents and outputs for illumination, while others leverage what geometrical tricks are available to squeeze more of the original photons from standard-sized chips, which do not require packages with thermal management. This is largely dictated by which markets are being targeted, and some of the different approaches being employed for nitride-based LEDs are described below.



CREE

Fig. 1. Cree believes that its new X-Bright blue LEDs are the brightest standard 5 mm devices currently on the market.

Cree pushes standard 5 mm LEDs

Cree's early generations of GaN-on-SiC devices consisted of relatively low-brightness chips. However, over the last three years and in particular the last 12 months, the company has increased the brightness of its standard 5 mm LEDs by a factor of three. Cree's latest commercial product, the X-Bright, is a series of new blue and UV InGaN-on-SiC LEDs, which offer up to a 50% brightness increase over its previous MegaBright chips. The new devices use geometric shaping to reduce losses due to total internal reflection, as well as flip-chip mounting to increase light extraction in the forward direction (see *Compound Semiconductor* December 2001, p9). The die have a p-n junction area of $0.25 \times 0.25\ mm^2$.

Blue devices have a radiant flux of 16 mW at 20 mA, obtained at a forward voltage of 3.7 V (see figure 1). Cree believes these new LEDs are the brightest standard 5 mm devices on the market. The company's earlier generation 505 nm green device, which is not flip-chip mounted, provides 8 mW under the same conditions and targets traffic signals and signs. While Cree has demonstrated 21 mW UV LEDs at an efficiency of 32%, its X-Bright 395 and 405 nm UV chips will target an external quantum efficiency (i.e. the efficiency of photon extraction from an unpackaged LED die) of 25% in production.

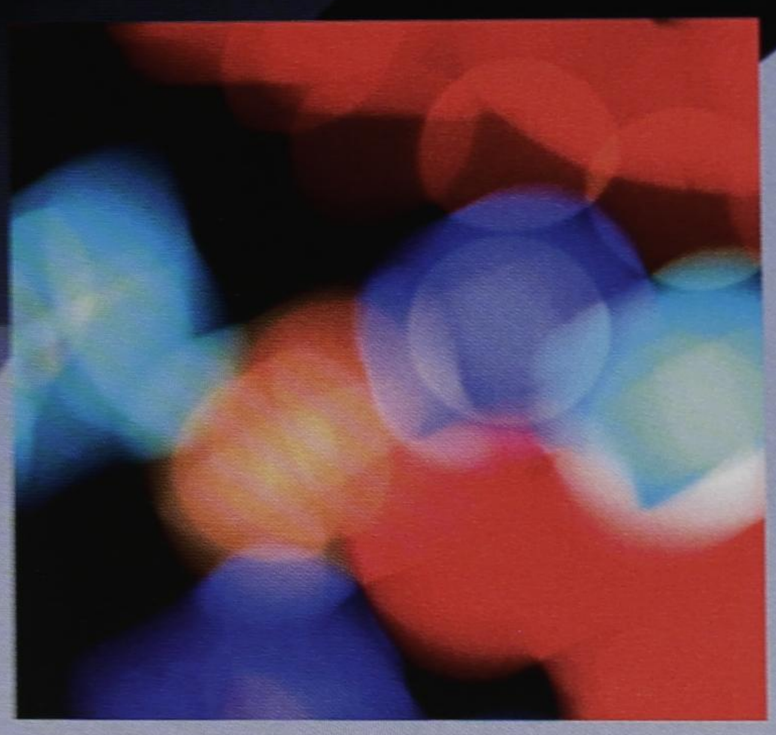
While larger die can provide more light, this is at the expense of efficiency. "The choice really depends on the application," says Cree's president and CEO Chuck Swoboda. "Other companies have been doing excellent work with packages and high-power chips, which are designed for high-output illumination applications, where large light output is more important than small size and efficiency." For many applications, including automotive stoplights, the light still needs to be distributed over a large area. "This is more efficiently achieved using many smaller devices," says Swoboda.

However, for certain applications Cree's customers would like to produce high-power light sources. "These are cases where it's not purely about efficiency, but also about having enough power to generate the most light in the smallest space," says Swoboda. "In those applications the power chip is probably a viable alternative, and we would like to support such requirements."

Uniroyal improves blue and UV

Uniroyal is also driving up the output power of its blue and near-UV LEDs, and it is targeting white-light emitter applications. Operating at 460 nm, Uniroyal's blue LED chips have a radiant flux of 3.4 mW (using a forward voltage of 3.61 V and 20 mA drive current), measured by simply mounting the die on a header without any additional heat sinking. According to senior device scientist Mary

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Crawford, the output of the device more than doubles when packaged; it is currently rated at 7.5 mW, and around 15 lm/W. The external quantum efficiency is 13.6% and the wall-plug efficiency is 10%; although 15 mW can be extracted at 50 mA, Crawford says the emitter suffers from a blue shift of around 3 nm.

The company is also developing shorter wavelength devices down to around 385 nm. Uniroyal's 405 nm device offers 2.4 mW in chip form and up to 5.3 mW of radiant power when packaged (measured at 20 mA). The wavelength is more stable than the blue LED, and the device offers around 8.6% external quantum efficiency in the package. However, such devices, which contain InGaN QWs and GaN barriers, suffer from a drop in efficiency and hence power at shorter wavelengths.

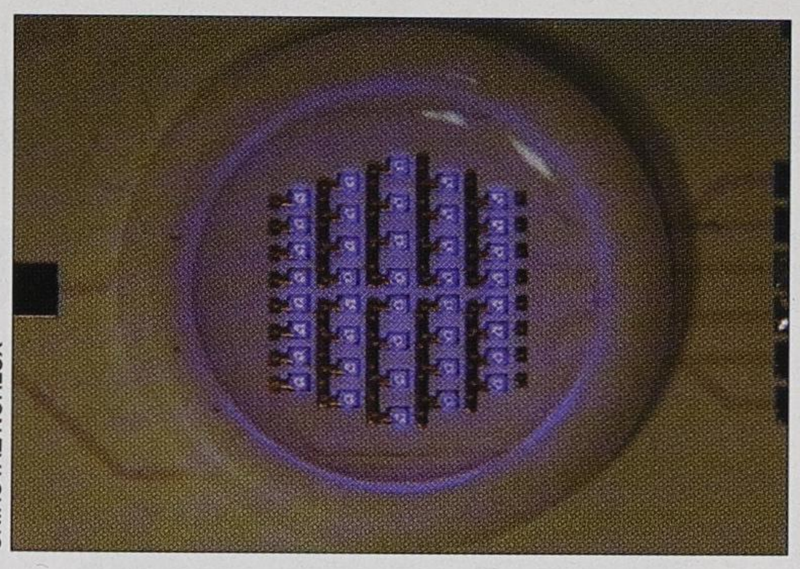
To overcome this problem, Uniroyal uses AlInGaN barriers to improve the carrier confinement. This leads to a low forward voltage and higher efficiency. It also provides a narrow line width, says Crawford, which reduces the visible "tail" from the emitter in a white-light source, where the emitter is also visible in addition to the white spectrum produced by the excited phosphor. Uniroyal has demonstrated 385–390 nm LEDs which have an external quantum efficiency of around 4.6% and 2.95 mW output power at 20 mA.

Crawford says Uniroyal is putting an emphasis on reliability and manufacturability. The company's near-UV devices offer low-voltage operation and exhibit smaller shifts in wavelength with current injection than its blue devices, providing stable color characteristics. However, LED performance varies with wavelength, so tight wavelength control is required.

"High wall-plug efficiencies and low cost are essential if LEDs are to compete with current light sources in white lighting applications," says Crawford. "Neither green nor blue LEDs appear to be as sensitive to non-radiative recombination defects as UV emitters, so the challenges for UV LEDs are different." Crawford adds that one of the main challenges for UV LEDs will be the development of highly manufacturable and cost-effective growth techniques that can dramatically reduce non-radiative defect densities in these materials.

Driving power packages

Uniroyal has developed high-flux LEDs in collaboration with its lighting subsidiary Norlux, which is developing packaging that eliminates UV degradation of encapsulants and die attach materials (see *Compound Semiconductor* June 2001, p9). The Norlux package uses a hexagonal shape for efficient placement in a scalable package, allowing many LEDs to be packaged and driven at a high total current. Using this approach, the company recently demonstrated a prototype 415 nm violet lamp (see figure 2) that offers over 300 mW for just under 6 W of input power (measured at a current of around 350 mA and a forward voltage of 16.5 V). An aluminum substrate is used as the heat sink, resulting in a temperature rise of only 10 °C per W of input power, compared with around 350 °C per W for a standard 5 mm LED.



UNIROYAL/NORLUX

Fig. 2. Norlux's hexagonal package contains 40 violet LEDs and has demonstrated a total output of over 300 mW.

The white Luxeon LED has a luminous efficiency of 30 lm/W and produces 150 lm at a drive current of 1.4 A, a very impressive figure for a single chip.

A preliminary data sheet for Norlux's 470 nm blue HEX package containing 40 LEDs shows a luminous efficiency of 4 lm/W, and a total output power of 0.13 W (i.e. 3.25 mW per device). Green 525 nm InGaN packages operate at 9.5 lm/W, while an RGB white package provides around 10 lm/W.

Uniroyal is also looking at other ways to increase the power of its blue LEDs. The company has just begun sampling a large-area version of its 450 nm blue LED that offers 60 mW of output, and contains a monolithic array of nine LED devices.

LumiLeds leads in high-flux chips

During 2001, LumiLeds launched its Luxeon range of large-area high-current devices, setting new standards for LED output power. The AlInGaP (red and amber) and InGaN (blue, green and white) devices target high-power lighting applications and are the result of a 17× improvement in flux over the last three years. Featuring die areas up to $1.0 \times 1.0\ mm^2$, the devices are flip-chip mounted on aluminum or copper heat sinks, which allows them to be driven at currents as high as 1.4 A. The LEDs are mounted in a plastic lens filled with silica gel, making a robust, reliable package (see figure 3).

This package enables a range of fixtures and white lighting sources, but will be too expensive for general lighting applications for some time to come, despite being twice as efficient as incandescent bulbs. "By paying close attention to packaging considerations and removing heat, we are able to push the output of these devices by driving the current very hard," says LumiLeds' Paul Martin. "While the devices are not as efficient at these high currents as standard InGaN LEDs operating at 20 mA, this is not important to the lighting designer, who is looking for a high total light output."

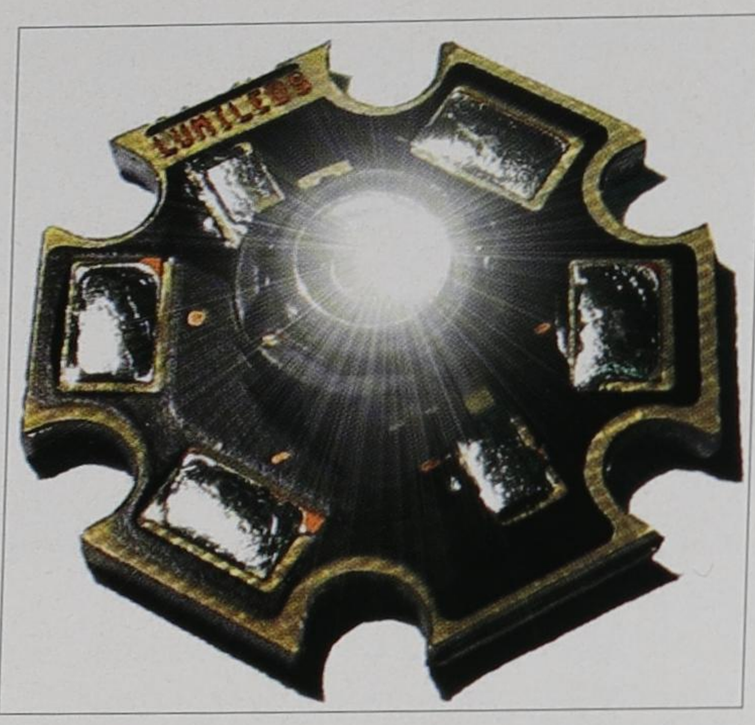
That said, LumiLeds' 450 nm blue InGaN/AlGaN chip offers a wall-plug efficiency of 24% and a luminous efficiency of 330 lm/W. The wall-plug efficiency, a measure of the amount of energy required to produce the specified light output level, drops significantly when the LED is placed in a YAG-phosphor-coated package to make a white Luxeon device. This is largely due to energy loss from conversion of a blue photon to a yellow photon. The white Luxeon LED has a luminous efficiency of 30 lm/W and produces 150 lm at a drive current of 1.4 A, a very impressive figure for a single chip. In comparison, a standard incandescent bulb produces 110 lm with an efficiency of 7 lm/W.

The use of phosphors to produce white LEDs also produces reliability concerns; for example, degradation of the epoxy can reduce the light output below usable levels, sometimes in under 5000 hours (see p45). This is much shorter than the 100 000 hours typically touted for standard-colored LEDs in clear glass packages. "Our white Luxeon devices have been tested independently and have shown no drop in output over 5000 hours," says Martin. "In addition, we have been able to keep the series resistance under control, particularly as the large chips are driven at such high currents. During operation across the range of 0–1 A, the series resistance of our chips increases from 0.8 Ω to just 0.9 Ω, which keeps heat changes small."

AXT looks to larger LED chips

AXT is another company that has introduced larger area blue and green LEDs. It has recently launched high-flux AlInGaN-on-sapphire LEDs covering the 450 to 525 nm range (see *Compound Semiconductor* November 2001, p59). At 1.25 × 1.25 mm^2, the new P2 series chips are up to 3× larger on a side than the company's standard die, which measure 0.325 × 0.375 mm^2. The larger area allows the device to be driven harder, and enables AXT to address target applications in traffic signals, automotive interior lighting, dental curing and eventually general illumination. Operating at 350 mA, the P2 includes current spreading layers to improve the uniformity of light emission, an optimized geometry for current injection, and back reflection to enhance light extraction.

In performance terms, the company's larger area 525 nm device provides a radiant flux of 27 mW and a luminous efficiency of 17.5 lm/W, which compares to 2 mW from its newest standard-sized green die. Designed for use in traffic signals, a high-power cyan LED offers 30 mW of radiant power and 12.5 lm/W luminous efficiency. In addition, AXT has a 450 nm blue chip that features a flux of 35 mW (compared with 4 mW from its conventional blue device) and features a luminous efficiency of 6 lm/W.

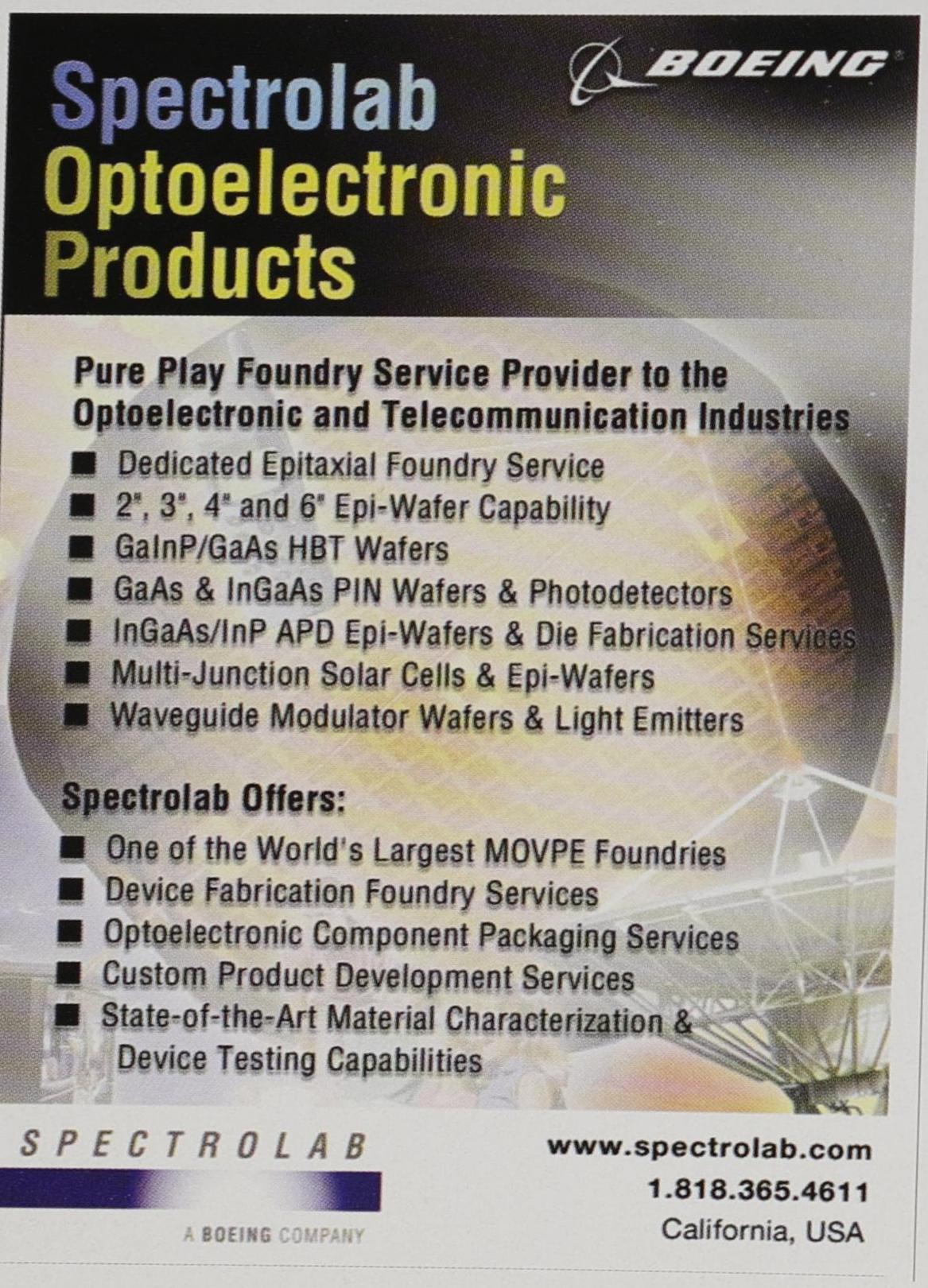


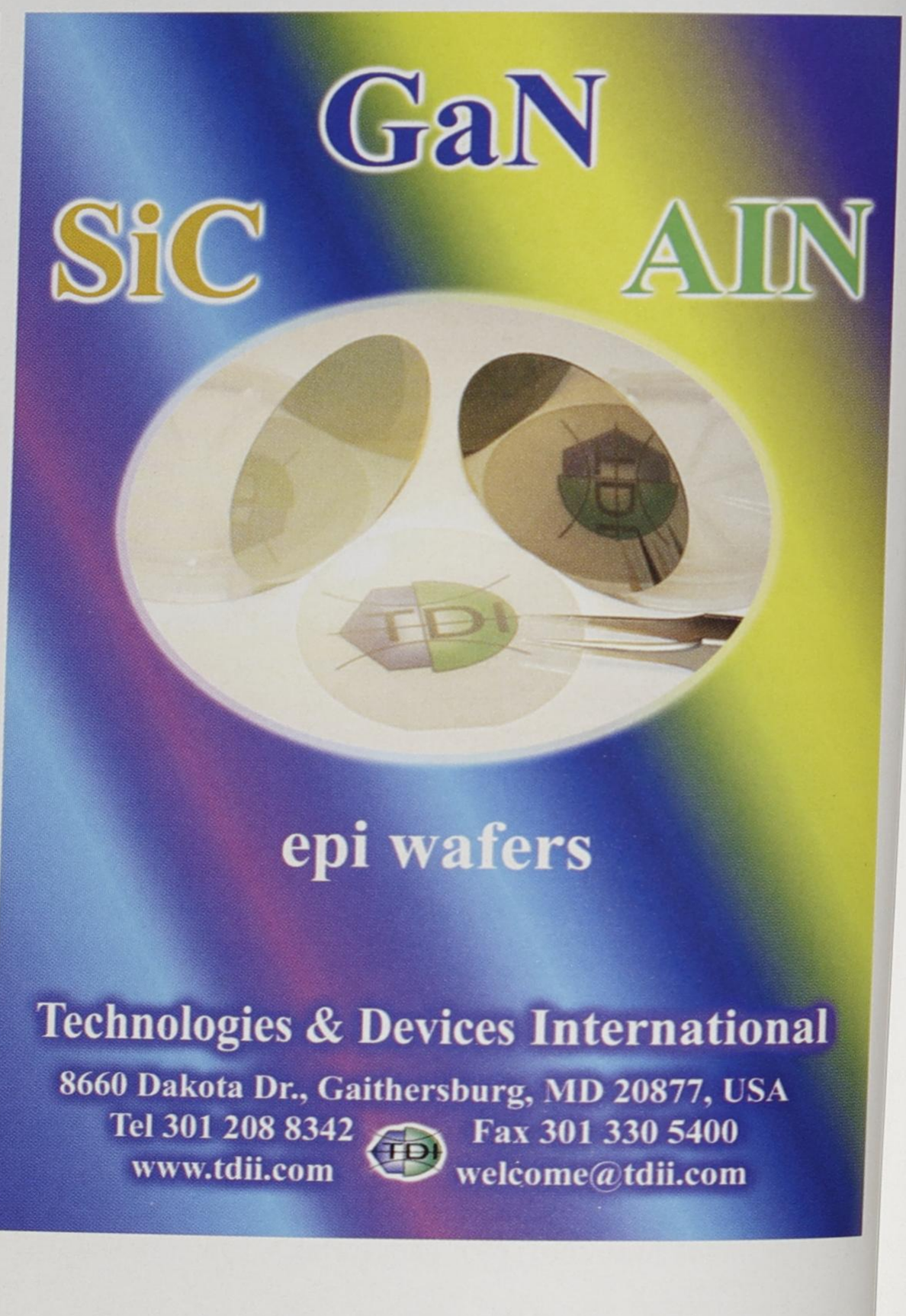
LUMILEDS LIGHTING

Fig. 3. The Star Luxeon package from LumiLeds has an efficiency of 30 lm/W and provides 150 lm from a single LED chip.

While the output of AXT's new LEDs is considerably higher than its standard chips, the wall-plug efficiency of around 2% is quite low. Preliminary data sheets indicate that these results were obtained on chips mounted on heat sinks that provide 32 °C per W, and do not have index matching of the epoxy encapsulant to ensure optimal output.

As AXT's chief technical officer Heng Lui notes, the output of the device changes with the thermal conductivity of the heat sink material. It also appears as if the P2 may be a preliminary device that will soon be superceded. "We are in the process of designing a new power chip called P3, which will provide at least twice as much power as the P2 at the chip level," explains Lui. "In general, for a high flux LED application we are targeting a packaged device that can deliver 300 mW, which could mean that we have to drive the chip up to 1 A in future. This will produce considerable thermal challenges at both the chip and the package level, and we are working with experts on some aspects of thermal management, in addition to theoretical and optical modeling."





Buried micro-reflectors boost performance of AlGaInP LEDs

The combination of wafer bonding using metal layers and the introduction of buried micro-reflector structures leads to thin and highly efficient AlGaInP LEDs that can be manufactured on 4 inch wafers, according to **Stefan Illek and co-workers** at Osram Opto Semiconductors.

The demand for high-brightness visible LEDs continues to increase, driven by applications such as traffic signals, automotive lighting and display back-illumination. In order to satisfy the steadily growing need for higher luminous efficiency and intensity, considerable progress has been achieved in both epitaxial growth and device optimization. For the spectral region from yellow to red ($\lambda = 580$–650 nm), the quaternary AlGaInP material system grown lattice-matched on GaAs substrates by MOCVD has proven to be the best choice. Carefully optimizing the layer sequence and growth conditions has led to impressively high internal quantum efficiencies in the red spectral region. However, the radiative efficiency drops significantly at shorter wavelengths for fundamental physical reasons – i.e. because of the approach of the direct–indirect bandgap crossover, and because of the much more difficult growth conditions for higher aluminum concentrations.

Using high-quality AlGaInP material, a very high photon density can be created by spontaneous emission inside an LED at moderate current densities (typically 40 A/cm^2). However, because of the large difference in refractive index between the semiconductor and the surrounding encapsulant (n ~ 3.5 and ~ 1.5 respectively), the extraction efficiency of conventional LEDs is limited to about 4% for each available extraction surface. Therefore improving light extraction is a major issue in fabricating high-efficiency LEDs, particularly for the AlGaInP/GaAs material system. Here the growth occurs on an absorbing substrate, which considerably limits device performance (figure 1). Several approaches have been developed to circumvent this constraint. The use of a distributed Bragg reflector (DBR), or replacing the GaAs substrate with transparent GaP after growth using wafer-bonding techniques, are well established in high-volume manufacturing. Implementing a thick GaP window layer and additional geometrical shaping, e.g. truncated-inverted-pyramid geometry, has pushed efficiency above 50% (Holcomb *et al.*)

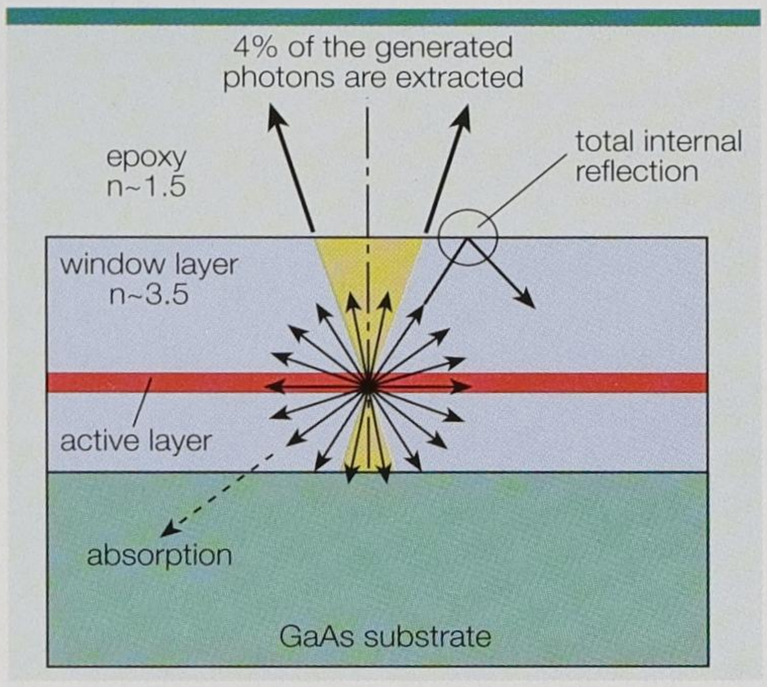


Fig. 1. Total internal reflection and substrate absorption limit the photon extraction efficiency of conventional LEDs grown on absorbing substrates.

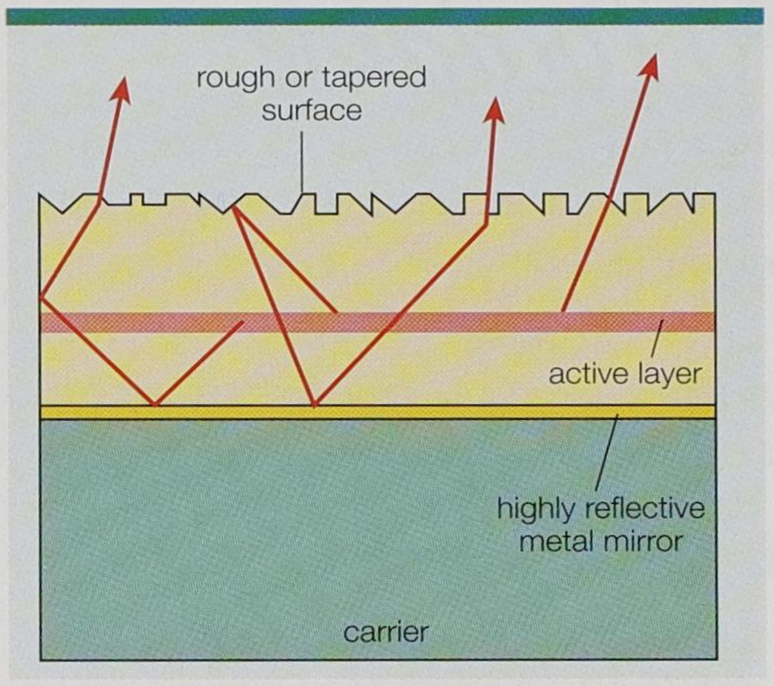


Fig. 2. In substrate-less LEDs a highly reflective metal mirror reflects all the downward-travelling light. The thin active layer minimizes internal absorption.

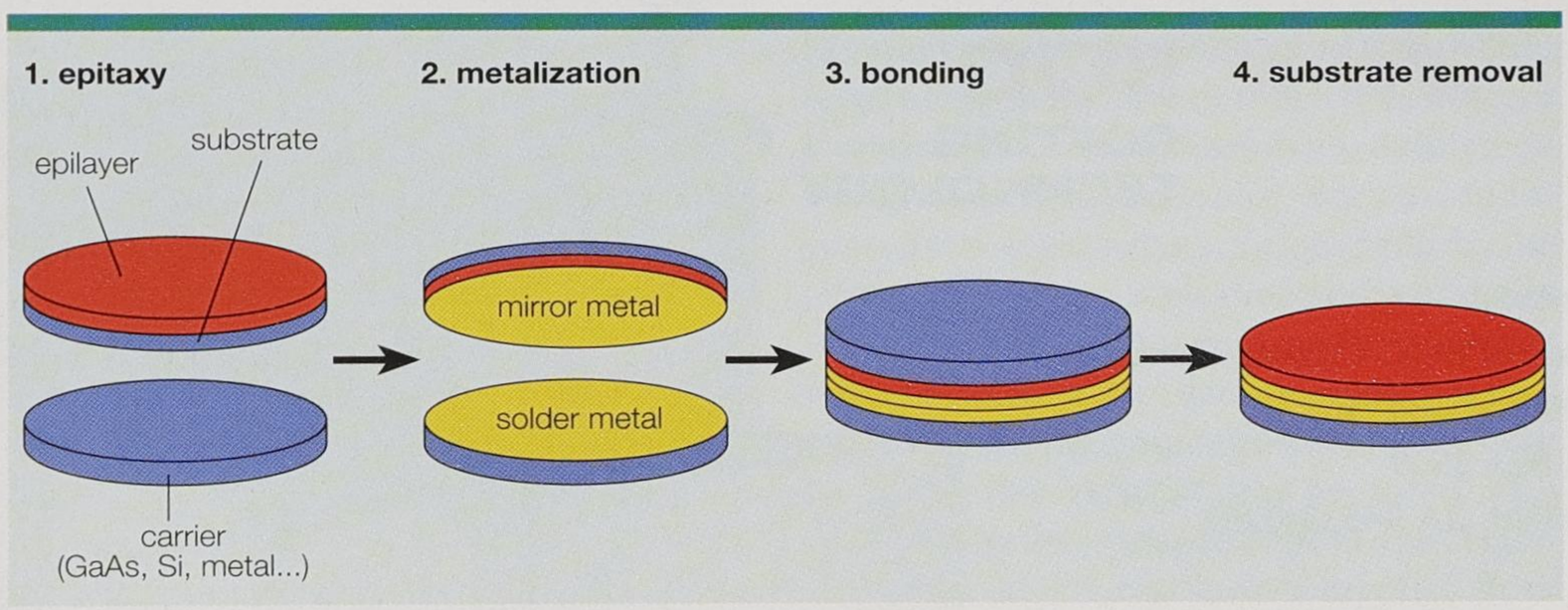


Fig. 3. A metal-bonding scheme used for creating an "artificial" wafer with epilayers on a new carrier and buried metal-mirror layers in between.

Substrate-less LEDs

Instead of replacing the absorbing GaAs substrate, using substrate-less devices has proven to be another interesting approach (figure 2). Placing the epitaxially grown semiconductor layers, including the active region, on a highly reflective mirror considerably eases some of the challenges of wafer bonding. Because the bonding interface need not be optically transparent, a metal–metal interface can be used. Thus in contrast with wafer bonding, neither ultra-smooth surfaces nor precise matching of crystallographic alignment are necessary.

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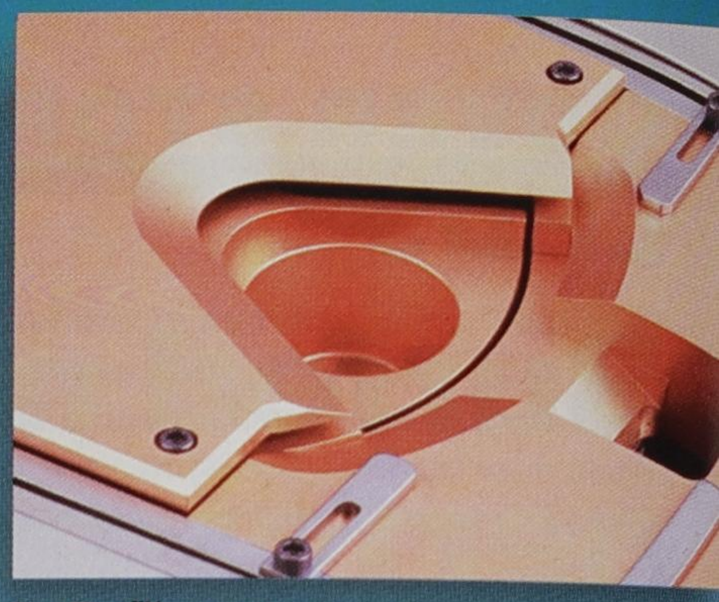
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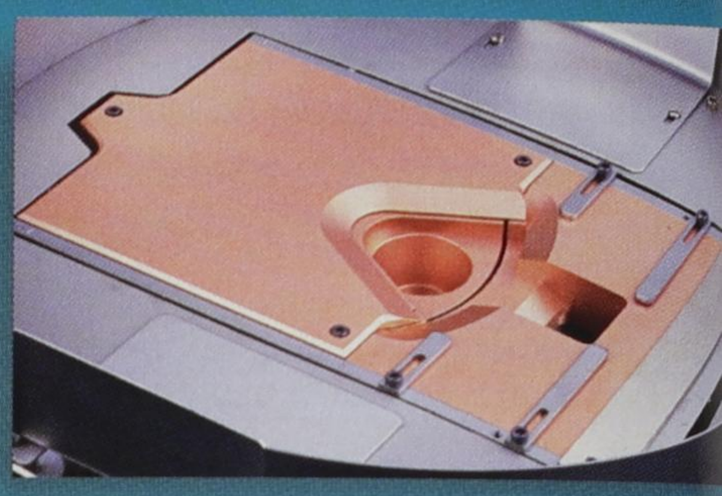
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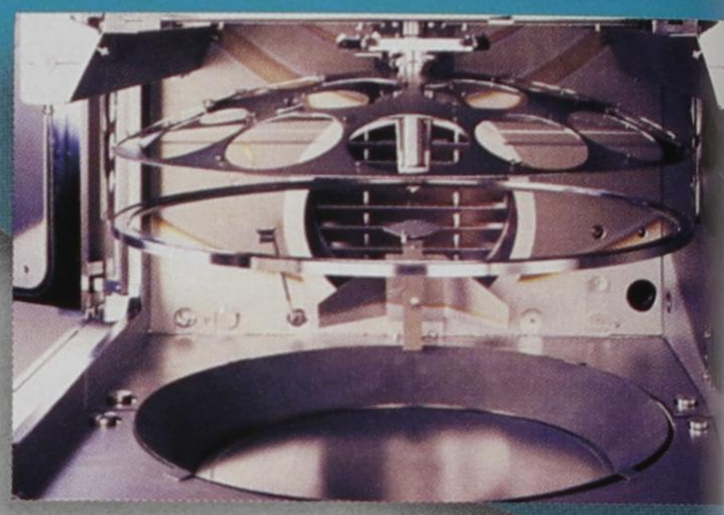


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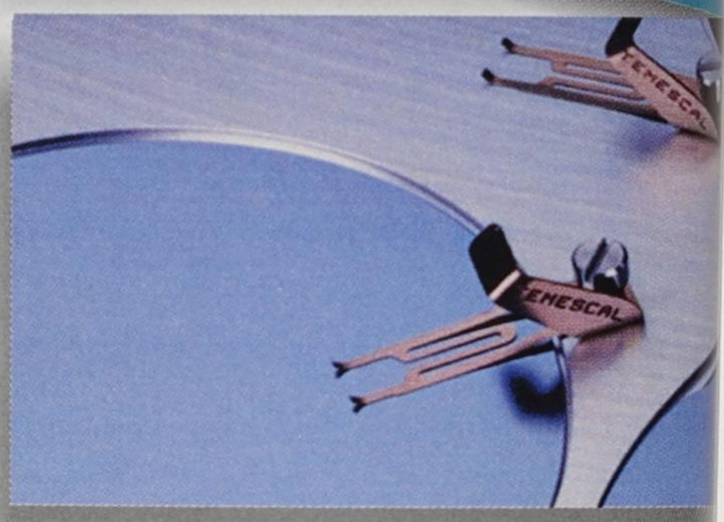


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of the thin-film concept can be exploited by incorporating a surface that randomizes or changes the angle of reflection of light otherwise captured within the semiconductor. Using diffuse reflection by surface-texturing or radial out-coupling tapers, efficiencies as high as 46% have been demonstrated in the infrared spectral region (Schmid *et al.*, Windisch *et al.*). However, substrate-less devices have so far only been demonstrated on a laboratory scale. In order to establish a process sequence suitable for high-volume manufacturing, a number of issues had to be addressed during development.

Most importantly, to be compatible with standard fabrication techniques, epitaxial layers cannot be handled as a fragile thin film. The process sequence for this is shown schematically in figure 3: the mirror layers are deposited on the epiwafer, whereas the carrier is coated with suitable solder layers. An n-doped 4 inch GaAs substrate wafer is used as a carrier, and is covered with an AuGe ohmic contact layer and a gold-tin solder layer with appropriate diffusion barriers. Only a short, low-temperature step is required for the metal–metal bonding – this is essential to avoid redistributing doping profiles within the LED structure. After bonding, the substrate of the epiwafer is removed by grinding and wet chemical etching, resulting in an "artificial" 4 inch wafer with epilayers on a new carrier with buried metal-mirror layers in between. The solder joint has proven stable enough to endure typical LED fabrication steps like high-pressure cleaning, sawing, laminating, wire bonding and thermal cycling.

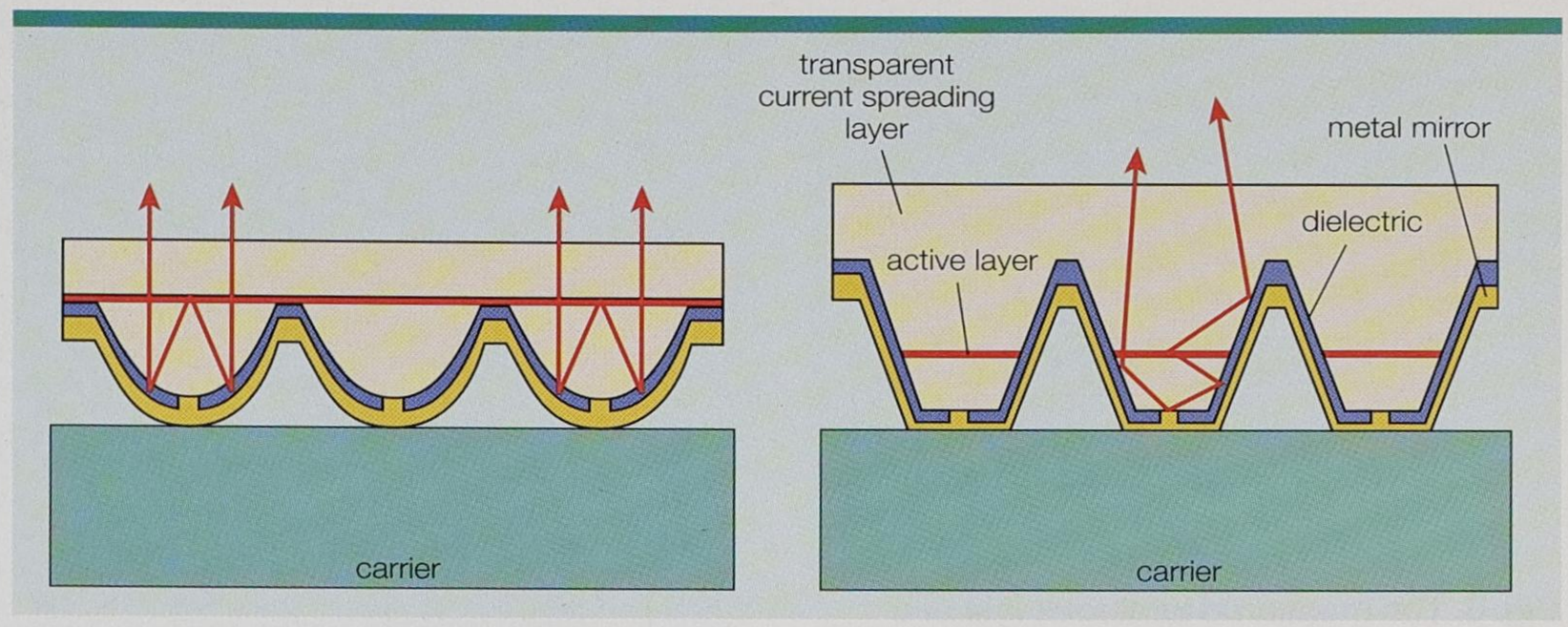


Fig. 4. Schematic cross-section of two designs of BMR LEDs. Light emitted from the active layer needs only a few reflections to escape from the semiconductor.

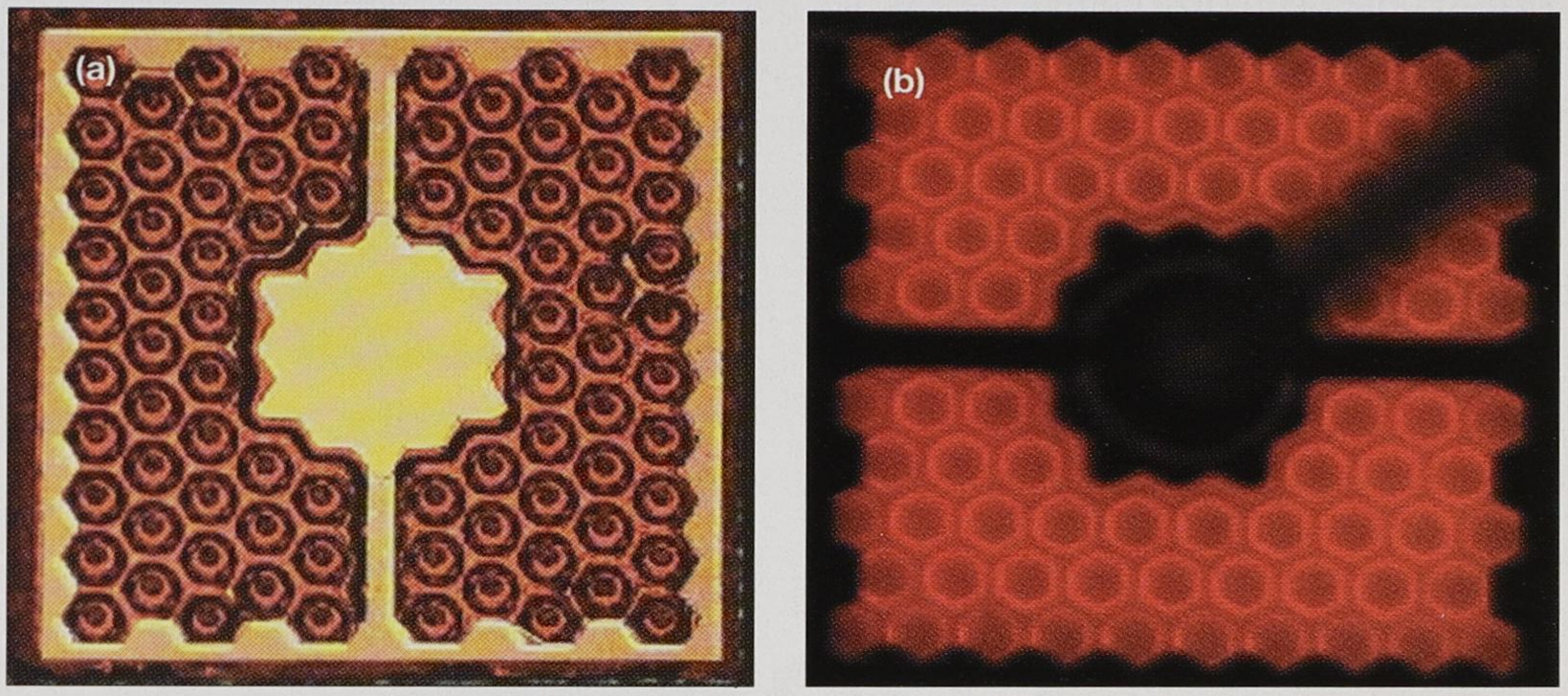


Fig. 5. Top view of a BMR LED (a) with external illumination and (b) operating at 1 mA.

Micro-reflector structures

In order to make thin-film LEDs more efficient, it is necessary to incorporate a surface that scatters light rays into new propagation angles, giving them a chance to lie within the extraction cone. However, realizing a diffuse reflecting surface using random surface texturing in the sub-micrometer range is not a standard production technique, and may be difficult to implement for large wafers. Therefore we have chosen a surface topography that is fully compatible with standard LED technology. Before depositing the mirror and bonding the wafer to the carrier, inclined micro-reflectors forming geometrical bodies like frustums or pyramids are defined in the upper part of the epitaxial layer sequence. The dimensions of the micro-reflectors are designed to allow simple manufacturing using conventional lithography and wet or dry-etching techniques, and to provide compatibility with the thin-film concept.

Figure 4 is a schematic cross-section of two designs, both containing an ensemble of buried micro-reflectors optically connected via the transparent semiconductor thin-film layer. Light emitted from the active layer with angles greater than the critical angle of total internal reflection has to travel only short distances within the semiconductor and needs only a few reflections to escape from the device. This significantly reduces the susceptibility to residual absorption (e.g. in the active layer) and non-perfect mirrors.

In addition because the reflectors redirect the light mainly to the top surface of the chip, light emission through the chip sides plays only a minor role. Consequently thick window layers to improve light extraction through the side faces of the LED are not required. In contrast with other approaches the micro-reflectors do not have to be scaled with chip area, allowing the use of thin epitaxial structures for realizing large-area LEDs. This saves growth time in the MOCVD reactor, enabling low-cost, high-power LEDs to be produced.

The reflectivity of the mirror is enhanced to values greater than 90% using a dielectric layer beneath the mirror metal. For current injection small contact areas are defined on top of each micro-reflector. Because these contacts are interconnected electrically by the mirror metal there is no shadowing of emission area. As an additional benefit, this leads to higher local current densities and therefore to greater photon generation in areas where the extraction efficiency is geometrically enhanced by the micro-reflectors. On the top side of the device, carriers are supplied from a common bond-pad to all micro-reflectors via the transparent semiconductor thin film, which acts as a current-spreading layer.

Device performance

Starting from the growth process used for standard AlGaInP LEDs emitting in the amber wavelength range ($\lambda = 615$ nm), some optimization was necessary concerning the thickness of the GaP window layer, the thickness of the current-spreading layer and the doping levels. Both wet and reactive ion etching were used to make the micro-reflectors. After the

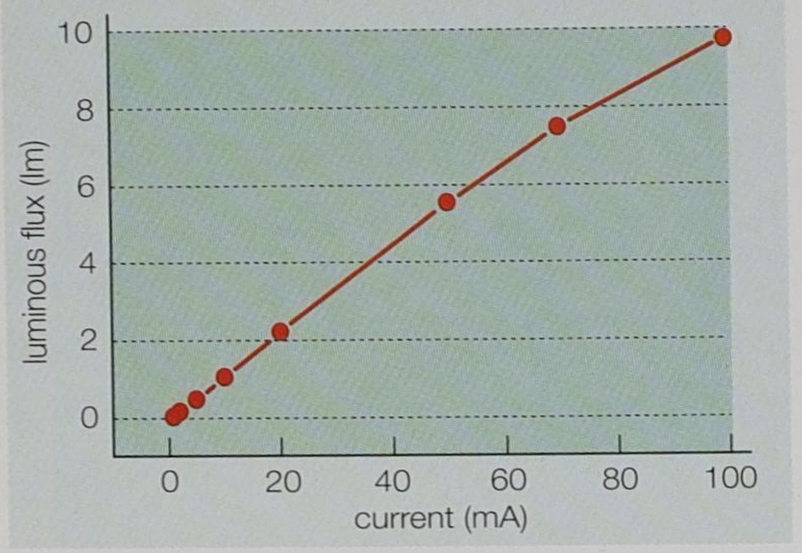


Fig. 6. The measured luminous flux of a BMR LED operating at 615 nm in a standard Power TopLED package. A drive current of 70 mA corresponds to a current density of approximately 60 A/cm^2.

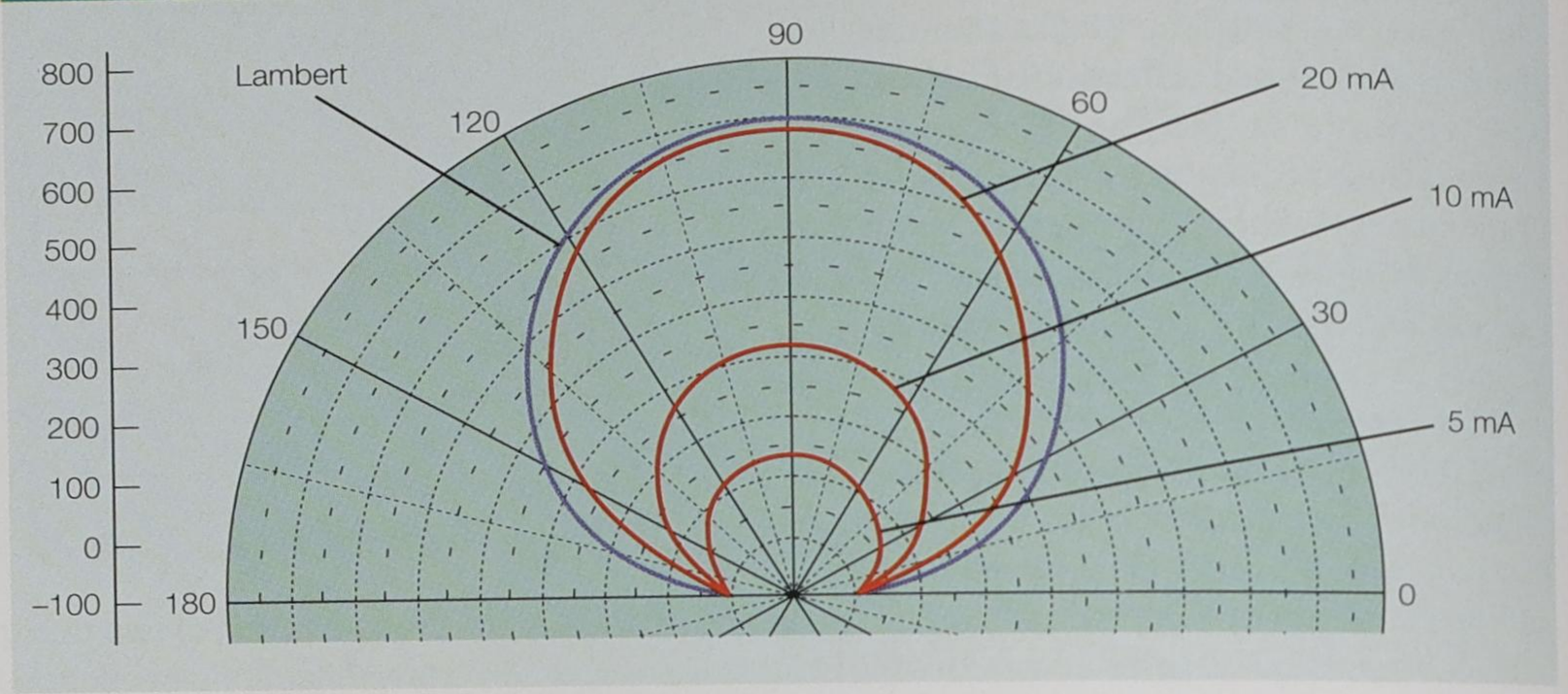


Fig. 7. The radiation pattern of a BMR LED at different drive currents. The emission pattern closely matches that of an ideal, planar Lambertian emitter.

dielectric mirror layer was deposited, contact openings were defined on top of the micro-reflectors, the mirror metal was deposited and the full 4 inch wafer was bonded to the carrier wafer as described above. After the growth substrate was removed, the top contact including the bond pad was defined. The final wafer-fabrication steps were thinning and depositing the back contact of the carrier wafer. LEDs measuring $350 \times 350\ \mu m^2$ were separated using a standard sawing technique.

Figure 5a shows a top view of a buried micro-reflector (BMR) LED with external illumination. Because of the very thin transparent epitaxial layers, the BMR structures located at the bottom side of the chip can be clearly seen together with the contact areas on top of them. In figure 5b the same device is shown operating at a drive current of 1 mA. The enhancement of light extraction due to the inclined sides of the micro-reflectors can be clearly seen.

A comparison was made with thin-film devices on the same wafer that had the same mirror and contact geometry but did not have micro-reflectors. This showed that the luminous flux of the BMR LED was enhanced by as much as 70%. Of course, this factor depends on the shape of the micro-reflectors. In contrast with other thin-film devices published so far, these BMR LEDs can operate at the same current densities as standard LEDs. A luminous flux of 7.5 lm at 70 mA and 9.5 lm at 100 mA has been achieved in a standard Power TopLED package (figure 6). The micro-reflectors emit the light predominantly normal to the top surface rather than towards the sides. Figure 7 shows the resulting radiation pattern for different drive currents. The emission pattern closely matches that of an ideal, planar Lambertian emitter. Therefore the chips can be used in all standard packages without compromising the overall performance of the lamp module.

Buried micro-reflector LEDs have enhanced the performance of substrate-less LEDs considerably, and quite clearly outperform advanced AlGaInP LEDs on absorbing substrates.

Low forward voltage

An important parameter of LED performance is the forward voltage required to drive a specific current. Neither the metal-bonding process nor the new contact layout increased the forward voltage. Values of 2 ± 0.1 V were typically achieved at a current of 20 mA (the observed distribution mainly reflects the usual spreading by epitaxy and the formation of electrical contacts). The use of a conventional epitaxial layer sequence in the BMR LED could lead to a discrepancy compared with the common "p-side up" configuration. A promising long-term stability of both light output and forward voltage of packaged devices at 50 mA and 85 °C demonstrates that the modified current-injection scheme has no detrimental influence. In addition the mechanical stability of the semiconductor thin film and the solder bond has been checked with standard thermal-cycling tests.

BMR LEDs have enhanced the performance of substrate-less LEDs considerably, clearly outperforming advanced AlGaInP LEDs on absorbing substrates. The fabrication process has been demonstrated to be compatible with state-of-the-art manufacturing techniques and there is no roadblock concerning the use of full 4 inch wafer processing. Compared with direct wafer bonding, the soldering process used is much more tolerant regarding surface roughness, topography and particles. However, special care is needed to minimize the size and number of particles during epitaxial growth and processing to achieve yields competitive with standard LEDs.

Additional advantages of this technique are thinner and therefore cheaper epitaxial layers, low-voltage and high-current operation, planarity of devices, scalability and compatibility with standard packaging techniques. Furthermore this technology may be beneficial for other material systems, e.g. AlGaAs/GaAs in the infrared spectral region. This approach will help to reach the goal of a reduced system cost and enable LEDs to penetrate new market segments.

Further reading

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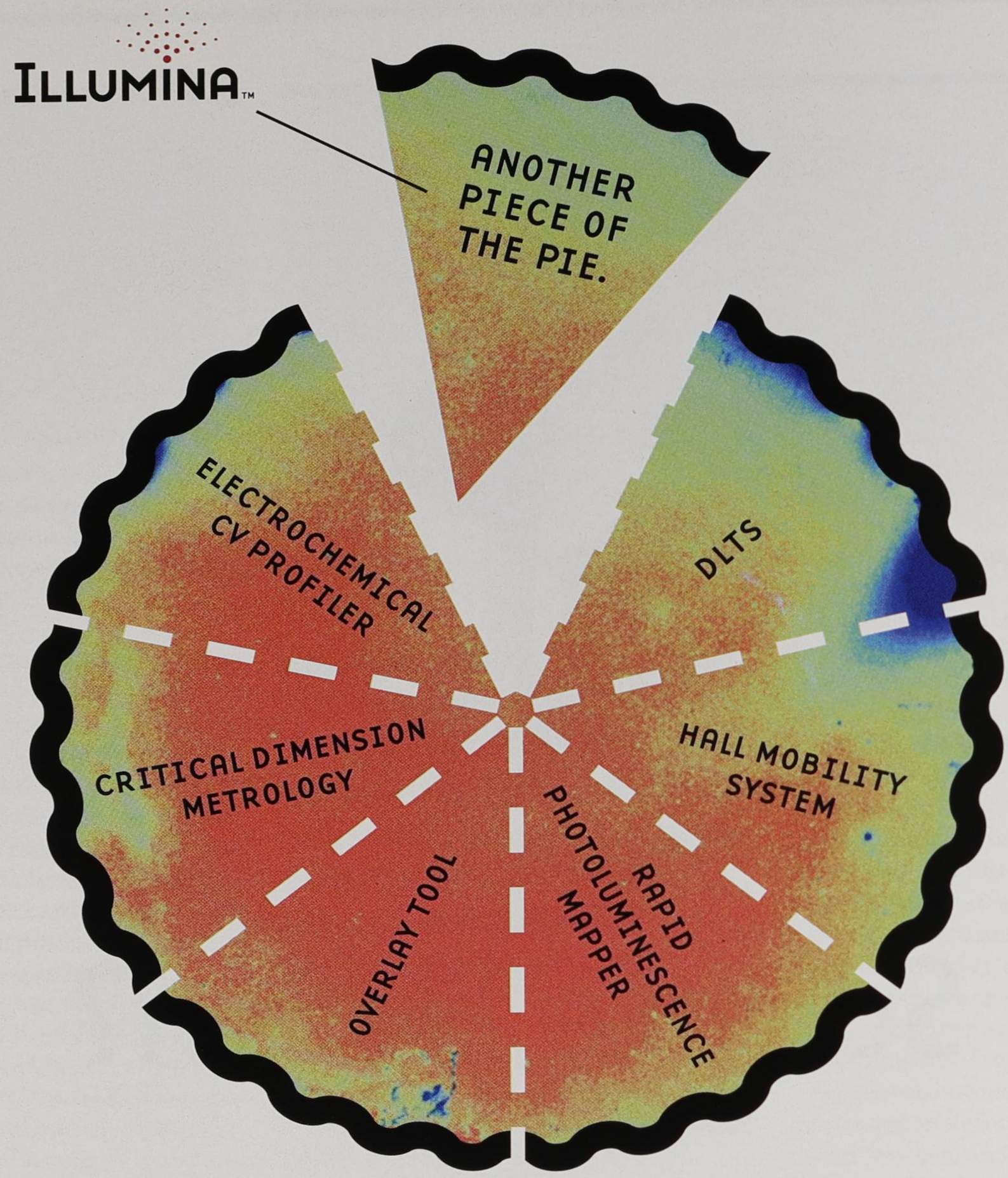
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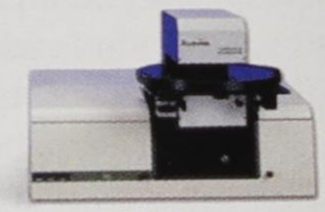
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LED package designs tackle lumen depreciation issues

Improvements in package design are expected to extend the lifetime of LED-based lighting fixtures towards 100 000 hours, according to **Nadarajah Narendran** and **Keith Toomey**.

In over a century since electric lighting was first introduced, just two types of light-source technology – incandescent and electric discharge – have coexisted. The standard residential light bulb belongs to the incandescent light source family, while the linear fluorescent lamps used in offices, and the sodium lamps seen in streetlights, are examples of the electric discharge family. But now, a third type of light-source technology – the LED – is emerging and appears to hold great promise. As the first solid-state lighting technology, LEDs have the potential to offer significant energy savings and long lifetimes. These factors have attracted the general lighting community to this new technology.

LEDs as efficient light sources

For most people, the term LED simply refers to the small indicator lights commonly found in electronic equipment, such as radios and remote controls. Although LEDs were first developed in the late 1960s, it took nearly three decades for researchers and developers to produce white light using this technology. During this period, however, the brightness of colored LEDs increased significantly, allowing them to be used in a wider variety of applications. During the latter part of the 1990s, LEDs began to replace incandescent lamps in traffic signals. In this application LEDs have been shown to save over 80% of the energy used compared with their incandescent counterparts. Such large energy savings are realized because the conventional colored signals use optical filters over incandescent lamps. These filters absorb, and thereby waste, a significant portion of the radiant energy generated by the light source. LEDs, on the other hand, emit light in a narrow wavelength band, and they can efficiently produce colored light.

As LEDs replaced incandescent lamps in traffic signals, it emerged that they were more than just energy-efficient; in fact some manufacturers claimed that their LEDs would last 100 000 hours. As white-LED technology evolved, industry experts predicted that LEDs would revolutionize the lighting industry, including the field of illumination. On hearing this, some early adopters quickly created light sources using arrays of 5 mm white LEDs packed inside a lamp envelope. These "LED lamps" mimicked standard incandescent bulbs and their manufacturers claimed that they were more energy-efficient than incandescent lamps and, like their colored counterparts, would last 100 000 hours. This led many to believe that white LEDs were ready to replace the incandescent lamps.

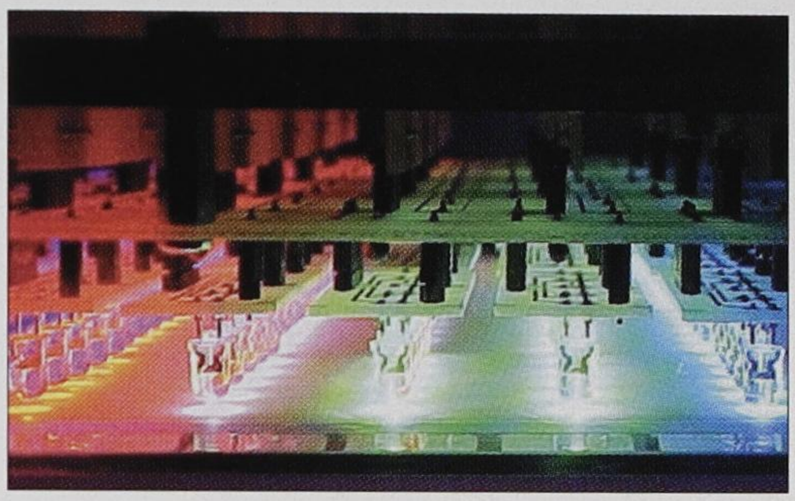


Fig. 1. LEDs in 5 mm packages under test in a temperature-controlled environment.

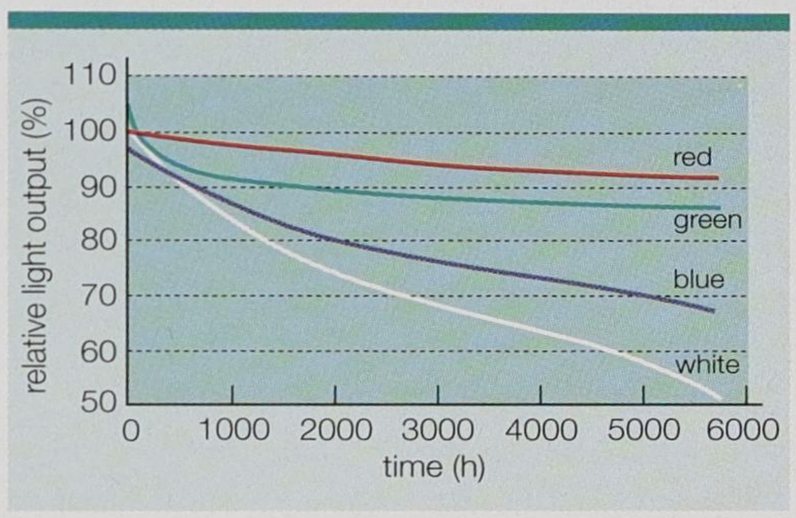


Fig. 2. Light output degradation of LEDs in 5 mm packages driven at 20 mA.

White LED lifetimes

Reality, however, did not live up to the initial claims. Early in 2000, research publications showed that the light output of these 5 mm white LEDs dropped very quickly. In only about 6000 hours, the light output dropped below half its original value (Narendran *et al.* 2000 and 2001a). Yet, despite this information, as well as numerous articles which have shown that 5 mm white LEDs degrade very rapidly, many manufacturers continue to claim that they will last 100 000 hours.

Another recent publication showed that even the different colored 5 mm LEDs do not degrade the same way over time (Narendran *et al.* 2001b). These LEDs were tested in a temperature-controlled room, and they were mounted on printed circuit boards as shown in figure 1. The light output degradation of LEDs with different colors is shown in figure 2. The light output of the red LEDs depreciated at a much slower rate than that of the white LEDs, while green and blue LEDs degraded at an intermediate rate. LEDs packaged inside an enclosed fixture, where the ambient temperature is higher than in the temperature-controlled study, will experience higher degradation rates. Therefore, the claim of 100 000 hours life for LED fixtures that use housed arrays of 5 mm LEDs, white or colored, is deceiving. The LEDs may indeed last 100 000 hours, but their light output may not be sufficient for the fixture's intended application. A useful life of 5000 hours may be more appropriate for the 5 mm LED fixtures.

Newer LED packages

Standard 5 mm LED packages were originally designed for use in indicator applications, but their design does not allow for sufficient heat transfer from the LED chip to keep it cool during operation. As the temperature of the chip increases, the device degrades more quickly. Another problem in 5 mm white LEDs is that yellowing of the epoxy reduces light output and increases the light output degradation rate.

There is reason for optimism, however; newer high-power LED packages have been designed for illumination applications. These

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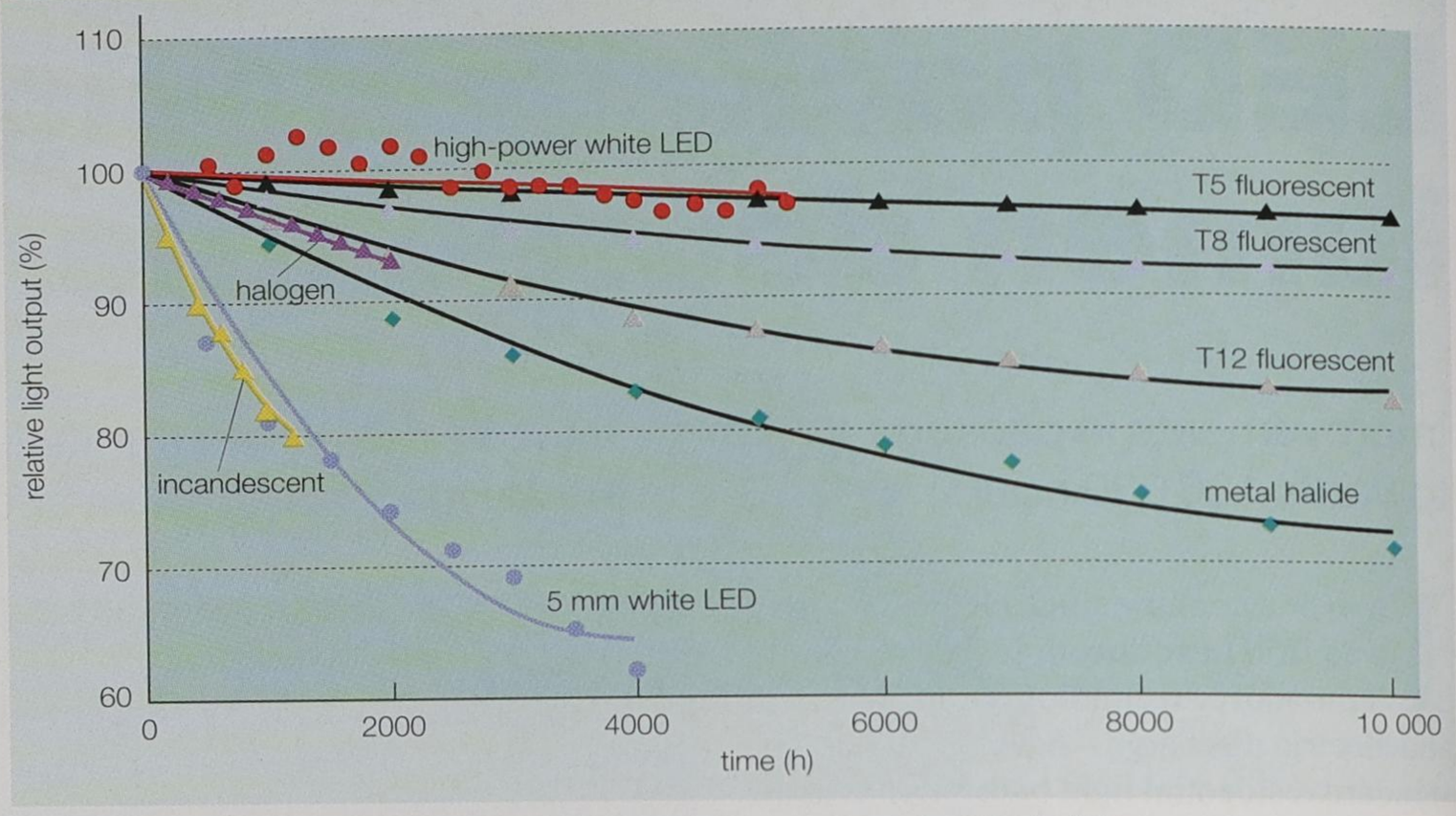


Fig. 3. A comparison of light output variation for a range of white-light sources.

high-power LEDs produce 10 to 20 times more flux per device and are more efficacious compared with the 5 mm packages. In addition, a recent publication has shown that the lumen depreciation of the new high-power white LED is reduced considerably compared with 5 mm packages (Narendran *et al.* 2001b). Some manufacturers appear to have solved lumen depreciation issues by properly extracting the heat and by packaging the LEDs in materials that do not degrade over time.

Even traditional light sources, such as incandescent, halogen, fluorescent and metal halide lamps exhibit light output degradation over their operating life. Figure 3 shows a comparison of light output variation over time for different white-light sources. The high-power LEDs have very low light output degradation, according to the preliminary data in figure 3.

Advances in device construction, light extraction and heat sinking have enabled the development of high-power LEDs that offer improved luminous efficacy and better lumen maintenance. These advances have made white LED technology more feasible for general lighting applications. If the LED industry can sustain these development trends, solid-state lighting could have significant market penetration in the next 5 to 10 years.

The future of LEDs in lighting

With LED performance improving, solid-state lighting is attracting more attention from the lighting world. The general illumination marketplace is huge, but penetrating that marketplace will require higher value LED products. Manufacturers will have to continue working on longer-lasting white LEDs with higher efficacy, higher luminous flux and improved color properties. The Lighting Research Center is currently identifying the parameters that can be improved to provide quality lighting that is acceptable to human subjects.

Illumination using LEDs could have a significant impact on architecture and design. Imagine architects who are free to design buildings with the entire illumination system built into the walls, ceilings, and even floors. As illumination LEDs achieve very long lifetimes, the chore of changing a light bulb will be relegated to a display in a museum. New lighting products that become part of a building will require an entirely new direction for industry, and that change may not be easy. Fixtures that now hang from ceilings or on walls could disappear, although designers may find more aesthetically pleasing ways to use LED technology other than simply hiding LEDs in walls. Manufacturers, as well as designers and architects, will need to change to keep up with the rapidly evolving LED.

Further reading

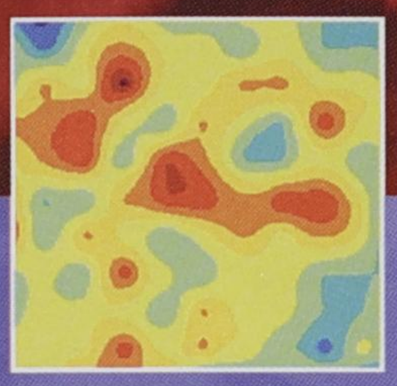
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Nadarajah Narendran and Keith Toomey work for the Lighting Research Center at Rensselaer Polytechnic Institute in Troy, NY.

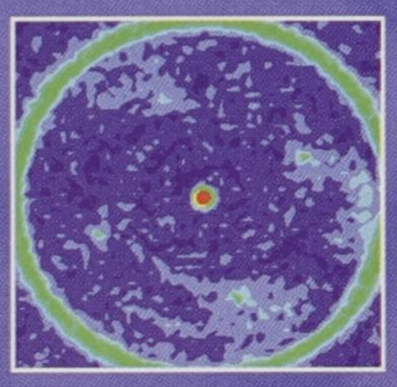
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SiGe Wafer Map; data collected on a Bede QC200™. Data courtesy of Dr Peter Zaumseil, IHP, Germany.



Texture pole figure - MnFe/Co/Cu Spin Valve Stack - taken on a Bede D1.



Rocking curve analysis of GaN (10-12) reflection taken on a Bede QC200™. Data courtesy of Dr Joong Seo Park, EpiValley, Korea.

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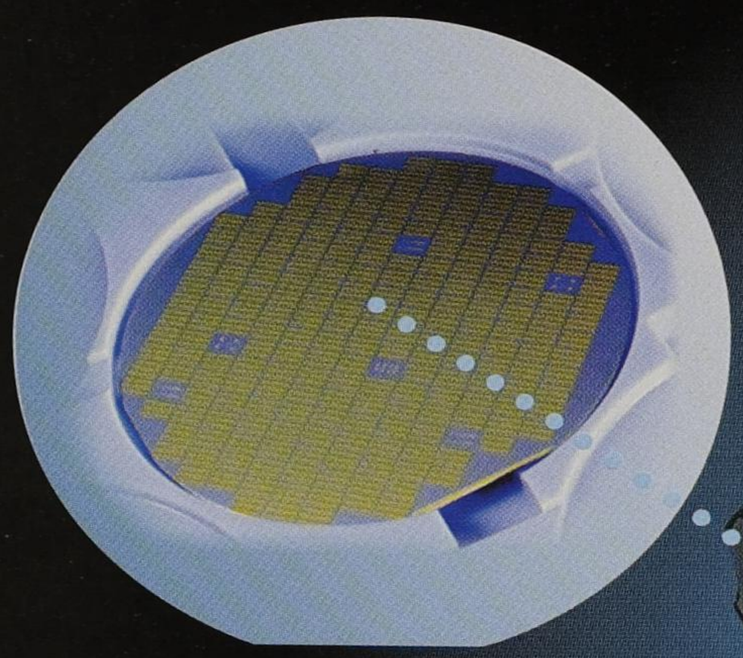
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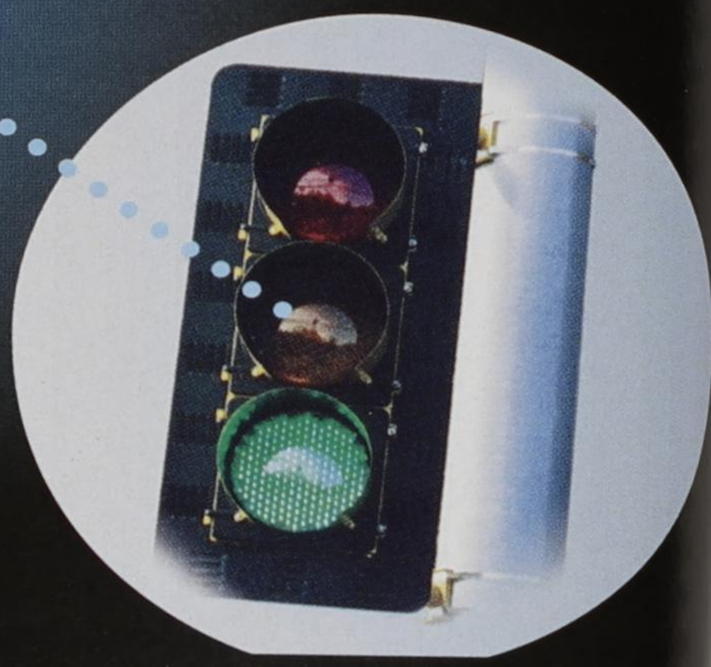




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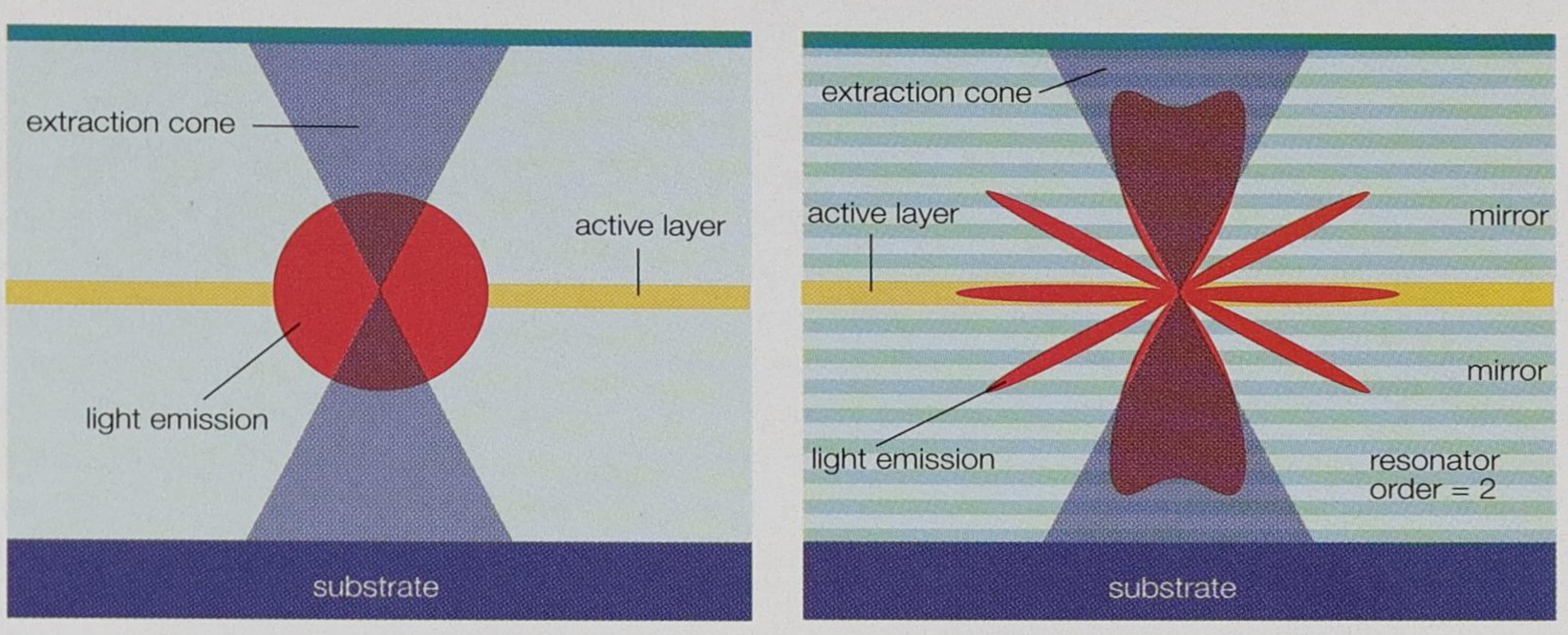


Fig. 1. In a conventional LED (left) the light emission is isotropic. Only a small percentage of the emitted light can be extracted. In an RCLED (right) the active layer and mirrors can be designed such that the light is emitted mostly inside the extraction cone.

Terms such as spectral purity, spatial coherence and high directionality are normally only used when discussing lasers. However, developments in LEDs mean this is no longer the case. A new type of opto-electronic semiconductor device is now available in large-scale production: a resonant cavity LED (RCLED) emitting red light. This LED is superior to its predecessors in luminous intensity, light purity and modulation capabilities. It is also less temperature sensitive and has a longer lifetime than competing laser light sources. RCLEDs such as those developed by Osram Opto Semiconductors are a key technology for the next generation of data communication via polymethyl methacrylate (PMMA) plastic optical fiber, which is now entering the information and entertainment or "infotainment" market in automotive and consumer applications.

The problem of internal reflection

Compared with light bulbs, where only a small percentage of the radiation is emitted as visible light, the generation of photons via the recombination of electrons and holes in semiconductors is so efficient that nearly all of the energy can be converted to light at a determined wavelength. Hence semiconductors would be ideal light sources if certain effects were eliminated. These effects can be observed from a swimming pool. If one were to look up while submerged in water, one would see the sky and clouds directly above. If the gaze were lowered, at a critical angle one would see a mirror image of the walls or bottom of the pool reflected from the water's surface. This angle of total reflection at the water–air interface is relatively large at around 40°.

Light trying to escape from a semiconductor crystal fares much worse because of the large refractive index of semiconductors. A semiconductor's angle of total reflection is typically 26°. Only about 4% of the light, which is generated isotropically, escapes. The rest is absorbed in the semiconductor crystal and converted to heat.

The resonant cavity

There are a number of successful approaches to making LEDs more efficient, such as additional lateral light extraction or internal multiple reflection on slanted surfaces. However, none of these solutions tackle the root of the problem: the isotropic spontaneous emission.

By using a resonator, a feature found in lasers, the RCLED does precisely that (figure 1). Conceptually, an RCLED consists of several regions: a high reflectivity lower mirror over the absorbing substrate; an extremely thin, one wavelength thick, light-producing layer; and a semi-transparent upper mirror through which light is extracted. (See box "How an RCLED works". A review on the RCLED principle can be found in Benisty *et al.*).

Although it seems logical to apply a mirror to the bottom of a light-producing layer in order to reflect as much light upwards as possible, it may seem somewhat paradoxical to apply a mirror on top of the light-producing layer if as much light as possible is to be extracted upwards. The trick is that the upper mirror together with the lower mirror forms a resonator. Other than in free space, the propagation of light is not possible in every direction for every wavelength in a resonator. In fact, there are directions of constructive and destructive interference, and so there are directions in which light may be emitted and others in which spontaneous emission is impossible. For a specific wavelength, the directions in which emission and propagation is possible are called resonator modes.

No problems occur with the extraction of light in semiconductor lasers because stimulated emission is used as the light-generating process. Photons of a specific mode induce emissions of other photons in the same mode. This effect is further strengthened by the number of photons already in the mode. Ideally, following a brief tuning phase, a single mode uses all the electron-hole pairs available, leaving no electron-hole pairs for the other modes. It is easy to construct a semiconductor laser in such a way that the direction of propagation of the winning mode is perpendicular to the semiconductor–air interface. Thus the problem of light extraction is solved.

In an LED, where spontaneous emission is used for light generation (i.e. the emission is not dependent on a photon field), a photon can only be emitted in an available mode, not in a direction of destructive interference. The modes and the spontaneous emission need to be tailored so that as many photons as

How an RCLED works

A typical RCLED consists of two distributed Bragg reflectors (DBRs), made of a semiconductor material, which form a resonator. An active layer is located between the mirrors and includes quantum wells a few nanometers thick for light generation. If the thickness of the active layer between the mirrors is an integer multiple of half the wavelength of the light, then the condition for vertical resonance is fulfilled. But there are also resonances at off-axis angles, and the more half wavelengths that fit between the mirrors (i.e. the higher the order of the resonator) the more off-axis resonances will be observed. The off-axis resonances are, however, outside of the extraction cone, which is defined by the angle of total internal reflection. Light in these resonances is absorbed not emitted. Since the same amount of light is emitted in every resonance, the cavity order has to be as low as possible (Schubert *et al.*). The penetration depth of the light in the DBR contributes to the effective resonator length. Even if the active layer is only about the size of a wavelength, the arrangement still amounts to a multiple of half wavelengths. But there are two tricks to increase the extraction efficiency.

The first is to adjust the sharpness of the resonance (i.e. the quality factor of the resonator) by tuning the reflectivity of the DBRs. The reflectivity of the bottom mirror is made as high as possible. The reflectivity of the top mirror is adjusted to reduce the emission angle of the forward-directed resonance to make it fit in the escape cone completely.

The other trick is to mistune the resonance wavelength relative to the quantum-well emission towards longer wavelengths. This is called detuning, and because of this the rays in resonance are not exactly perpendicular to the layers, but slightly slanted, though they are still inside the extraction cone (figure 2). This is how an RCLED's characteristic "rabbit ears" in the far field intensity come into being. The advantage is the larger solid angle element of the rays lying in the escape cone.

So far the quantum-well emission has been assumed to be monochromatic. In reality, the emission spectrum of the wells is about 16 nm wide. As the resonance conditions of the different wavelengths are fulfilled for different propagation angles, the shortwave part of the spectrum is seen under the larger off-axis angles, whereas the longer wavelengths are directed more to the front. Depending on the solid angle element, which may be coupled into a fiber, the emitted light has a higher spectral purity than a conventional LED. This effect underlines the wave-optical nature of the component.

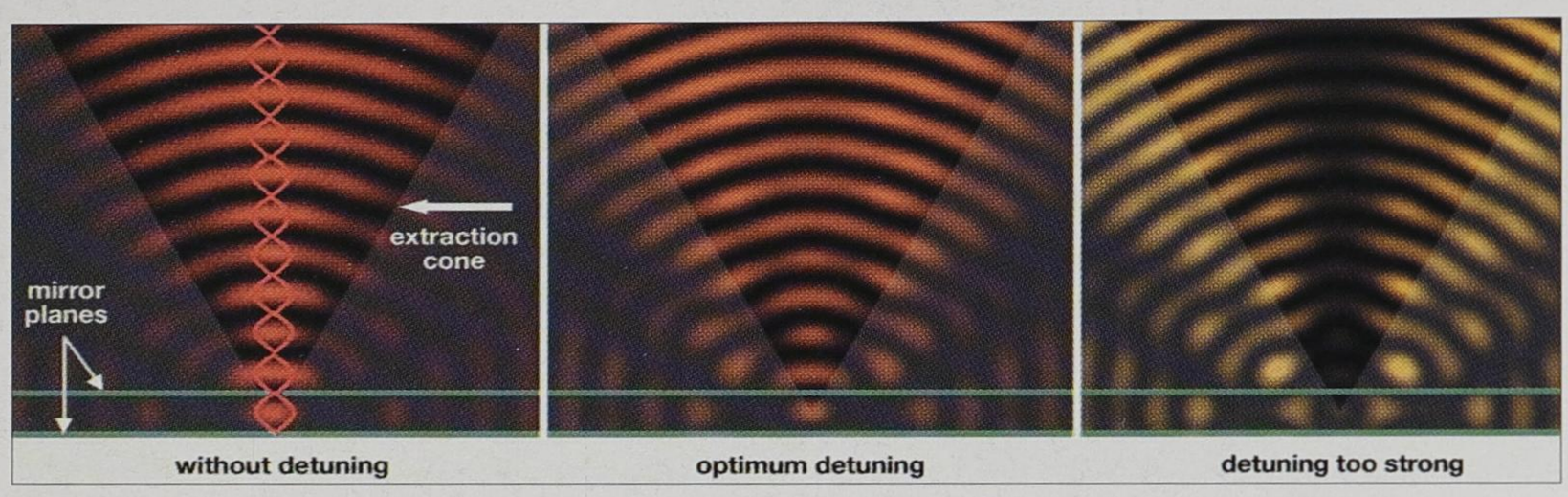


Fig. 2. A schematic of the wavefield for a point light source in a resonator. Optimal detuning occurs when the wavelength of the quantum-well emission is slightly shorter than the vertical resonance wavelength. Under these conditions, light extraction is maximized.

possible are emitted in the light extraction cone defined by the angle of total reflection.

The actual light generation in an RCLED occurs in quantum wells just a few nanometers thick, which are positioned at a maximum of the cavity standing wave pattern. This not only increases the extraction efficiency, but also enhances the directionality of the emitted light when the resonator is designed appropriately (see box "Growing an RCLED structure"). The current world record for RCLED efficiency in the visible wavelength region is 12% and is held by our team at Osram Opto Semiconductors (Wirth *et al.*).

Applications for RCLEDs

Of course, an RCLED can be used in any arbitrary LED application, but a surface emitter with forward-directed radiation displays its strength in applications that require a lot of light inside a small solid angle, such as photo sensors or scanners. The integration of many small RCLEDs on a chip makes it possible to establish a "lightcomb", which is needed for LED printers and allows for a much larger page throughput than provided by laser printers.

However, the RCLED will find its first high-volume application as an emitter for data transfer through plastic optical fiber (POF). A POF system comprises emitters, drivers, fibers and detectors. Plastic step-index fibers of 1 mm diameter are the fibers of choice for low-cost networks in consumer markets. They offer a local absorption minimum at 650 nm. The absolute absorption minimum is located in the green and yellow spectral range where the detector is less sensitive. The 650 nm regime has so far offered the best compromise between detector sensitivity and absorption by the fiber.

Due to their large core diameter, typically 0.5–1 mm, POFs place fewer demands on the tolerance of the fiber-optic connector. For good coupling of the light in glass fibers with a diameter of 0.005–0.05 mm, the semiconductor laser in question must be positioned within a few microns of the front of the fiber.

RCLEDs in the automotive industry

The comparatively low cost and robustness of POF systems has already initiated some applications in the automotive sector. Several companies have jointly developed a new data bus standard – the media oriented system transport (MOST) – specifically for the infotainment network inside the car. While copper cables can meet the 22.5 Mbit/s requirements of the MOST data bus, there are still advantages to using POFs, such as low weight and resistance to electromagnetic interference.

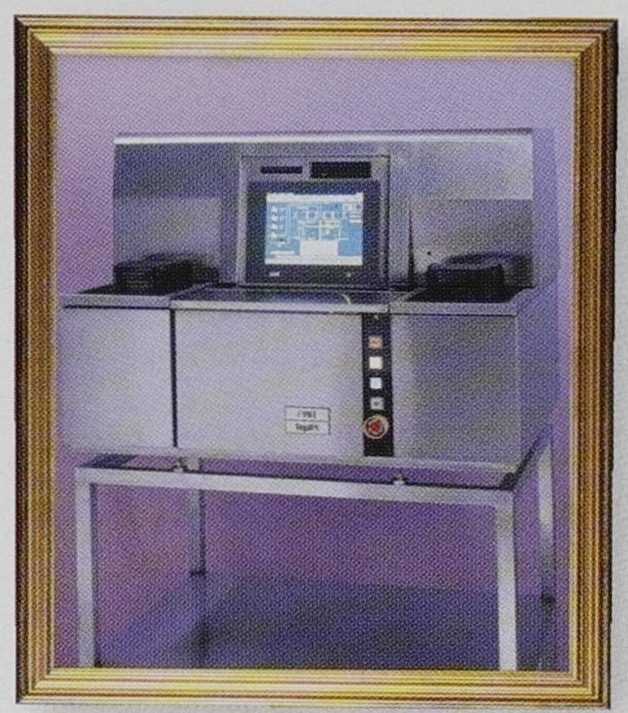
Nevertheless an increasing number of functions inside the car require higher and higher bandwidths. One example is the introduction of real-time video processing systems which are expected to be available by about 2005. RCLEDs can provide a system with the required data rate of up to 500 Mbit/s. Forecasts predict that in 2006 nearly 50 million meters of fiber will be installed in cars (Zeeb *et al.*).



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Growing an RCLED structure

The structure and performance characteristics of Osram's 650 nm RCLED were described in a recent paper (Wirth *et al.*). The structure was grown by MOVPE on a 4 inch GaAs substrate. After depositing a GaAs buffer layer, the bottom n-mirror, which consisted of 34 repeats of $Al_{0.5}Ga_{0.5}As$/$Al_{0.95}Ga_{0.05}As$, was grown. The active region contained five compressively strained 5 nm thick quantum wells separated by AlGaInP barriers. $Al_{0.51}In_{0.51}P$ confinement layers were used to maximize the p-barrier height for electrons. The total thickness of the active region was approximately 200 nm. A top p-mirror was grown, followed by a highly doped 10 nm GaAs contact layer.

For epoxy-encapsulated 300 x 300 µm devices, a maximum wall-plug efficiency of 10.2% was reported at a maximum output power of 12.2 mW at 100 mA. Smaller 80 µm diameter devices gave a wall-plug efficiency of 9.5% and yielded 2.9 mW at 20 mA. Large-area devices with 700 x 700 µm chip size gave 12% efficiency at 20 mA.

RCLEDs challenge lasers

But why should an RCLED be ideal for these applications? Conventional LEDs, edge-emitting lasers and VCSELs can all provide emission at 650 nm. LEDs have poor coupling efficiency and slower modulation speeds than RCLEDs. The high coupling efficiency of an RCLED allows devices with a smaller active area to be used – a typical RCLED chip design has an active area only 80 µm in diameter. Since the rate of spontaneous emission rises with increasing carrier density in the active area, an RCLED is much faster than a traditional LED, enabling 500 Mbit/s operation.

While lasers are capable of such speeds, the mode dispersion for cost-effective commercially-available POFs limits bandwidth to around 500 Mbit/s. Relatively high cost makes the use of edge-emitting lasers undesirable. VCSELs, which have become increasingly important in infrared glass fiber communication, can operate at 650 nm, but fail as their temperature reaches about 50 °C. Systems using VCSELs in hot environments would be unreliable, and cooling adds considerably to the production and running costs. Also, reaching a lifetime of more than 10 000 hours currently constitutes a great challenge for red VCSELs, but for RCLEDs lifetimes are now estimated to be 30 000 hours.

POF network applications

POF networks seem very promising, not only for automotive applications, but also for intra-building multimedia applications. This is because of low costs, robust optical transmission, and easy installation and handling compared with glass fibers. Applications can be broken down into two types: narrow-band services like phone or home automation, and broad-band services based on the POF IEEE1394b standard, known as "Firewire" or "i-link". This covers applications such as digital TV, PCs, DVD and the Internet (Schunk *et al.*).

The home-networking market will initially emerge in Japan where many of the POF manufacturing companies are located. This has led to a high level of acceptance of plastic fibers at the expense of copper cables. There are offices and hospitals in Japan which have already installed POF for their in-house networks.

The IEEE1394b standard for long distances will need a high-speed emitter. The RCLEDs developed at Osram surpass usual LEDs in speed and will be an essential element in the high-speed systems of the future.

The Osram RCLED provides world-record efficiency, low voltage, long lifetime and minimized burn-in effects. Currently there are two chip types: one optimized for high-speed POF applications, and another designed for applications such as scanners, optical mice and indicators. In the next few years, the RCLED will become more important among optoelectronic chips, since it combines the advantages of both the LED and the laser.

Further reading

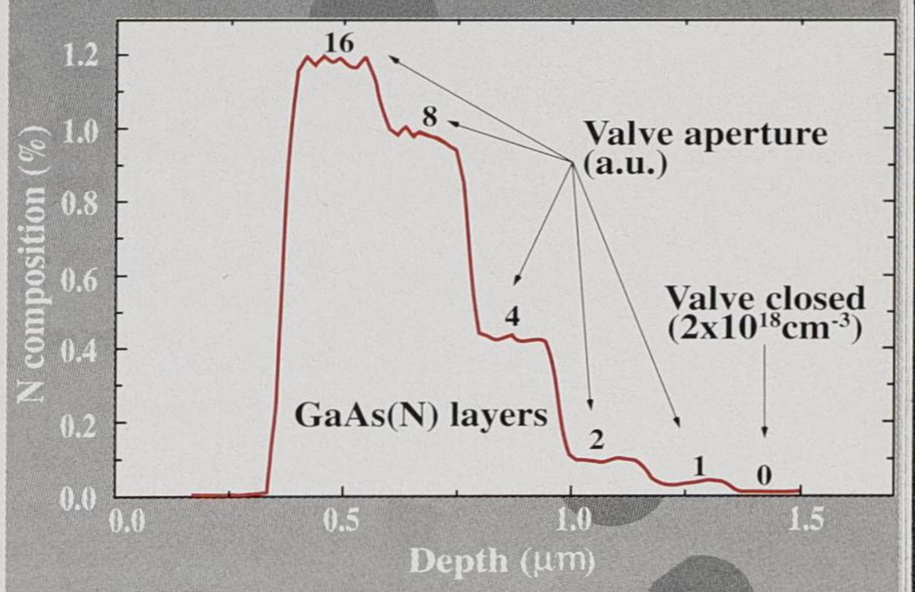
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Ralph Wirth, Wolfgang Huber, Christian Karnutsch and Klaus Streubel are with Osram Opto Semiconductors, Regensburg, Germany. E-mail ralph.wirth@osram-os.com.

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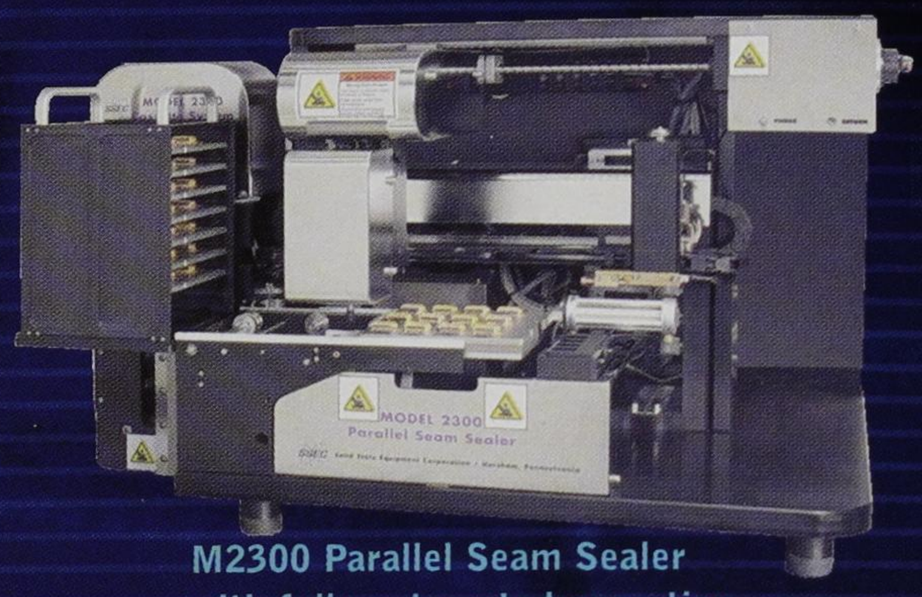
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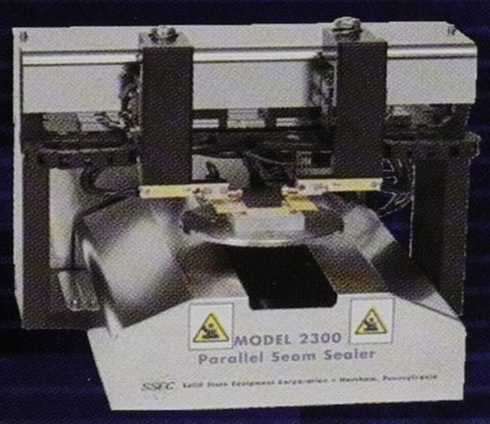


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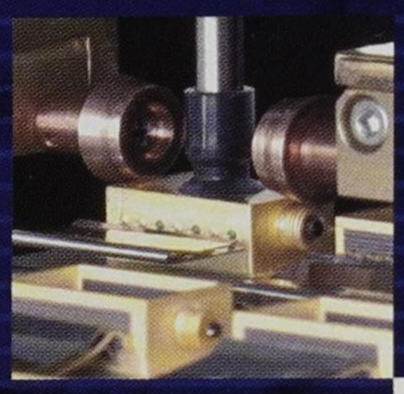


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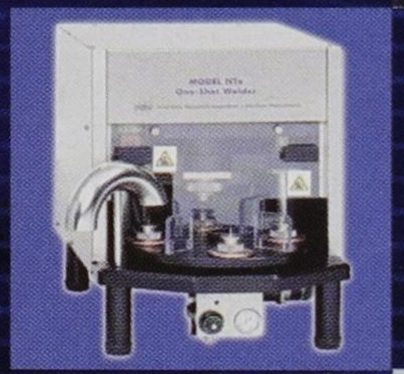
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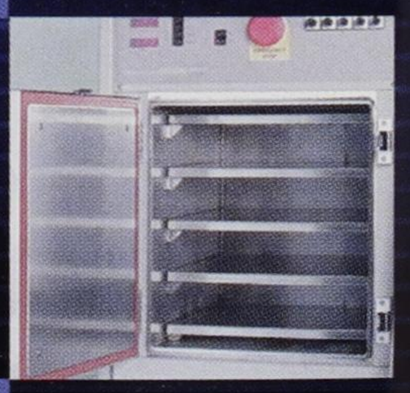
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Interface abruptness controls telecom laser performance

In MOCVD-grown long-wavelength lasers, the abruptness of the interfaces in the MQW region has a strong influence on performance, according to **Sherman Li and colleagues** from Emcore.

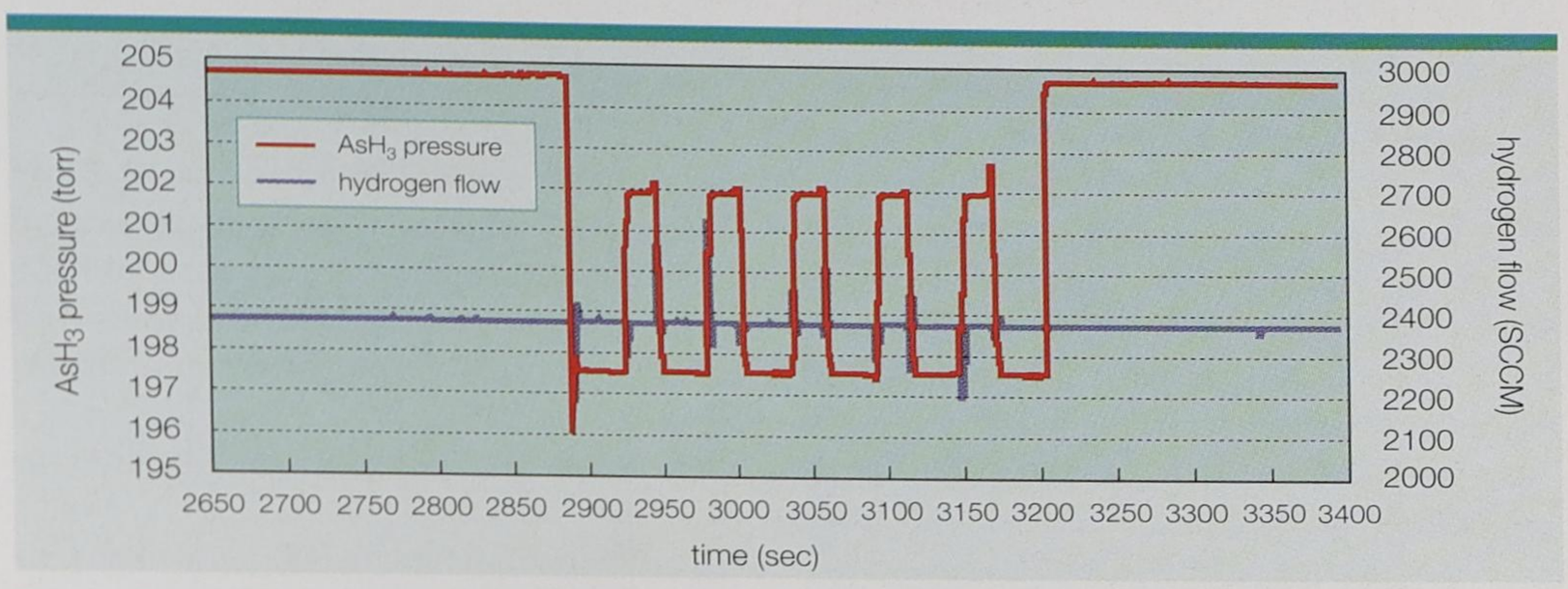


Fig. 1. Gas switch characteristics in a vertical rotating disk MOCVD reactor. The square wave indicates abrupt hydride gas switching between well and barrier layers during the growth of a 1550 nm InGaAsP laser with five quantum wells.

The optical communications market currently consumes a large quantity of long-wavelength semiconductor lasers operating at wavelengths of 1310 and 1550 nm. While just about anyone in the compound semiconductor industry is capable of growing lasers, the performance of the laser is distinguishable by the ability to control the interface abruptness during epitaxial growth. For heterogeneous semiconductor structures it has been said that "the interface is the device" (Kroemer). It is also well known that the power output, threshold current, and lifetime of solid-state lasers are strongly affected by the active region interface abruptness between the quantum well and the barrier. Therefore, a device with a more abrupt interface will demonstrate better performance.

The major factor controlling the interface abruptness during MOCVD epitaxial growth is the rapid, controlled switching of chemicals at the injector block, in the gas inlet and on the wafer surface. It is critical for MOCVD tool manufacturers to design their systems for effective gas switching. This is especially important for MOCVD tools used to grow InGaAsP/InP lasers, where typically a large quantity of AsH_3 is switched, resulting in a change of the flow compositions from the barrier to the well materials.

Controlling the interface

The first factor in controlling the interface is the physical switch of precursor chemicals at the injector block. Most commercial MOCVD systems can achieve rapid reactant gas switches using different mechanisms. When large gas volumes are being switched, an additional flow of hydrogen, sometimes referred to as a "phantom flow", is switched in opposition to aid the gas switch and minimize the pressure fluctuation in the injector block. A perfectly tuned switch will exhibit a square wave flow through the remote pressure transducer as precursors are switched from barrier to well compositions, as shown in figure 1. Some MOCVD systems use hydrogen push flow to replace the switched gas volume during switches, which may not result in an abrupt physical gas switch because the density and the viscosity of each gas is different. The physical switch of different precursors in gas phases is much more complicated than a simple volume replacement.

MOCVD growth conditions

condition	*growth chamber pressure (torr)*	*disk rotation speed (rpm)*	*momentum boundary-layer thickness (cm)*
a	50	800	2.196
b	70	800	1.856
c	60	1200	1.637
d	70	1400	1.403

Table 1. The relationship between momentum boundary-layer thickness and growth conditions in an InGaAsP material growth tool. Increasing the growth chamber pressure or the rotation speed reduces the boundary-layer thickness.

The second important factor in growing high-performance lasers is to maintain the abrupt gas-phase interface during the gas transfer from the injector block to the wafer surface. A well-established flow pattern prevents the hydride and alkyl gas streams from mixing after they are injected into the reaction chamber. A good flow pattern also maintains the abrupt interface of the gas phase as the precursors approach the wafer surface. The mechanism by which good flow patterns are achieved is inherent in the design of vertical rotating disk reactors capable of high rotation speeds, which is well documented (Breiland, Li). If a reactor flow pattern includes recirculation, then the abrupt gas-phase interface will not be maintained. It is therefore crucial to have a well-established laminar flow pattern.

The final and most important factor in creating abrupt interfaces is the reaction in the gas–solid boundary layer, near the wafer surface. The momentum boundary layer in a vertical rotating disk reactor is defined as the point where the gas velocity transitions from axial velocity to radial and tangential velocities. The boundary-layer thickness is defined as the distance between the boundary layer and the wafer surface. Each precursor has a unique viscosity, thermal conductivity and bonding energy, and so the boundary-layer thickness for each precursor is different. The key to growing abrupt interfaces in the solid phase is for all reactant species transported across the boundary layer to arrive at the surface of the wafer simultaneously. In this way, the abrupt gas-phase interface will be incor-

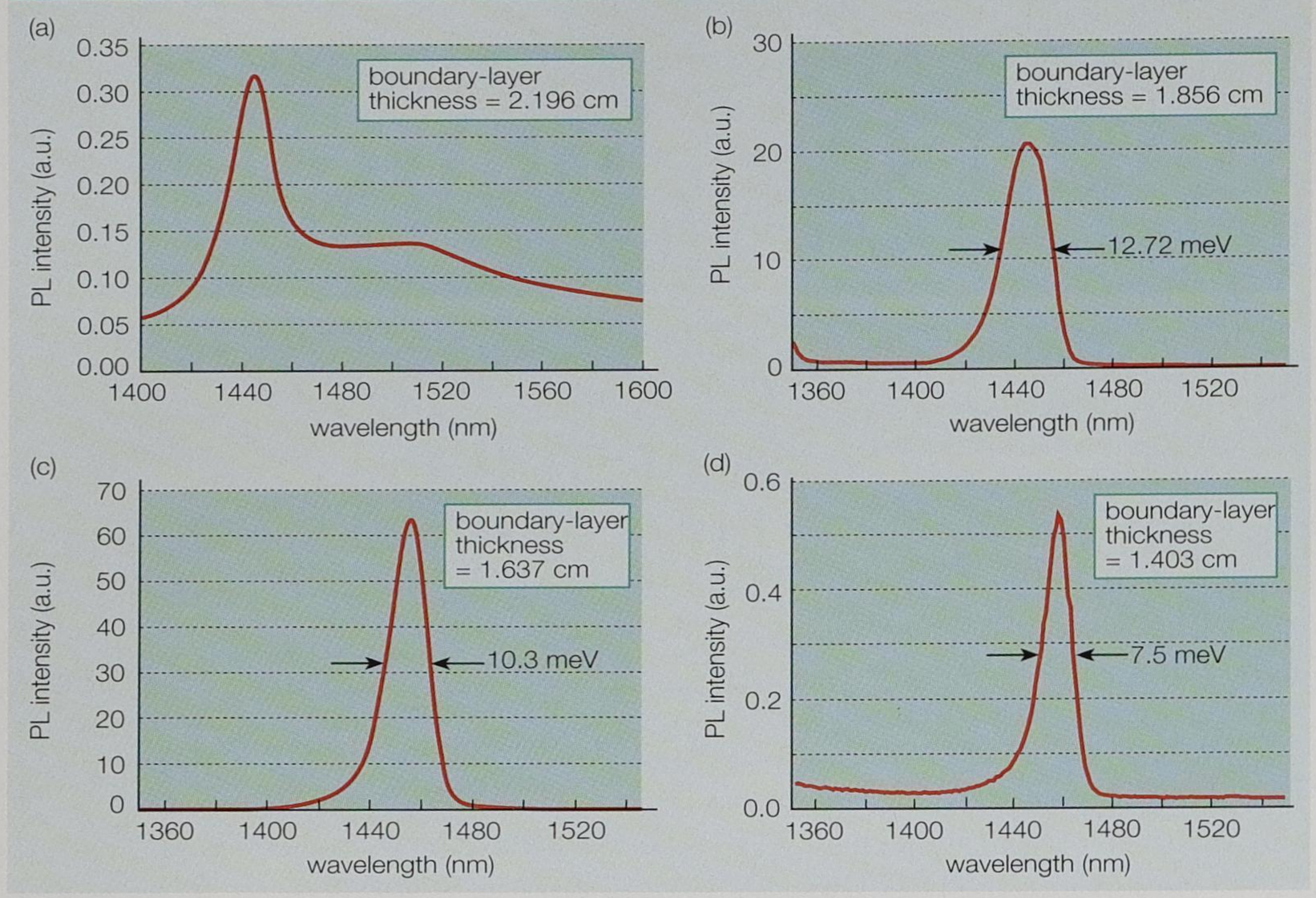


Fig. 2. PL spectra of 1550 nm InGaAsP laser structures recorded at 77 K (the low temperature blue-shifts the PL wavelength). Letters a to d refer to the different growth conditions shown in table 1. Peak (d), corresponding to the smallest momentum boundary-layer thickness, shows the narrowest PL spectrum.

porated as an abrupt solid-phase interface. The boundary-layer thickness of a rotating disk reactor can be changed by altering the growth conditions, as shown in table 1.

The effect of boundary-layer thickness

A number of long-wavelength InGaAsP/InP laser structures were grown to evaluate the relationship between boundary-layer thickness and photoluminescence (PL) intensity. The active regions were composed of 15 strain-compensated quantum wells ($\lambda = 1.55$ μm for the wells, $\lambda = 1.1$ μm for the barriers) and the target wavelength of the final MQW structure was 1550 nm. The material composition was $In_{0.82}Ga_{0.18}As_{0.70}P_{0.30}$ for the wells and $In_{0.75}Ga_{0.25}As_{0.39}P_{0.61}$ for the barriers, making this a challenging structure to grow because of the large change in AsH_3 flow when switching between wells and barriers.

Structures were grown using an Emcore Discovery LDM reactor equipped with an emissivity-corrected pyrometry control system, which is referred to as RealTemp (Ramer, Hoffman). Standard MOCVD precursors of trimethylgallium, trimethylindium, arsine and phosphine were used and the growth temperature, measured at the wafer surface by RealTemp, was 650 °C. Prior to each growth, the physical switch of the hydride precursors was optimized. The interface abruptness was evaluated by the measured full width at half maximum (FWHM) of the PL peak at 77 K. The growth conditions shown in table 1 were designed to achieve a different momentum boundary-layer thickness (Breiland). The hydrogen shroud flow was also adjusted to match the pumped gas volume of the rotating disk in order to maintain a laminar flow condition and avoid recirculation and turbulence.

The 77 K PL spectra shown in figure 2 were recorded from 1550 nm laser structures grown under the conditions shown in table 1. The FWHM of the MQW emission peak decreased as the boundary-layer thickness decreased. The PL spectrum of the MQW grown with the largest boundary layer in this study, figure 2a, showed a shoulder on the right side of the main emission peak. This clearly indicated that the switching of reactants at the boundary layer was poor, resulting in a transition layer of uncontrolled composition at the interface. Reducing the boundary-layer thickness by increasing the growth chamber pressure resulted in a structure having the spectrum shown in figure 2b. Although this eliminated the long-wavelength shoulder, the FWHM of 12.7 meV was still quite large. With a further reduction in momentum boundary-layer thickness, the PL peak became narrower (figures 2c and 2d). Figure 2d was recorded from the structure grown with the smallest momentum boundary-layer thickness of 1.4 cm, and exhibited the narrowest PL FWHM for this structure at 7.5 meV. The peak intensities in figures 2 a–d can not be directly compared to evaluate the quality of the laser, because the spectra were recorded with different neutral density filters, although, in general, the narrower the PL FWHM the brighter the PL intensity.

A second MQW structure with only six wells was grown under similar conditions to those of d in table 1. This structure demonstrated a FWHM of 6.9 meV at 77 K; as shown in figure 3, which was almost as narrow as the theoretically predicted ideal interface. The energy spreading due to thermal disturbance at 77 K was approximately 6.64 meV. Assuming the thermal energy spreading was the only contributor to the PL FWHM value, the PL FWHM at 0 K for this six-period 1550 nm InGaAsP laser would be about 0.25 meV. To our knowledge, this is the best result ever reported for any type of MQW structure.

Growth interrupts

An alternative approach to improving interface abruptness is to employ growth interrupts during gas switching. In this method, the growth is intentionally stopped by diverting the metal alkyl flow from the growth chamber to the vent. The precursor flow compositions are adjusted while flowing hydrides to the growth chamber. Growth resumes when the alkyl flow is switched back into the chamber. While this method could allow the precursor compositions to be switched, it may cause the accumulation of impurities at the interfaces, which can be detrimental to device performance. Also, it may not eliminate the uncontrolled material at the interfaces due to group V exchange at the wafer surface during the growth pause.

Two structures were grown to examine the effect of growth interrupts on MQW quality, using 6 second pauses during the well and barrier switching. One was grown under the same conditions as the MQW shown in figure 2a, which had the largest boundary-layer thickness in this study. The inclusion of a growth interrupt eliminated the shoulder from the 77 K PL spectrum, which had a 15.5 meV FWHM. However, for structures grown under other conditions, the growth interrupt did not provide the narrowest FWHM or the best interface quality. A structure grown under the same conditions as the MQW shown in figure 2d,

resulted in a PL spectrum with a FWHM of 11.9 meV (compared with 7.5 meV for figure 2d). It therefore appears that the use of growth interrupts to manufacture abrupt heterostructures is not the best method for producing laser structures, and growth interrupts are not necessary in rotating disk reactors which are properly tuned for optimal switching of the challenging InGaAsP/InP material system.

Summary

Interface abruptness control in a vertical rotating disk reactor was demonstrated by the achievement of unprecedented narrow PL FWHM values at 77 K in the InGaAsP quaternary material system, by tuning the gas switching and reducing the momentum boundary-layer thickness. The ability to control the interface abruptness and adjust the boundary-layer thickness to match with the materials system is paramount to the performance of long-wavelength lasers. The vertical rotating disk reactor meets the three basic conditions which are needed for abrupt interface growth control, namely the gas physical switch at the injector block, the well-defined flow pattern that maintains the gas-phase interface abruptness, and the adjustable boundary-layer thickness. ●

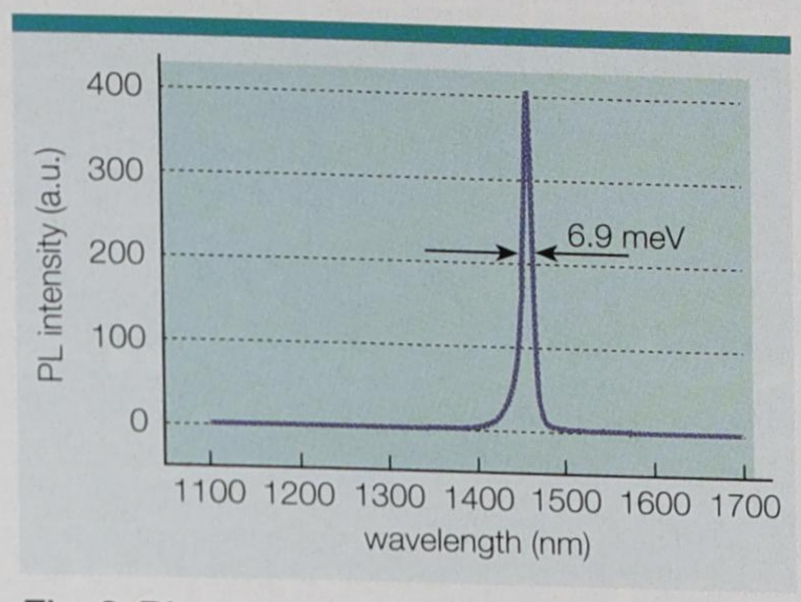


Fig. 3. PL spectrum at 77 K of a 1550 nm laser active region. The narrow FWHM of 6.9 meV shows the interface abruptness between wells and barriers. The structure is a strain-compensated six-period MQW; the 120 Å barriers (λ = 1.1 μm) have –0.4% strain and the 70 Å wells (λ = 1.55 μm) +1.0% strain.

Further reading

H Kroemer 2001 Heterostructures for everything *1st International Photonics Technology Conference* (Gwangju, Korea) 1.
W Breiland *et al.* 1998 AlGaAs OMVPE in a rotating-disk reactor: the anatomy of a VCSEL *Ann. Rev. Mater. Sci.* 1–20.
S Li *et al.* TurboDisc MOCVD theory and applications: a fluid dynamics approach *Proceedings of China–Japan Workshop on Nitride Semiconductor Materials and Devices* 115.
J Ramer *et al.* 1999 Emissivity compensated pyrometry of the substrate surface during MOVPE growth of InGaAsP/InP materials in rotating disc reactors *Proc. Fall Materials Res. Soc.* (Boston, MA) 309.
R Hoffman *et al.* 2001 InGaAsP laser structure wavelength control using *in situ* emissivity corrected pyrometry during epitaxial growth in rotating disk reactors *Japanese J. Appl. Phys.* (in press).

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Tel. +1 732 271 9090; Fax +1 732 271 9686; E-mail Sherman_Li@emcore.com.

AUCTION

By Order of Matsushita Communication Industrial UK Limited due to Relocation of Manufacturing Facility

On Tuesday 19th February 2002 at 11.00am
At Daytona Road, Thatcham, Berkshire, UK

MOBILE PHONE MANUFACTURING PLANT
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'MPAV' Quad Flat Pack Twin Head Chip Placers (2 off, 1998)
'SPPV' Screen Printers (2 off, to 1998)
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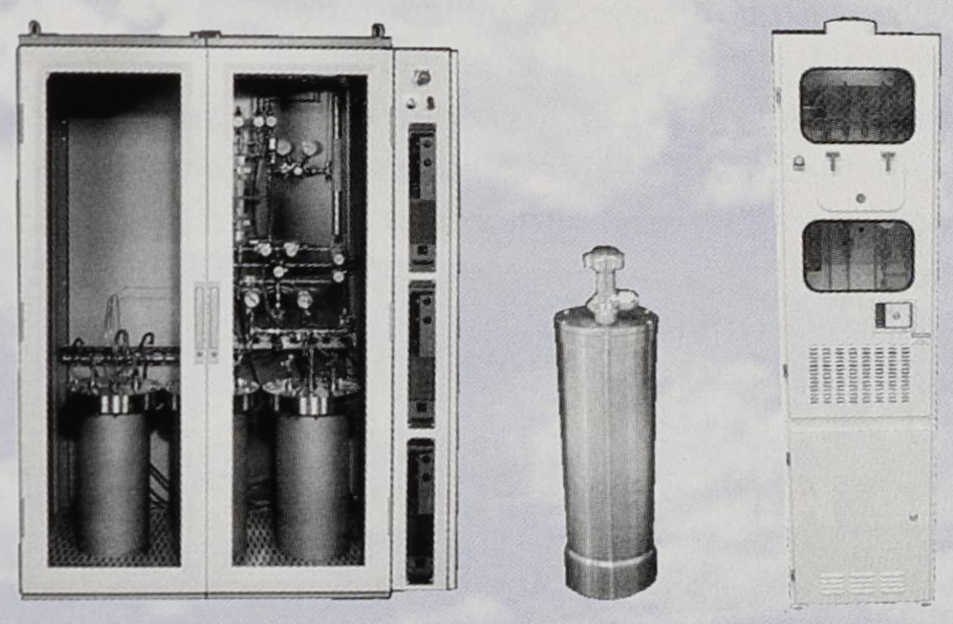
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On Site Hydride Gas Generators

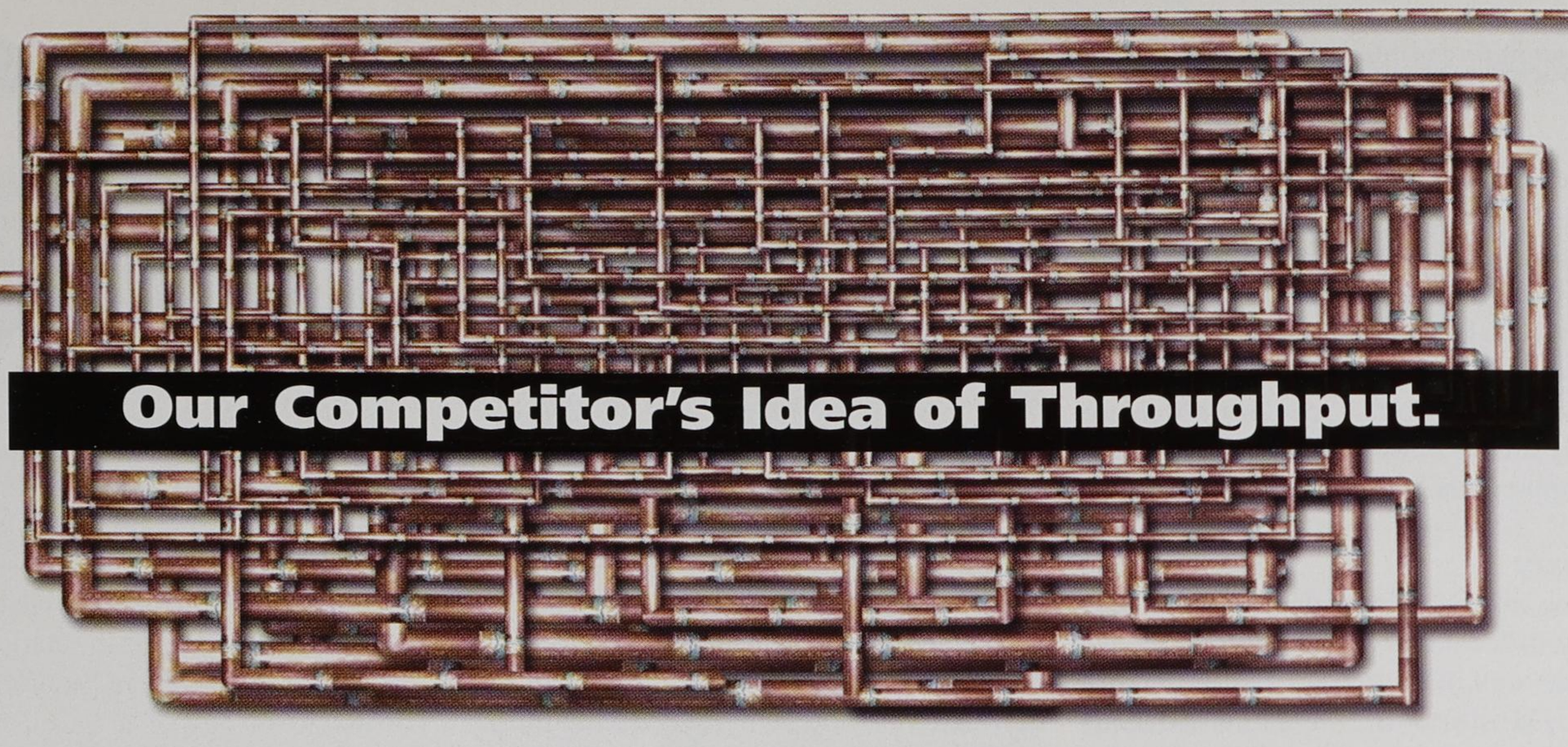
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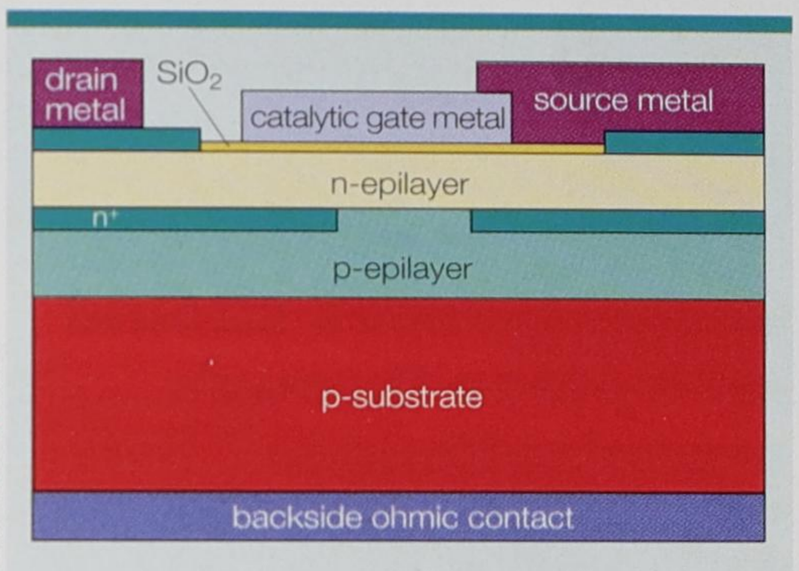
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Silicon carbide moves further towards commercialization

Speakers at ICSCRM 2001 revealed that some important milestones have been passed in the quest to develop SiC into a commercially viable electronic material, writes **Mark Johnson**.

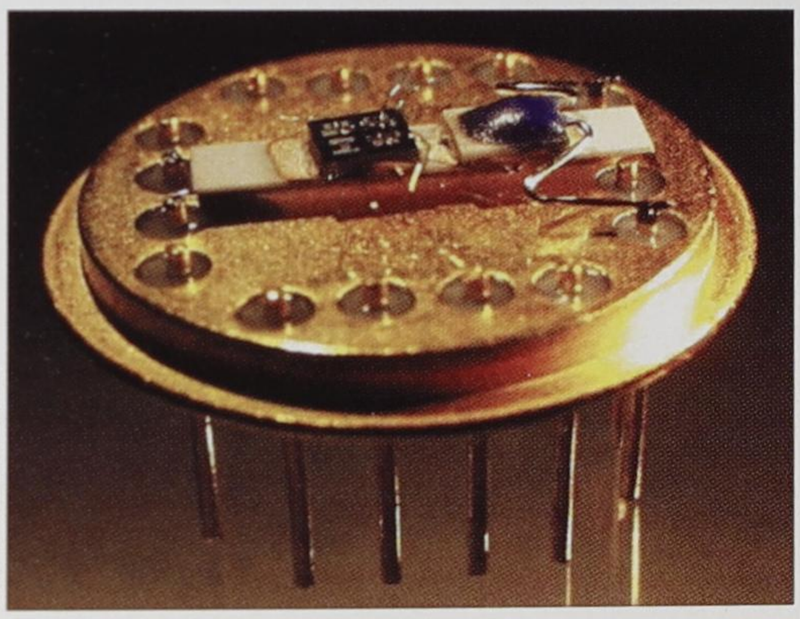
It was clear from the outset of the Ninth International Conference on SiC and Related Materials (ICSCRM 2001) that the SiC community was optimistic and in a bullish mood. Dietrich Stephani (general manager of SiCED, Germany) told the 500 delegates at the conference banquet that it was his firm belief that 2001 would be remembered as a milestone year for SiC. His opinion is based on the fact that Infineon is now selling the first commercial SiC power devices and that SiC MOSFETs are now approaching commercialization.

The conference, which was held in Ibaraki, Japan, on 28 October – 3 November, was made up of 23 technical sessions covering material growth; progress in fabrication and performance of all of the major device types; and theoretical studies. Three panel sessions gave delegates plenty of opportunity to air their views on "A roadmap for SiC technology", "What affects the performance of SiC devices?" and "Ion implantation of SiC".



LINKÖPING UNIVERSITY

Fig. 1. The structure of Linköping University's MISiCFET gas sensor.



LINKÖPING UNIVERSITY

Fig. 2. The packaged version of Linköping University's MISiCFET gas sensor.

MOSFETs

In his plenary talk, Hiroyuki Matsunami of Kyoto University emphasized the recent achievements in SiC material and device technology, before concentrating on some of the outstanding issues, in particular that of the MOS interface in 4H-SiC. The very low inversion channel mobilities that are achieved on 4H-SiC have for many years prevented the fabrication of the low-resistance MOSFETs that would be able to demonstrate the potential of SiC as a material for power devices. Indeed, the MOS interface and MOSFETs in general attracted a great deal of attention at this year's conference.

Two approaches have emerged as being effective in improving the quality of the MOS interface: the use of nitrogen during post-oxidation annealing and the use of alternative crystal faces for the formation of the MOS channel. Matsunami referred to recent work by his group and others that showed dramatic improvements in MOS channel mobility by using the $(11\bar{2}0)$ crystal face rather than the more commonly used (0001) face. Results showed a greatly reduced density of interface states, a small temperature dependence of threshold voltage and a negative power law dependence of channel mobility with temperature: $T^{-2.2}$ compared with $T^{2.6}$ for typical MOSFETs grown on the (0001) face.

Results on MOSFETs produced on the $(11\bar{2}0)$ and $(03\bar{3}8)$ crystal faces were also encouraging. Senzaki *et al.* from the Agency of Industrial Science and Technology (AIST), Japan, reported some significant improvements in the channel mobilities of MOSFETs fabricated on the $(11\bar{2}0)$ face using a hydrogen post-oxidation anneal. A peak mobility of 110 cm^2/Vs was reported for an enhancement mode device with an inversion channel. Work by Hirao *et al.* of Kyoto University focused on the $(03\bar{3}8)$ face and achieved an improvement in mobility by a factor of four, and an order of magnitude improvement in current drive capability when compared with devices fabricated on the more common (0001) face.

The highest levels of channel mobility and the highest current MOSFETs were, however, reserved for buried channel devices. Using the $(11\bar{2}0)$ face, Harada *et al.* of AIST reported MOSFETs with a peak channel mobility of 216 cm^2/Vs, while Ryu *et al.* from Cree reported a peak channel mobility of 195 cm^2/Vs for MOSFETs fabricated on the (0001) face. Cree also reported large-area (10.5 mm^2) buried channel devices capable of handling currents of up to 10 A with voltage blocking capabilities of up to 2.4 kV.

John Williams (Auburn University, AL) presented results from experiments on the passivation of the SiC-SiO_2 interface with nitric oxide, showing an order of magnitude reduction in the level of interface states and a corresponding increase in current drive capability. However, interface state densities were still two orders of magnitude higher than those that are achievable with state-of-the-art Si MOS technology. The technique has been adopted by Cree and was used to demonstrate high current (2 A) large area (2 mm^2) lateral MOSFETs with record low on-resistance. Further results from Cree have indicated that nitrous oxide was equally effective in improving the MOS interface.

JFETs and MISFETs

Of the other FET devices, JFETs were strongly represented. Peter Friedrichs of SiCED, Germany, expressed his belief that the first commercial SiC switching device would be

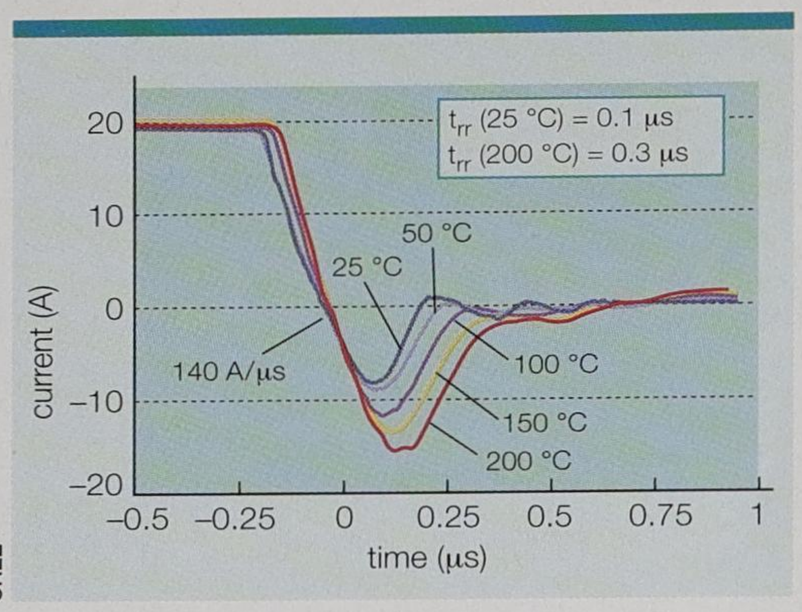
a SiC JFET cascode connected with a low-voltage Si MOSFET. The device would be targeted as a replacement for high-voltage (up to 2 kV) Si MOSFETs, which are currently employed in switched-mode power supplies and CRT deflection circuits. Claimed advantages over the Si MOSFET included an improved short-circuit capability and better dynamic characteristics. A 3 × 4.1 mm^2 1800 V SiC JFET die was presented with a current-carrying capability of 15 A at an on-state voltage of just 2 V. The technology was said to be viable at voltages of up to 4.5 kV.

Further work worthy of note came in the form of a SiC MISFET gas sensor, reported by Anita Lloyd Spetz *et al.* from Linköping University, Sweden (figures 1 and 2). As part of a collaborative effort involving Volvo, Ford and Swedish company ACREO, sensors have been made with the ability to detect hydrocarbons and ammonia. The sensors have been used in a range of environments at temperatures of up to 500 °C, and they showed excellent stability and reliability.

Stacking faults and bipolars

In his plenary presentation, Peter Bergmann from Linköping University provided an overview of a range of defects in SiC, including near-band defects, deep intrinsic defects, the influence of dislocations on lifetime and stacking faults. Since the presentation made by Heinz Lendenmann (ABB, Sweden) and his team at ECSCRM 2000, stacking faults have been attracting a great deal of interest. Lendemann's team put the degradation of the electrical characteristics of bipolar SiC devices down to these faults. Indeed, following ECSCRM 2000, it was mooted that stacking faults might prevent the realization of any long-term reliable SiC bipolar device. Such was the concern over this issue that research groups from around the world combined their efforts to understand the phenomenon better and to identify methods to reduce or eliminate these faults.

Eight papers dealing with stacking faults were presented at ICSCRM 2001. Lendenmann gave a presentation on the characteristics and reliability of high-power SiC diodes, which included time-lapse video sequences of the propagation of stacking faults through diodes under forward bias. He noted that process improvements had eliminated the worst effects of stacking fault-induced degradation – a remark supported by Cree, which had carried out some similar investigations during the past year. Bergmann had previously noted in his talk that stacking faults required a nucleation site – if the nucleation sites were removed from the material, then the problem would be solved. The longer-term goal is therefore to address this fundamental material quality issue.



CREE

Fig. 3. The temperature dependent reverse recovery (t_{rr}) measurements that were made on Cree's 10 kV SiC *pin* diode.

Standardization of SiC wafer specifications and processes should take place through organizations such as SEMI and much could be gained at this precompetitive stage by the cross-licensing of technology.

High-power bipolars

Of the bipolar devices reported at the conference, the most impressive results came from Cree, which announced 10 kV, 200 A pulsed power performance from a 3 × 3 mm 4H-SiC *pin* diode. The device had been successfully operated at temperatures of up to 200 °C and it displayed low levels of reverse recovered charge even under these conditions (figure 3).

A team from Rutgers University, NJ, and United Silicon Carbide, NJ, reported results from an all-SiC half-bridge inverter using 4H-SiC power bipolar transistors at voltages of up to 400 V and current levels of up to 22 A. The group also reported 4H-SiC junction barrier Schottky diode fabrication and characterization in an inductively loaded half-bridge inverter at power levels of up to 100 kW.

In the final session there were two papers claiming demonstrations of IMPATT diodes in SiC. Konstantin Vassilevski (Ioffe Institute, Russia, and Newcastle University, UK) described the design, fabrication and test of an IMPATT diode with oscillations in the X-band range. Predictions based on Monte Carlo simulations indicated that it may be possible to produce oscillations at frequencies approaching 450 GHz.

Implantation

The doping of SiC by ion implantation for the formation of active regions and contacts was a subject of much interest at the conference and formed a topic at one of the three evening discussion sessions. Researchers have only just begun to explore in detail the mechanisms involved in implantation and annealing, and their effects on the crystal structure and its electronic properties. Laube and Pensl from the University of Erlangen, Germany, compared the effectiveness of nitrogen and phosphorous implanted regions. Nitrogen gave lower resistivity at concentrations of less than 10^{19} cm^{-3}, while phosphorous gave lower resistivity above this concentration.

Negoro *et al.* from Kyoto University reported the results of phosphorous implantation into (0001) and (11$\bar{2}$0) oriented epilayers. On (11$\bar{2}$0) material, a sheet resistance of 27 Ω/square was achieved, representing the lowest recorded values on 4H-SiC. Schmid *et al.* from the University of Erlangen, Germany, had also carried out implantation into (0001) and (11$\bar{2}$0) oriented epilayers, discovering that (11$\bar{2}$0) epilayers give significantly higher carrier mobility at room temperature.

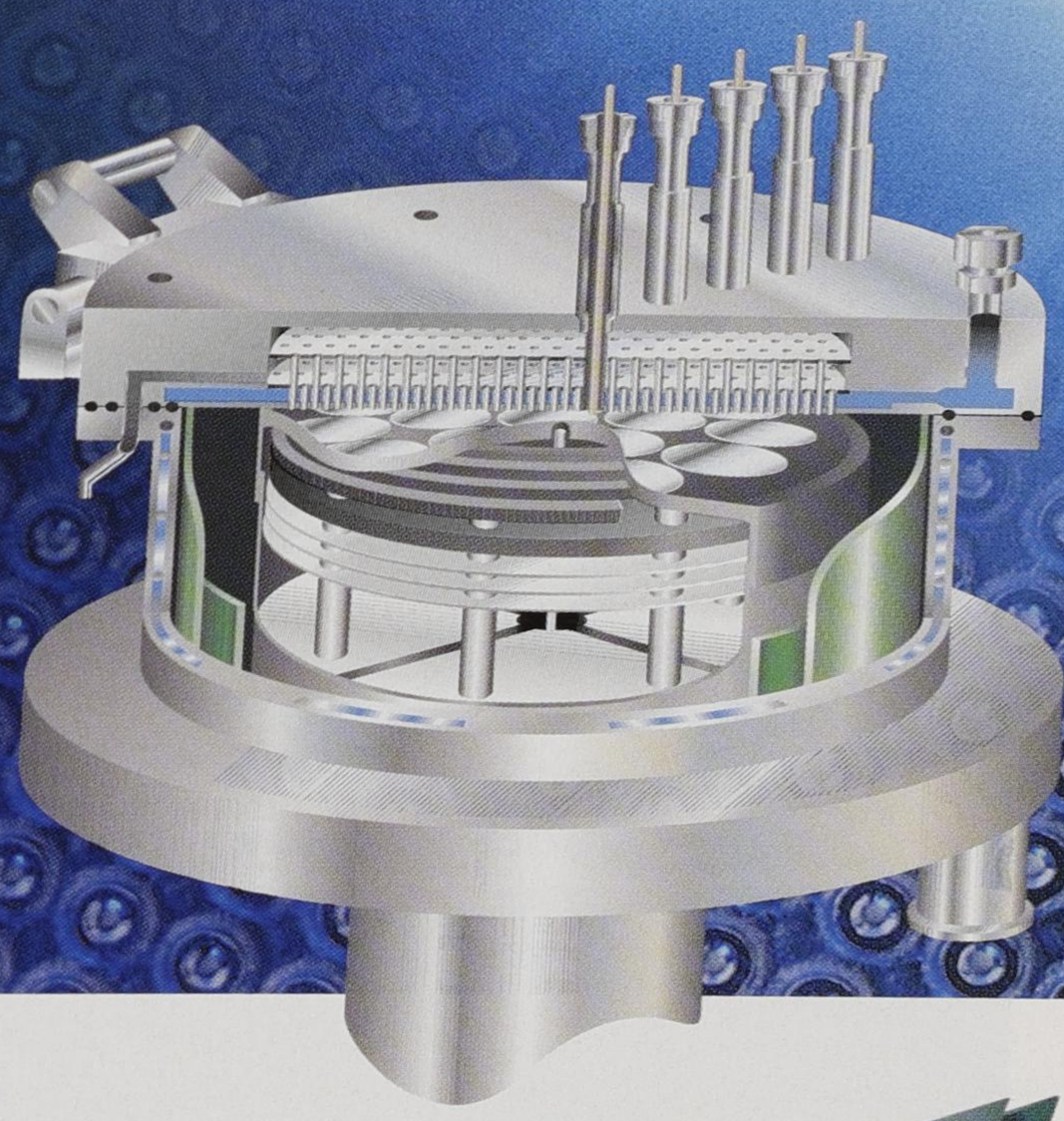
Bulk material

The increasing maturity of SiC materials technology was demonstrated by the growing number of companies in the exhibit offering SiC substrates both with and without epitaxy. While most still favored seeded sublimation growth by the physical vapor transport (PVT) method, Okmetic is now offering an alternative grown by high-temperature CVD. In a paper presented by J Bluet (LPM INSA, Lyon, France), RF MESFETs fabricated on semi-insulating CVD substrates demonstrated an improved performance when compared with those fabricated on PVT-grown substrates. Both Cree and Sterling Semiconductor reported non-vanadium-doped semi-insulating substrates that they say will alleviate the current collapse problems that are seen in RF MESFETs. Otahni *et al.* (Nippon Steel, Japan) reported the growth of (11$\bar{2}$0) oriented substrates, noting that perfect polytype control

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and zero micropipe densities were possible. There was, however, a relatively large number of stacking fault defects that were associated with the quality of the seed material. Nakayama *et al.* from SiXON, Japan, reported the growth of the first 4H-SiC (03$\bar{3}$8) oriented substrates. As with the (11$\bar{2}$0) material, micropipes were effectively eliminated from the surface of the grown wafer but there were more stacking faults.

Epitaxy

Epitaxial growth featured highly in the technical program of the conference, with no fewer than three dedicated sessions and a large number of poster presentations. Groups from the University of North Carolina and from Hoya Corporation, Japan, presented papers on the growth of 3C-SiC on Si substrates. Phil Neudeck of NASA Glenn Research Center, OH, described a "web growth" technique that allowed the termination of c-axis screw dislocations. Several papers tackled the difficult task of modeling the growth process and it was generally accepted that more work would be needed before a complete understanding of the growth kinetics was realized.

A roadmap for SiC

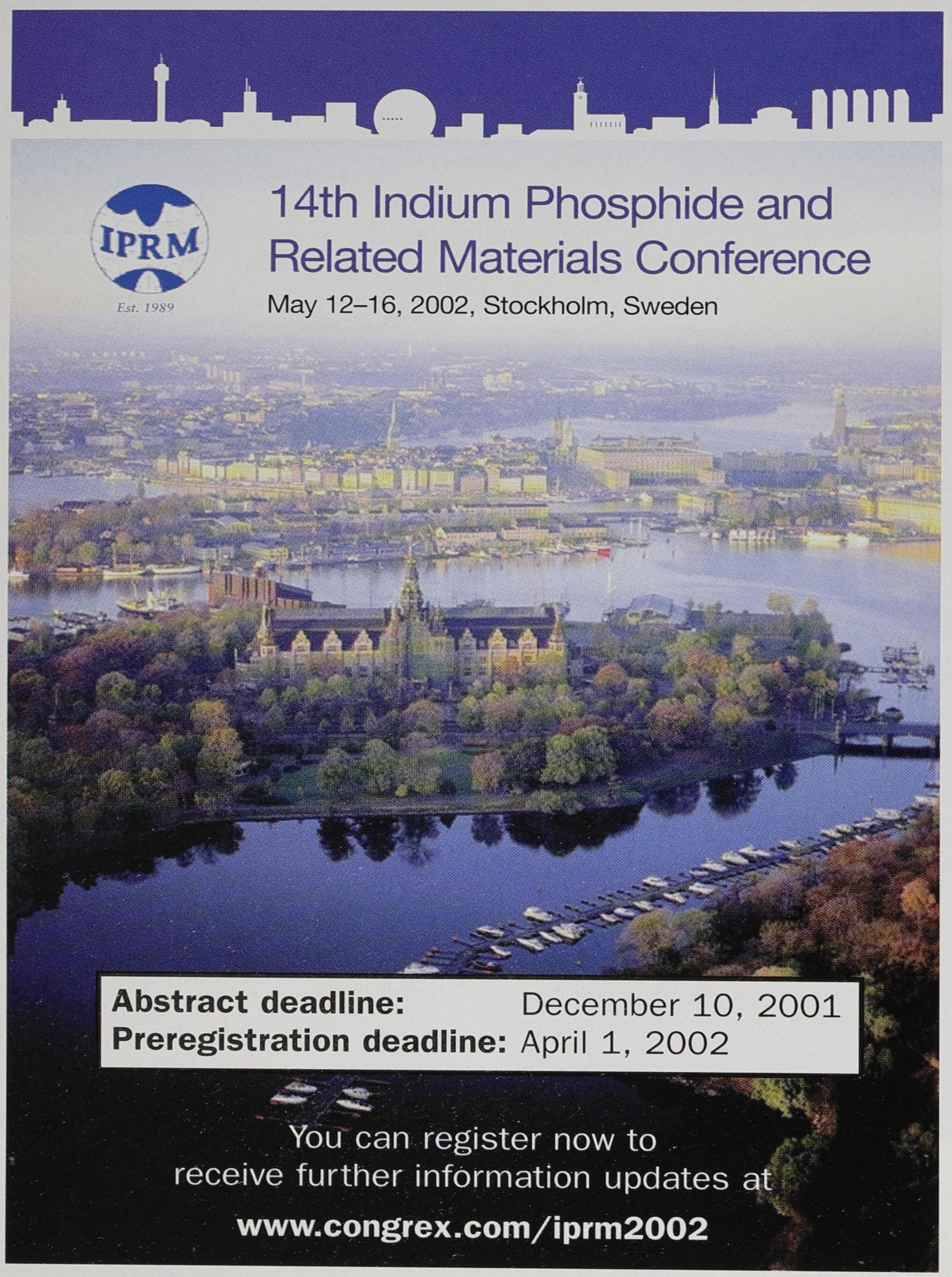
Material also formed a central theme of the discussion session dealing with a roadmap for SiC technology. The major material suppliers – Cree, Sterling, Nippon Steel, SiXON and Okmetic – made predictions concerning the availability and price of SiC substrates. These included 4 inch production wafers by 2005, moving to 6 or 8 inch wafers by 2015, depending on demand. The minimum cost of a PVT-grown substrate will be around $300, and, by 2015, micropipes will be of historical interest only. Asko Verhanen of Okmetic noted that mass-production of devices would be needed to drive up the volume and drive down the cost of SiC. He believes that the standardization of SiC wafer specifications and processes should take place through organizations such as SEMI and that much could be gained at this precompetitive stage by the cross-licensing of technology. Jan-Olov Fornell of Epigress expects epitaxial growth on 3 inch substrates to be possible by the end of 2002, and that growth on 4 inch substrates will be seen in 2005 or 2006. Much has been done to improve the homogeneity of grown layers. Thickness uniformity is now around 1% and doping uniformity, measured as (max–min)/mean, is around ±3.6%. The key issues for the future were seen as epitaxy on low off-angle substrates, higher growth rates and the control of the growth environment.

Dietrich Stephani noted that, at present, material costs represent 75% of the manufacturing cost for commercial SiC Schottky diodes. By 2003 he hopes to see a 40% reduction in material costs and larger wafers with no reduction in quality. By 2005 he expects micropipe density to be less than 3 cm^{-2}, with improvements in the uniformity of epitaxy and no increase in cost.

Further reading

The proceedings of ICSCRM 2001 will be published by Trans Tech Publications, Uetikon-Zuerich, Switzerland.

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2002 International Conference on Compound Semiconductor Manufacturing Technology

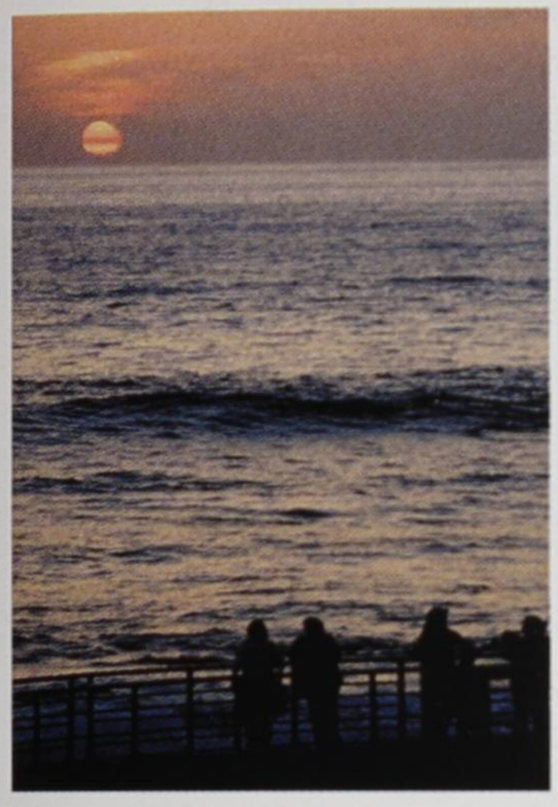
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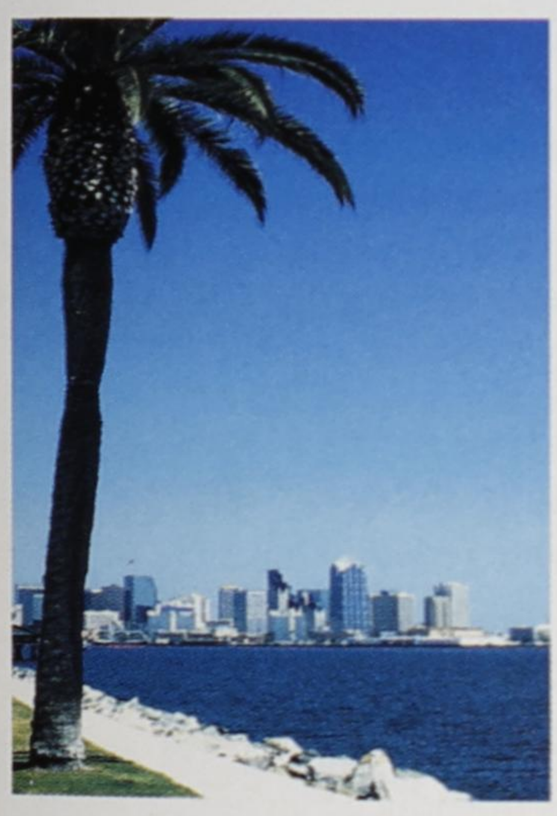
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❑ **Workshop:** To meet the rapid demand, GaAs MANTECH will again sponsor an intensive four-topic workshop led by industry experts on April 8th, the day before the main conference. Workshop topics include:

- InP Technology
- Semiconductor Band Gap Engineering
- Fundamentals and Modeling of III-V MOVPE
- Telecom Basics: The Role of Compound Semiconductors

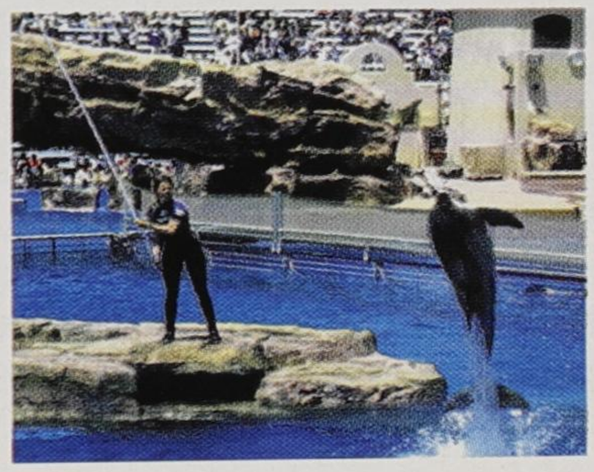
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Cascade demonstrates its vector software



WinCal 3.0 is a software suite from Cascade Microtech designed to automate the steps required for calibrating vector network analyzers (VNA), reducing calibration time and improving accuracy. Using the front panel of the VNA to perform a manual short, open, load and through calibration, the deviation from NIST benchmarks can be as much as 18% at 40 GHz, compared with 3% using the automatic calibration supplied by WinCal. Execution times for manual calibration typically take about five minutes, while the company's automated package shortens this to around 45 seconds.

Cascade's new program integrates with the company's wafer probing stations, and measures raw data and error coefficients, verifies calibration integrity and stores error terms. The intention is that it will also support the VNA instruments supplied by Agilent and Anritsu.

Contact Ellen Payne, Cascade Microtech, 2430 NW 206 Avenue, Beaverton, OR 97006, USA
Tel. +1 503 601 1181
Fax +1 503 601 1002
E-mail ellen_payne@cmicro.com

Exsil extends wafer restoration to GaAs

Exsil has extended its silicon wafer reclaim processes to include dedicated lines for reclaiming 4 and 6 inch GaAs wafers. Exsil believes the wafer shortages and price increases previously associated with silicon substrates are likely to exist with GaAs in the future. With prime 6 inch GaAs wafers currently costing $350–450 each, and mechanical grade wafers $175–250, the company says a restored GaAs wafer will offer an economical solution at $85–100.

Exsil provides reclaimed 425 and 550 μm thick GaAs substrates with 4 and 6 inch diameters, respectively. On the front side, the substrates contain no orange-peel effect, dimples, haze or chips, and are specified for a maximum of three scratches. Also, both sizes of wafer contain only 100 low light point defects at 0.3 μm.

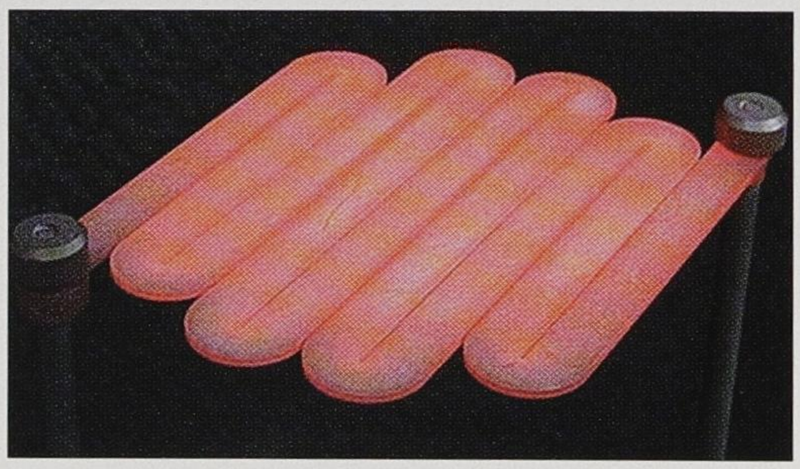
Contact Harald Mynster, Exsil Inc, 6541 Via Del Oro, San Jose, CA 95119, USA
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Fax +1 408 629 3168
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Morgan AC launches new SiC heaters



Morgan Advanced Ceramics is a supplier of ceramics to the medical, telecommunications, semiconductor and aerospace markets. The company's new SiC heater is designed for semiconductor and electronics processing chambers where rapid heating to a very high temperature with low contamination is a requirement.

Fabricated from high-purity CVD-grown SiC, the company's heaters feature a high thermal conductivity and thermal shock resistance. In addition, the new heaters offer a low outgas rate and thermal mass, and have a low contact resistance to electrodes and uniform electrical resistivity of 0.010 Ω cm.

Contact Morgan Advanced Ceramics, Bewdley Road, Stourport, Worcestershire, DY13 8QR, UK
Tel. +44 1299 872 210
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E-mail info@mac-sales.co.uk

On-site treatment of hydride waste

On-site treatment of arsenic and phosphorus liquid-waste streams is now possible with the Excalibur waste-treatment plant. According to manufacturer IEM Technologies, the treatment of exhaust hydride gases offers financial, safety and environmental advantages compared with current practices such as disposal at a licensed facility or long-term storage.

Excalibur's treatment allows the waste stream's arsenic and gallium content to be reclaimed by further processing. The new systems are designed to handle up to 600 liters of liquid effluent in a 24 hour period. Operation of the system is automated, but a manual version is available.

Contact Peter Vernon, IEM Technologies Ltd, Colley Lane Industrial Estate, Bridgwater, Somerset TA6 5JJ, UK
Tel. +44 01278 420 555
Fax +44 01278 420 666
E-mail IEMuk1@aol.com

Sensor cuts the cost of optical testing

Agilent has introduced an optical power head and sensor that enables optical component designers and manufacturers to measure optical power levels up to +37 dBm. The aim is to aid the optical R&D and component manufacturing industries in order to significantly reduce the cost of testing operations.

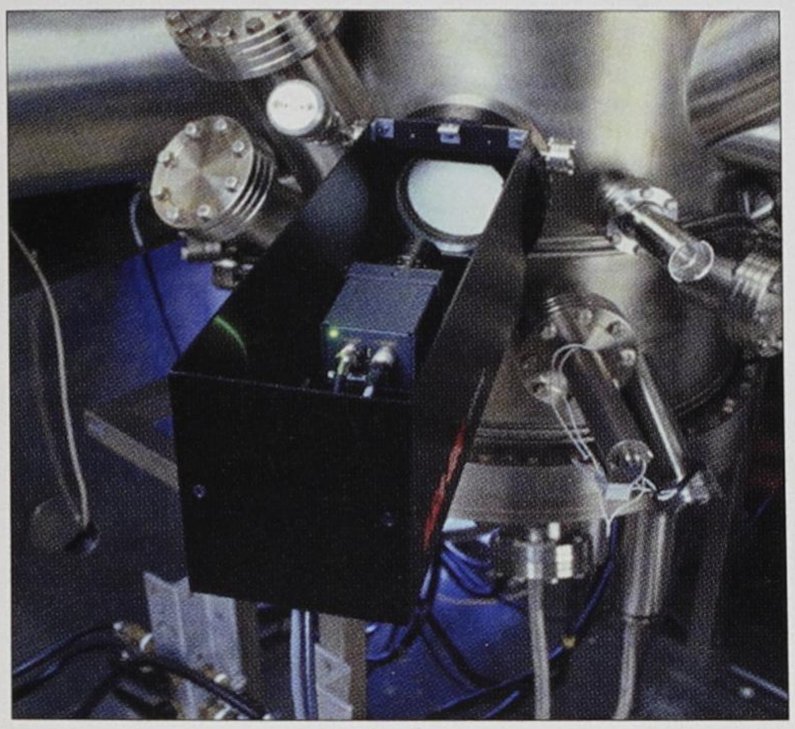
The 81628B high-power optical head also enables fully traceable measurements within a wavelength, ranging from 800 to

1700 nm. The company has also introduced a second sensor that allows measurements up to 28 dBm with a wavelength range of 970 to 1650 nm. The 81630B unit provides low polarization-dependent loss values and is optimized to reduce testing time.

Contact Sales, USA region
Tel. +1 800 452 4844
Web www.agilent.com/comms/comp-test

High-speed RHEED camera from kSA

k-Space Associates has introduced a RHEED analytical camera with a 10 bit acquisition capability and 100 fps scan rate. The kSA 400 determines growth rate in

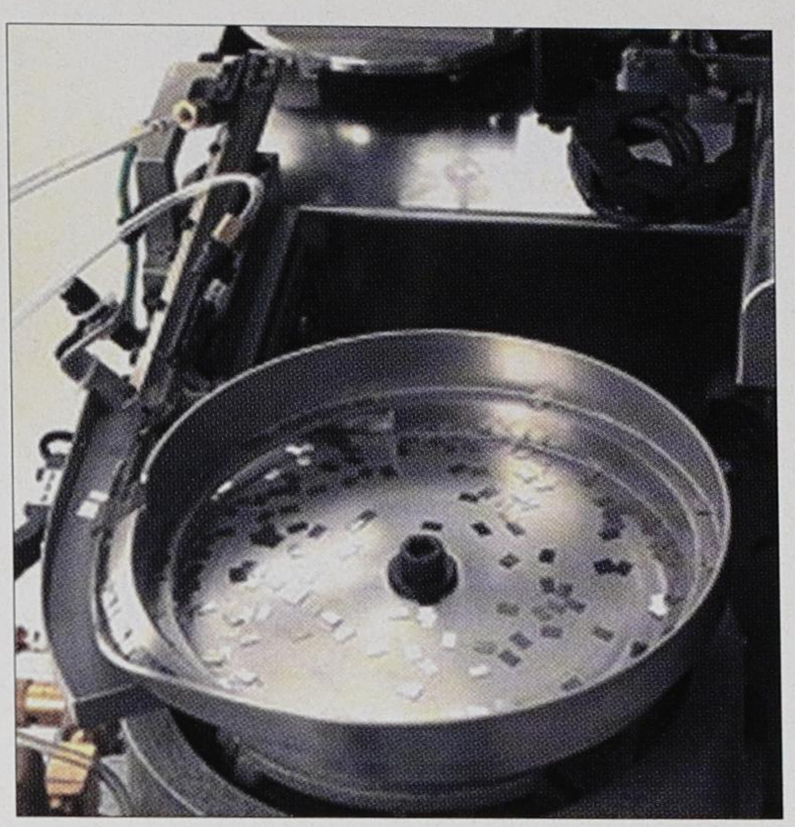


reactors, and analyzes features such as time-evolving lattice spacing, strain and reconstruction. The camera has 659 × 494 pixels and 56 dB signal/noise ratio.

Contact Sales, k-Space Associates, 3626 West Liberty Road, Ann Arbor, MI 48103, USA
Tel. + 1 734 668 4644
Fax +1 734 668 4643
Web www.k-space.com

SSEC designs ceramic package sealer

The new high-speed sealing system from Solid State Equipment Corporation automates the closing of small ceramic packages at throughputs of over 1800 packages per hour. The 2300 HS production tool handles parts in matrix trays, with lids fed from bowl feeder, stick feeder or lid cassettes. Software versatility, quick-change electrodes, and fast bowl feeder size



set-up allows for the rapid change of package types and sizes.

The 2300 HS seals packages as small as 2 mm^2 with conventional parallel seam sealing, weld sealing or tack solder sealing. SSEC's automatic gas mixing with helium enables fine leak testing immediately after the sealing process has been completed.

Contact Terri Kolodziejski, Solid State Equipment Corporation, 185 Gibraltar Road, Horsham, PA 19044, USA
Tel. +1 215 328 0700 ext. 737
Fax +1 215 328 9410
E-mail tkolodziejski@ssecusa.com

Package reduces thermal resistance

LSI Logic claims that its new wire bond package will provide 20% lower thermal resistance than standard plastic BGA packages. The new plastic ball grid array, the EPBGA-T, targets communications, and consumer and storage applications.

LSI's package integrates a copper heat-spreader in the mold cap and uses a four-layer micro-strip substrate. The latter accommodates split power and ground planes while maintaining the same mechanical and material attributes used in the company's existing EPBGA package family. The EPBGA-T family comes in body sizes ranging from 27 to 40 mm and ball counts ranging from 272 to 928.

Contact Valerie Atkins, LSI Logic, 1551 McCarthy Boulevard, Milpitas, CA 95035, USA
Tel. +1 866 574 5741
Web www.lsilogic.com

Matheson upgrades its phosphine product

Matheson Tri-Gas is marketing a new grade of phosphine (PH_3) intended for the compound semiconductor epitaxy market. The company says the Ultima PH_3 has substantially improved levels of moisture and oxygen-containing impurities, as well as electrically active trace impurities.

Independent mobility measurements performed on thick undoped InP layers grown on InP wafers reveal average mobilities of 287 000 cm^2/Vs at 77 K. This represents a 30% improvement compared with InP prepared using the company's standard electronic grade phosphine.

Contact Brenda Kennedy, Matheson Tri-Gas, 625 Wool Creek Drive, San Jose, CA 95112, USA.
Tel. +1 408 971 6500 ext. 270
E-mail bkennedy@matheson-trigas.com

OC White's optical inspection system

OC White has introduced an optical inspection system to characterize surface-mount assemblies, including ultra-fine pitch components, solder joints component



alignment and surface defects. The system has a high-quality lens and CCD camera for the analysis of densely featured assemblies, and is constructed from ESD-safe components to accommodate electronic circuits.

The system's light source provides four fiber-optic light bundles with intense white light at 5500 K, enabling accurate color rendering and color balance.

Contact Sales, OC White, 2039 Bridge Street, Three Rivers, MA 01080, USA
Tel. +1 413 289 1751
Fax +1 413 289 1754
Web www.ocwhite.com

7–8 February
Strategies in Light (LED conference organized by Strategies Unlimited)
San Francisco, CA, US
Web: www.strategies-u.com

11–15 March
Int'l Symposium on Blue Lasers and LEDs (ISBLLED 2002)
Cordoba, Spain
Web: www.die.upm.es/research/

17–21 March
Optical Fiber Communications (OFC) Conference
Anaheim, CA, US
Web: www.osa.org/mtg_conf/

18–20 March
International Symposium on Quality Electronic Design (ISQED)
San Jose, CA, US
Web: www.isqed.org

21–22 March
LED Lighting Institute
Lighting Research Center, NY, US
Web: www.lrc.rpi.edu/LEDInstitute/LEDinst.htm

26–28 March
RF & Hyper Europe
Paris, France
Web: www.birp.com/hyper

1–5 April
MRS Spring Meeting
San Francisco, CA, US
Web: www.mrs.org/meetings/

8–11 April
GaAs Mantech
San Diego, CA, US
Web: www.gaasmantech.com

16–18 April
Semicon Europa
Munich, Germany
Web: www.semi.org/web/wexpositions.nsf

12–16 May
Indium Phosphide and Related Materials (IPRM)
Stockholm, Sweden
Web: www.congrex.com/iprm2002

15–17 May
Wireless Design Conference
London, UK
Web: www.wirelessdesignconf.com

19–24 May
CLEO/QELS
Long Beach, CA, US
Web: www.cleo-online.org/

20–24 May
29th IEEE Photovoltaics Specialists Conference (PVSC)
New Orleans, LA, US
Web: www.ewh.ieee.org/soc/pvsc/

3–5 June
LightFair
San Francisco, CA, US
Web: www.lightfair.com

3–7 June
IEEE MTT-S International Microwave Symposium
Seattle, WA, US
Web: www.ims2002.org/

3–7 June
International Conference on MOVPE
Berlin, Germany
Web: www.icmovpe.physik.tu-berlin.de/

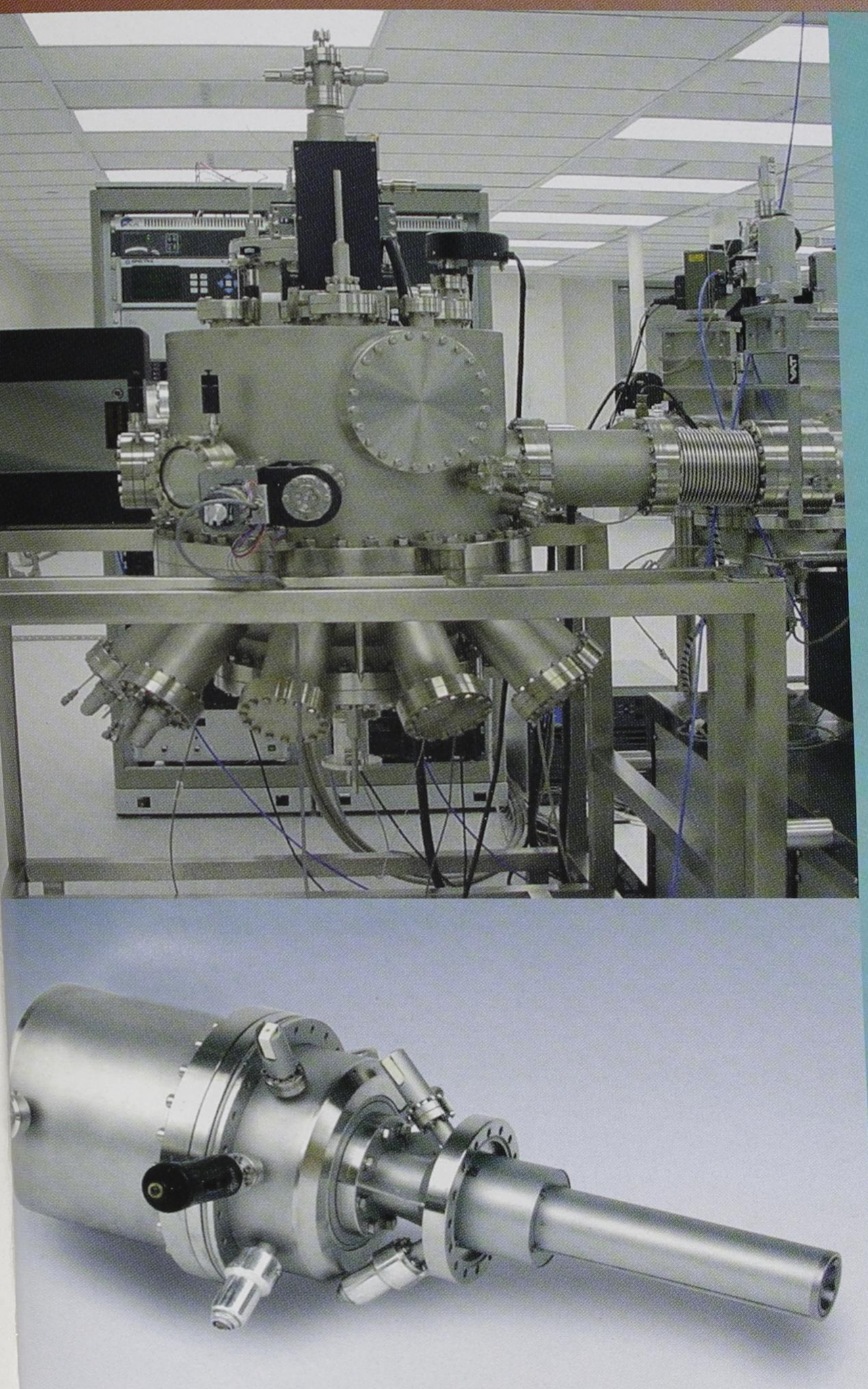
11–13 November
Compound Semiconductor Manufacturing Expo (CS-MAX)
San Jose, CA, US
Web: www.cs-max.com

For links to event Web sites, visit the Calendar section of our Web site at www.compoundsemiconductor.*net*.

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Proven Technology for Production MBE



DCA production MBE systems now cover run capacities of 3x2", 4x4" and 7x6". The P600 and P900 systems, with 3x2" and 4x4" capacities, are designed for the precise production of high-quality complex compound semiconductors.

The P7X6 system provides the highest throughput with the possibility to process seven 6" wafers simultaneously.

These production MBE systems complement DCA's wide range of R&D systems for III-V, Ga-N and Si/Ge epitaxy.

DCA High Capacity Effusion Cells and Crackers are known for their rugged design and long lifetime. The cells and crackers are now available as a retrofit for most production MBE systems on the market.

For your nearest representative please visit our web site at: **www.dca.co.uk**
or email us at: **dcausa@worldnet.att.net**

DCA
INSTRUMENTS

Announcing Purification for MOCVD Production Tools

Aeronex Infinity Gas Purification Systems provide a continuous supply of pure gas at ambient temperature

Purification Enables Process

In MOCVD and MBE films, atomic oxygen shifts the emitted wavelength, increases the bandwidth for optical devices, reduces device life through lattice instability, and decreases the carrier mobility in the film, thereby reducing the speed of the device. Aeronex purification technology improves the performance and lifetime of compound semiconductor optoelectronic and wireless devices by removing oxygen and other contaminants.

Without Interruption

As the process moves from R&D to Production, demand increases for purified nitrogen, hydrogen, and ammonia. Previous purification technologies required halting the process to replace the purifier bed. Today's process engineers require a high flow of pure gas and continuous up-time to maximize return. To meet these challenges Aeronex has developed the Infinity GPS™, which delivers a continuous supply of ultra pure gas without interruption.

Performance

Aeronex purifier technology sets the standard for pure gas. The patented media removes contaminants such as moisture, oxygen, CO, CO_2, and hydrocarbons from gas or liquid sources. This unique inorganic media operates at room temperature and handles high flows at very low pressure, a requirement for next generation MOCVD equipment.

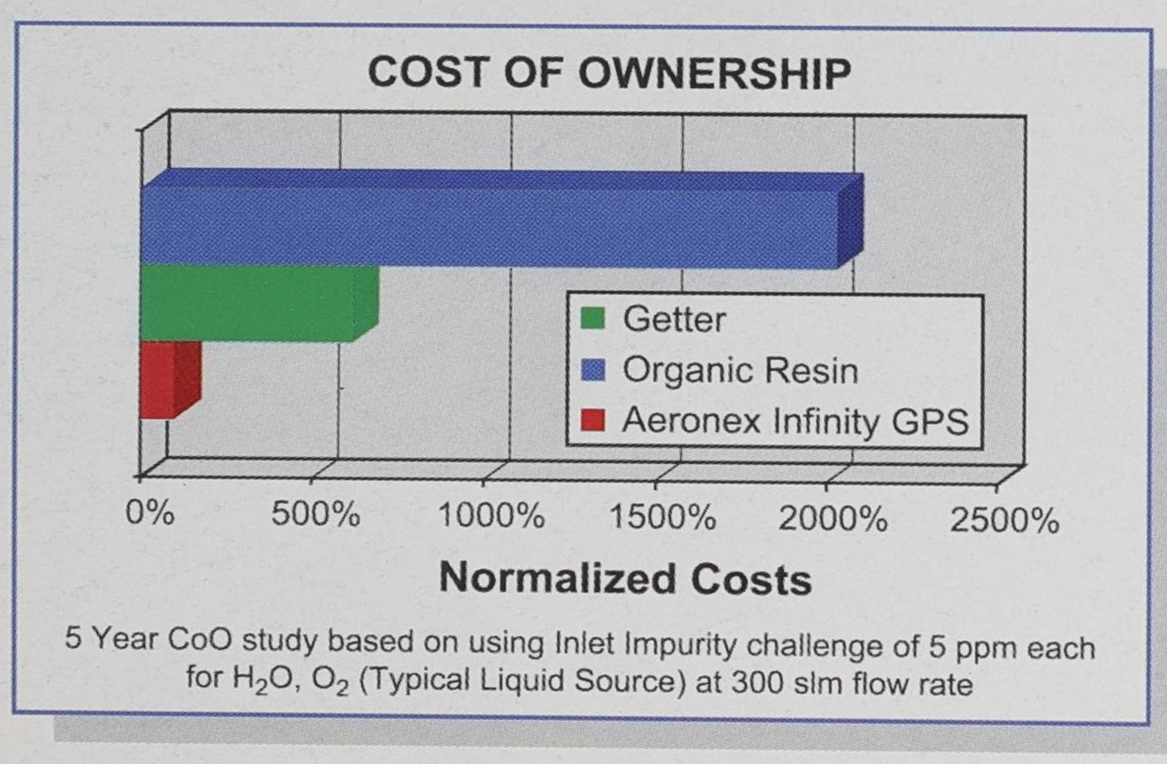
To provide a continuous supply of pure gas, the Infinity is designed with two purifier beds in parallel. While one bed is on-line, the second is automatically regenerating. Preconditioning time is eliminated, as is running on a spent or cracked purifier. No special gas blends are needed for start-up and hydrocarbons are never outgassed.



Value

The Aeronex purifier delivers the lowest cost of ownership. The Infinity GPS provides continuous savings through reduced labor and continuous uptime (see graph below). Competitive purifiers become a hazardous waste once spent, generating high costs in time, money, and liability. All related downtime and disposal costs are eliminated.

The Infinity accommodates different gas grades from either liquid or gas sources to significantly reduce your total tool operating costs through reduced cylinder change-out and lower gas costs. The purifier is hydrocarbon free, removing the possibility of expensive tool repair or chamber clean-up from system upsets. The result: reduced liability, lower operating costs, and increased product throughput.



5 Year CoO study based on using Inlet Impurity challenge of 5 ppm each for H_2O, O_2 (Typical Liquid Source) at 300 slm flow rate

Safety

Safety is a major concern at Aeronex. By enabling gas purification at ambient temperature and low pressure, safety is increased. The Infinity GPS regenerates in-situ, so technicians are no longer routinely exposed to process gas during purifier change-out. Automated monitoring minimizes potential loss that could occur from system upsets. There are no disposal or hazardous waste issues as in competitive technologies.

Total Purification Solution

Aeronex Purifiers are the only total purification solutions that provide improved performance, value, and safety. Contact Aeronex for more information on GateKeeper® and Infinity products for hydrogen, nitrogen, or specialty gases such as ammonia.

Aeronex purifiers are the choice for the leaders in III/V semiconductor films.

Call Aeronex to find out why.

AERONEX
The Source for Gas Purification

www.gaspurifier.com

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