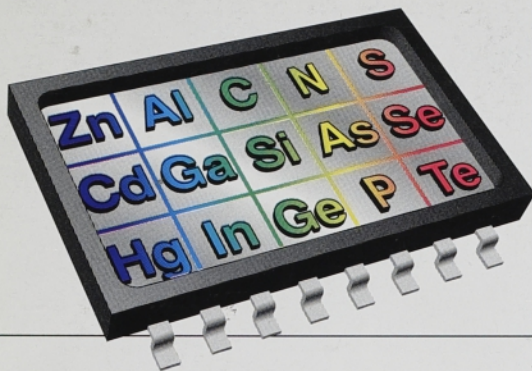




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April 2001

Volume 7 Number 3

LEDs

- Advances in AlInGaP
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- Optical Measurement

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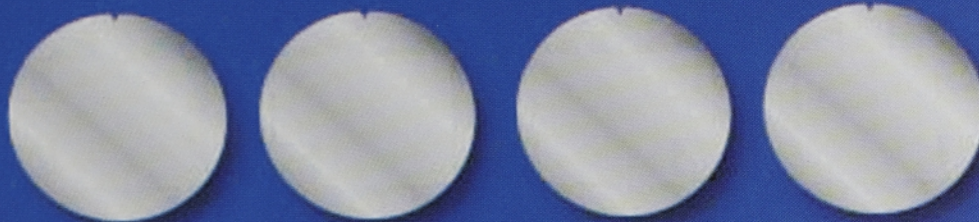
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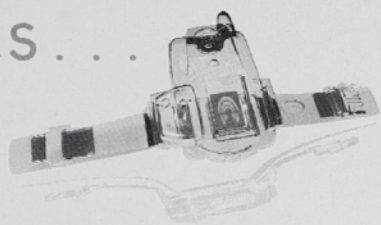
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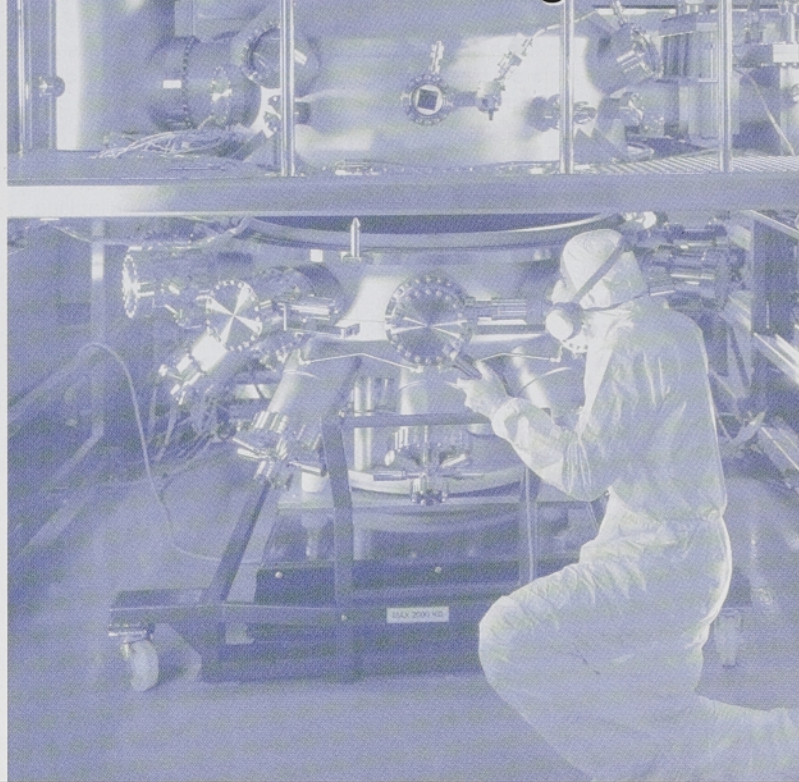
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(Job Code: CSD00-286)

Routine duties involve the collection and entry of lifetest data, failure analysis on devices from ongoing lifetest programs, and device testing in support of Engineering. Requires an AS degree or the equivalent and experience with device testing, preferably of opto-electronic devices and/or laser diodes. Familiarity with optical microscopes is essential; troubleshooting skills and cleanroom experience preferred.

Senior Staff Development Engineer

(Job Code: CSG00-207HK)

Duties include troubleshooting existing laser diode burn-in and lifetest equipment; designing and developing laser diode control electronics and power supplies; serving as an in-house consultant on electrical engineering issues for CSG, Engineering, Manufacturing, and Marketing; and interfacing with EE groups in Finland and the Software Group in Santa Clara. Requires a BSEE with 5 years of experience. The proven ability to integrate electronic systems is essential, as is familiarity with opto-electronic systems. Experience integrating hardware with software preferred; knowledge of laser diodes and optical systems a plus.

Senior Development Engineer

(Job Code: CSG00-29HK)

Duties include developing high new turn-key laser diode systems, supporting the existing systems product line and interacting with Sales/Marketing as well as customers on system issues. You will also interface with EE groups in Finland and our software group in Santa Clara, California. Requires a BS in Physics, Optics, Mechanical Engineering, Electrical Engineering, or a related field plus 3 years of experience. Prior experience with laser-based systems is preferred.

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Duties include creating new applications for ultra-fast and pulsed solid state lasers in the areas of material processing and process development, working closely with customers on specific application developments, and providing technical support for trade shows, marketing, and the worldwide sales force. Requires an advanced degree in Materials Science, Physics, Physical Chemistry, EE, ME or the equivalent.

Senior Development Engineer

(Job Code: CLG00-254HK)

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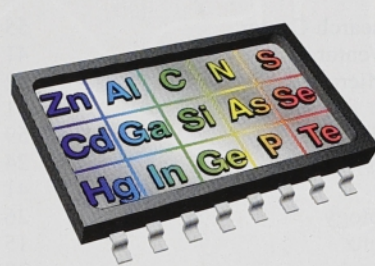


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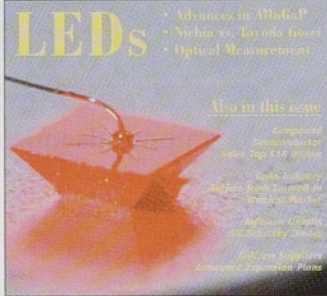
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On the cover: the truncated inverted pyramid geometry employed by LumiLeds in its latest high-power LEDs.

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Karl Suss

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Compound Semiconductor in strategic alliance

On February 14 Franklin Publishing, the publishers of this magazine, and Institute of Physics Publishing (Bristol, England) announced a strategic alliance aimed at meeting the rising demand for information resources in the compound semiconductor industry. One of the first fruits of this alliance is an improved look for *Compound Semiconductor*, introduced in this issue.

Franklin Publishing is the leading media company in the compound semiconductor industry. IOP Publishing's portfolio includes the highly respected *Physics World* and *Opto & Laser Europe* magazines, as well as several fast-growing publications in the telecommunications field including *FiberSystems International*, *FibreSystems Europe* and *Wireless Europe*.

The two companies will work together to further enhance *Compound Semiconductor* magazine and its associated Web site www.compoundsemiconductor.net. Franklin Publishing will continue to perform all editorial functions for the magazine and Web site, providing both content and direction, and key staff roles will remain unchanged. Marie Meyer, who founded *Compound Semiconductor*, will remain as managing editor, while Richard Dixon and Tim Whitaker will continue to serve in their current roles as news editor and editor-in-chief, respectively. Under the terms of the alliance, IOP Publishing



A global portfolio: Institute of Physics Publishing produces a number of highly respected international titles.

has acquired ownership of *Compound Semiconductor* magazine and will take over the production, sales and distribution functions.

This alliance will enable new and better products and services to meet the needs of the compound semiconductor industry. Circulation for *Compound Semiconductor* will be doubled in 2001, distribution in

the Asian and European markets will be increased, and delivery times to all locations will be shortened. Enhanced services for advertisers will also be added and the www.compoundsemiconductor.net Web site will be expanded. This site is already the largest of its kind in the industry, hosting 25 000 individual user sessions and more than 100 000 page views per month.

In addition, Franklin Publishing and IOP Publishing will jointly produce a major new event in 2001. To be held in Boston in July, the Compound Semiconductor Manufacturing Expo (CS-MAX) will be the first conference and exposition for the entire compound semiconductor industry to focus on high-volume manufacturing topics.

"Everyone at Franklin Publishing is very excited about this alliance," said Marie Meyer. "Working together, we'll be able to greatly enhance and improve the services that we provide to the compound semiconductor industry."

"Franklin Publishing has the respect and support of the global compound semiconductor industry. We are delighted to be working with them to further enhance their contribution," said Jerry Cowhig, managing director at IOP Publishing. "Together we expect to expand existing opportunities and create exciting new ones for companies operating in the compound semiconductor field."

Gallium producers ramp up capacity to cope with explosive demand

In response to sharp increases in demand, major gallium producers have announced plans to increase capacity. GEO Gallium, the world's largest extractor of virgin gallium metal, plan to increase their output by more than four times in 2002. The company will spend \$40 million to rebuild an existing extraction facility in Pinjarra, Western Australia. The plant was mothballed in 1997 when the market was flooded with exports from the former Soviet Union, and technical problems subsequently prevented its re-commissioning. Production is scheduled to begin in the second quarter of 2002, with what a company spokesperson described as "a very quick ramp up to the equivalent of

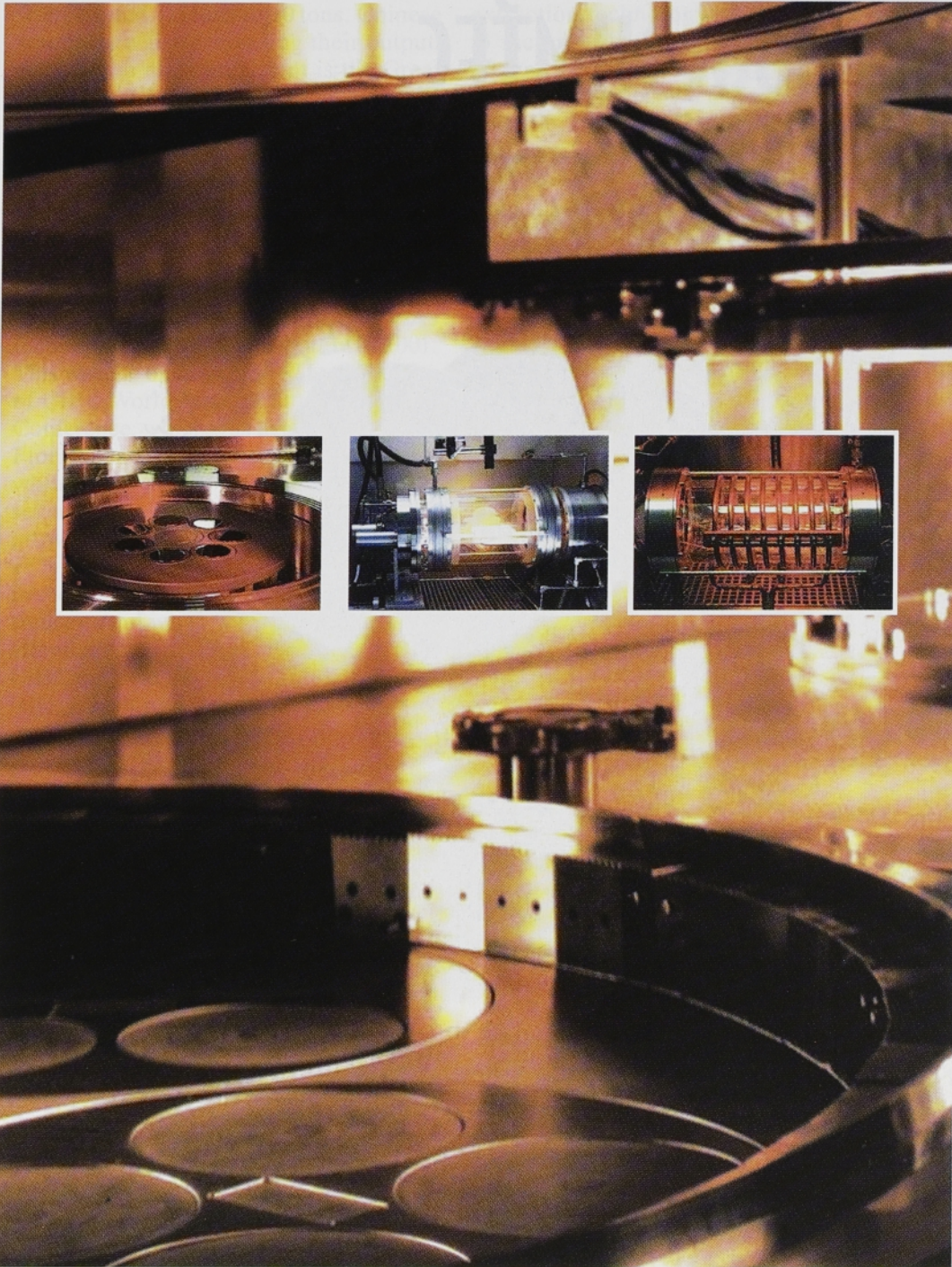
50 tons per year". The ultimate capacity of the plant is 100 tons. GEO also has capacity for extracting approximately 33 tons per year at a site in Germany. The total worldwide consumption of virgin gallium in 2002 was approximately 120 tons. (The term "virgin" refers to gallium which has been obtained by extraction from alumina ore, and is used to distinguish it from gallium obtained via recycling.)

Feedstocks for the GEO facility will be supplied by ALCOA's alumina plant in Pinjarra. GEO will produce 4N (99.99%) gallium metal in Pinjarra that will then be purified to 6N, 7N and MBE grades at GEO's plants in Germany and France.

"GEO is committed to aggressively expand its capacity to extract and purify gallium metal," said George Ahearn, GEO Specialty Chemicals' CEO. "We are responding to the explosive demand for gallium in today's high-technology wireless and LED products. Our new facility will help stabilize the worldwide supply and demand for gallium. At the same time, this major expansion will solidify our position as a world leader in gallium production."

Other new sources are coming on line as well. In recent months the Ukrainian government has announced that its Mykolayiv aluminum plant will increase their annual production of gallium >>

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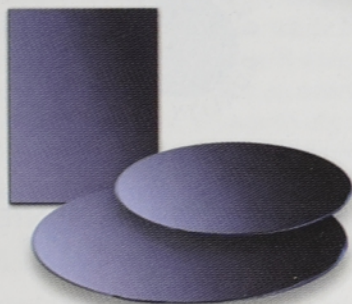
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from around 1.5 tons to 10 tons. Chinese sources are also increasing their output. Among the most important is the Great Wall Aluminum Company, which has licensed Sumitomo Chemical's gallium

extraction technology. Great Wall plan to increase their output from 6 tons to 20 tons in 2002. Sumitomo Chemical previously ran its own gallium extraction operation in Japan, but it was rendered

uneconomic by the high cost of utilities in that country.

In recent months gallium spot market prices have risen as high as \$3 000 per kg, nearly five times more than 2000 prices.

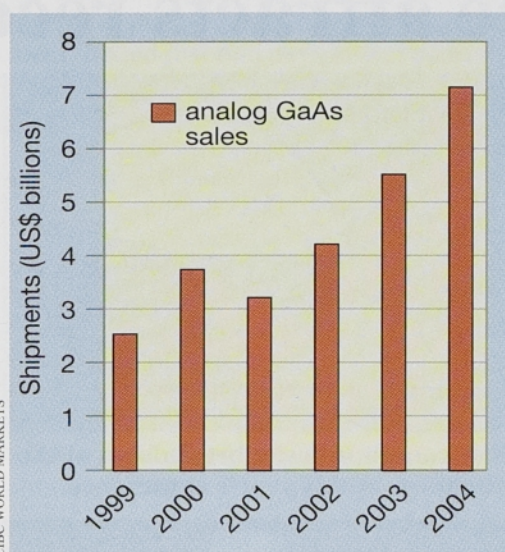
GaAs industry warned of uncertain future

Unless there is a dramatic turn-around in the mobile phone business, the GaAs industry is headed for a downturn in 2001. This was the opinion offered by Dale Pfau of CIBC World Markets at the 2001 Key Conference, which was held in Key West, Florida on March 5–6. Pfau said that while GaAs device shipments have seen several years of steady, even spectacular growth, they may decline by as much as 15% in 2001, causing the first recession in the GaAs industry's brief history (see figure). And while other presenters and attendees were of the opinion that the CIBC outlook was unnecessarily pessimistic, a rash of earnings warnings from major GaAs fabs, issued while the conference was in session, seem to support Pfau's conclusions.

The slowdown is due to a sudden and sharp drop in the production of wireless handsets. Pfau told the audience that in February CIBC cut their forecast for 2001 handset sales from more than 500 million units to 475 million units. In comparison, approximately 410 million units were sold in 2000. But, Pfau noted, there is already a great deal of inventory in the pipeline, with perhaps as many as 50 million handsets having gone unsold in 2000. He told the audience it is therefore conceivable that production of mobile phones will show virtually no growth in 2001. In this set of circumstances, Pfau believes that handset manufacturers will exert pressure on all their suppliers, including the GaAs IC companies, to lower their average selling prices (ASPs) more quickly than would otherwise be expected.

Under pressure

It is this "double whammy" – lower unit volumes and lower ASPs – that leads Pfau to the conclusion that 2001 will be a disappointing year and that these woes may persist into 2002. "The GaAs industry, which has thrived on performance, is now going to be faced with price pressure – and I think that is a significant threat," said Pfau.



Trouble ahead? Eight months ago, CIBC World Markets predicted that the total world market for analog GaAs devices would exceed \$5 billion in 2001. Now, the same firm is forecasting that total sales will actually decrease in 2001 compared to last year, signaling the first recession in the GaAs industry's history.

Eight months ago, in the pages of this magazine, CIBC set out a fairly rosy forecast for the GaAs industry (see *Compound Semiconductor* August 2000, p27). Not surprisingly, conference attendees wanted to know what lay behind the dramatic downgrade of the short-term outlook. Pfau explained that the collapse of the stock market is a significant factor. Though now more than a year old, the bear market was, until recently, blamed largely on the bursting of the "Internet bubble", with the assumption that "real" companies would soon bounce back. Now, however, the markets are denying new capital to telecom carriers and equipment companies alike, forcing them to curtail plans to build up more infrastructure and causing a major slowdown in efforts to attract new subscribers. This therefore results in far fewer new handsets being needed. Pfau also noted that there are virtually no new handsets on

the market to generate consumer enthusiasm, and so the replacement market is also slowing down.

New services that require new phones are also lacking. Pfau noted that wireless application protocol (WAP) services, which were introduced last year to provide mobile phone users with rudimentary Internet connections, have been a total disaster. And there have been significant delays in the roll-out of GPRS phones, the so-called 2.5G handsets that are supposed to provide a vast connectivity improvement over WAP phones. GPRS is now expected to be introduced in Europe in the second half of this year. Pfau advised the industry to keep a close eye on this development. "If GPRS is a success, it will provide the carriers with more revenue and should speed the transition to 3G, and another round of handset buying," he said. "However, if GPRS is a failure, then the recovery scenario for GaAs in 2002 is in jeopardy."

Winners and losers

Pfau predicted that the current turmoil in the handset market would create opportunities for companies offering RF modules as opposed to RFICs. Some GaAs companies, most notably Alpha and RF Micro Devices, are already making strides in this area. However, the move to modules may also allow silicon IC manufacturers to gain market share. "Modules have the potential to be disruptive because you are not required to have the 'best-of-breed' technologies inside them," Pfau noted. "We have actually seen companies with a weak silicon-in-module format beat guys with good GaAs technology because they had good packaging or maybe unique filtering technology inside."

And while Pfau believes that all of the established GaAs fabs have sufficiently large financial reserves to ride out this storm, he did state unequivocally that new companies offering GaAs foundry services were going to suffer. Several ventures of this type are in the works, >>

especially in Taiwan. While the foundry model continues to be popular in the silicon industry, Pfau noted that the downturn he was describing means that there is no longer a lack of capacity in the GaAs market. "We don't see the need for any additional [GaAs] capacity for the next

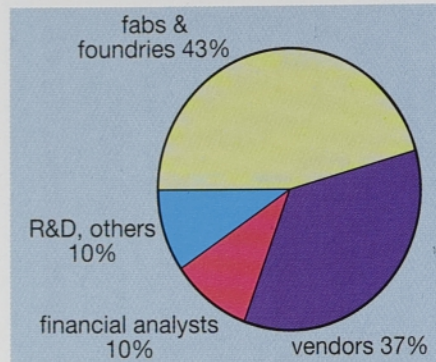
two years," said Pfau. "Under this scenario, most of the current GaAs foundry projects may not survive."

When asked to identify some possible silver linings behind the gathering dark clouds, Pfau expressed enthusiasm for millimeter wave point-to-point radios –

but not other high-frequency applications such as LMDS and MMDS. Pfau also explained that he is very enthusiastic about the prospects for InP technology. "I'm as bullish about InP as I have ever been about any sector that we've looked at," he told the audience.

Key Conference attracts record numbers

Attendance at the 2001 Key Conference on Compound Semiconductors in Communications was up more than 40% from the previous year, underscoring the growing importance of this sector. The Key Conference, which is hosted by *Compound Semiconductor Magazine*, was held on March 5–6 in Key West, Florida. "We had 275 registrants this year, and while we're obviously very pleased by the turn-out, we were even happier to see that the fabs, the vendors and the financial communities were all well represented," said managing editor Marie Meyer. "The presentations



Key communities: a breakdown of the attendees at this year's conference.

were extremely good. We also like to foster general discussion – and to do that you need to have all sectors of the industry in attendance." Twenty-two presentations dealing with telecommunications markets, applications and technologies were made during the two-day event.

The Key Conference will return to the Wyndham Casa Marina Resort in 2002, on March 7–8. Interested parties can register for updates by visiting the conference Web site at www.keyconference.com. Presentation materials from the 2001 conference are also available on the site.

Leading US GaAs fabs issue profit warnings

Profit warnings from six major GaAs IC companies in the first two weeks of March lent support to CIBC's theory that the GaAs industry is entering into a recession (see "GaAs industry warned of uncertain future", page 7). On March 7, Alpha Industries announced that its revenues were slowing by around 20% and that its profit targets for the March quarter would be slashed from around 20 cents per share to 5 cents. The company cited slowing demand from both handset and infrastructure customers.

On March 8, RF Micro Devices announced for the second time that it would not meet Wall Street expectations for the March quarter. The company's figures had already been revised downward after a similar warning on January 16, and this second revision indicates that the situation is worse than previously believed. RFMD cited slowing demand from handset, infrastructure and broadband customers, and said that it is seeing some orders pushed out as well as some cancellations. Their new forecast is a loss of 3–4 cents per share, down from the January projection of 2 cents per share profit. Revenue is

expected to be \$55 million, down from \$85 million in the same period last year.

Fabless supplier Stanford Microdevices has also been rattled by the turmoil in the wireless industry. The company now anticipates first-quarter net revenues of \$7.6–8.0 million, which is 25% lower than previous projections. Analysts had been expecting income of around 5 cents per share for the quarter; the company now says that they expect to merely break-even. The company blamed "the actions and plans of the worldwide telecommunications industry to reduce component inventory levels and planned equipment production volumes, and to delay the build-out of new wireless network infrastructure."

The wireless area is not the only disappointment for GaAs makers. TriQuint Semiconductor lowered its expectations, indicating that it expects to show little or no growth in revenue in the first three quarters of this year. The company reported slowness in most areas, but fiber optics, which accounted for 29% of TriQuint's revenue in the December quarter, was noted as particularly weak. Wireless sales, which accounted for 48% of revenue in the fourth quarter, were also down. Unit volumes remain high, with analysts indicating that TriQuint is using

nearly all of its capacity. ASPs, however, have dropped leading to significant decreases in revenue.

Slowing demand for CATV components is clouding the outlook for Anadigics. On March 13 the company confirmed that while it is on track to meet estimates of \$28.5 million in first-quarter revenues, there may be a drop-off of as much as 25% in the June quarter. A loss per share of 14 cents for the first quarter and 25 cents in the second quarter is expected, due primarily to substantially reduced gross margins because of lower fab utilization. According to the company's statement, "gross margins are expected to temporarily dip into the 25–30% range for the first half of 2001". Bami Bastani, president and CEO of Anadigics, predicted a recovery by the end of this year.

And Vitesse, the leading manufacturer of digital GaAs ICs, warned that revenue expectations for the March quarter should be lowered from \$180–190 million to \$150–160 million and projected net income would likely be 21–22 cents per share, 5 cents lower than previously expected. The company cited weakness in its communications and data storage businesses, saying that it continues to see strong growth in its network processor, switch fabric and OC-192 module product lines.

Laser fab deal stands despite share crash

Nortel dropped a bombshell on the financial markets on February 15 when it cut its forecast for growth in revenue and earnings in half, saying the economic downturn in the United States will continue well into the fourth quarter.

The news was shocking primarily because Nortel had assured investors in December that its outlook remained bright despite the turmoil in the telecommunications industry at large. These reassurances were then repeated in January. The company was expected to report \$8.1 billion in revenue and 16 cents per share in earnings. It now looks like Nortel will struggle to achieve \$6 billion in revenue and will post a loss of 4 cents per share.

Possibly no one was more surprised than the top executives at JDS Uniphase. Just 9 days earlier JDSU had agreed to sell their 980 nm pump laser fab in Zurich, Switzerland to Nortel, in order to secure the approval of the US government

for JDSU's merger with SDL (see *Compound Semiconductor* March 2001, p5). The deal closed one week later, and JDSU received \$2.5 billion in Nortel stock, which was then trading at \$30. Most analysts expected JDSU to quickly liquidate the shares in order to add to JDSU's cash reserves. However, the Nortel announcement, issued just two days later, sparked a massive sell-off in Nortel shares that dropped to \$20, shaving \$800 million off the value of JDSU's holdings. Nortel shares have subsequently dropped to \$15, further damaging JDSU's position.

Nortel is currently threatened by at least a dozen class action lawsuits, all revolving around Nortel's statements in December and January. Naturally, there was rampant speculation that JDSU would enter the fray as well. Several companies were rumored to be interested in buying the Zurich plant. When Nortel was announced as the winning bidder, JDSU's

chief financial officer indicated that there were two major reasons behind the decision. First, Nortel is JDSU's largest customer, and the deal seemed like an excellent way to further cement their relationship; and second, "Nortel was willing to pay a fair price for Zurich." However, that price has now been cut in half, and it is difficult to imagine that Nortel executives did not know about their company's rapidly deteriorating outlook when they were negotiating the purchase price.

Nevertheless, JDSU have indicated that they do not plan to sue, despite the fact that their proceeds from the sale have, in effect, been cut in half. JDSU's CFO was recently quoted as saying "Of course we're talking to lawyers, but it's not easy to sue your largest customer." So it seems likely that the deal will stand. Analysts now expect JDSU to hold on to their Nortel shares for longer than expected, in the hope that their price will rebound.



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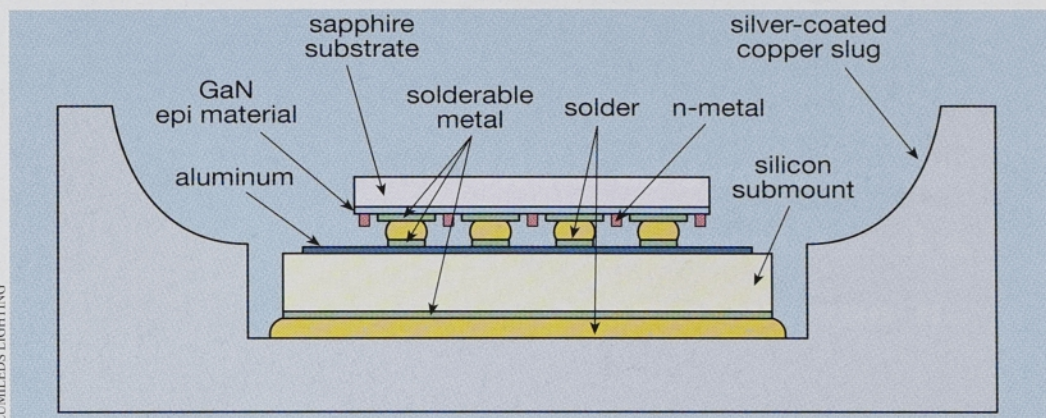
LumiLeds demonstrates high-power LEDs

LumiLeds Lighting (San Jose, CA) has announced record results from its high-power monochrome and white InGaN-based LEDs, enabled by a combination of developments in large area, high-current chips, as well as light extraction and packaging. The results build on LumiLeds' previous announcements in this area (see *Compound Semiconductor* December 2000/January 2001, p19). The company will shortly introduce these devices as part of its Luxeon family of high-power LEDs.

"These are the most efficient, highest flux, large junction devices in the world," said Frank Steranka, LumiLeds' materials R&D and product development manager. "Where the rest of the world is talking about 1 lumen devices, we are exhibiting up to 55 lumen devices in certain colors."

LumiLeds say the higher flux devices could find use as backlighting for LCD computer monitors and TVs. The use of LEDs could lend these applications brighter colors than the conventional backlight sources, and better power consumption than a CRT. Flashlights that use single high-power LEDs with outputs of 25–50 lm are also expected to be on the market within the next year.

One of LumiLeds' recent demonstrations was a single white LED with a light output of 17 lm, a value that is four times greater than the best commercially available white LED. This device features



Schematic of LumiLeds' high-power package design, in which the GaN-on-sapphire device is flip-chip mounted to a silicon submount to improve heat dissipation.

high current operation at 350 mA and a forward voltage of just 3.2 V. This is a significant achievement as it is the first single point white LED in the light output range required for general lighting applications such as map lights, airplane reading lights and emergency lighting. A well-controlled single point light source allows lighting designers to construct compact fixtures and couple the light to a single optic in the light fixture. This approach is not possible with conventional 5 mm white LEDs which do not provide enough light on their own, necessitating bulky designs with multiple LEDs.

LumiLeds also announced a laboratory demonstration of a 425 nm InGaN LED

(250 mA DC operation) with a wallplug efficiency of 25%, exceeding the previous record from Cree Lighting of 22% (see *Compound Semiconductor* August 2000, p25). The wallplug efficiency is the ratio of the light output against the energy input, and is a measure of the amount of energy required to produce the specified light output level. According to LumiLeds, one of the keys to keeping energy requirements low is to retain a low forward voltage. LumiLeds' device can be driven at much higher currents: overall, the new high-power device emits over 200 mW, 10 times higher than previous devices. At a current of 1 A, the company has demonstrated over 525 mW of output power.

GELcore meets traffic-light energy standards

GELcore (Valley View, OH) has become the first partner of a program set up by the Institute of Traffic Engineers (ITE) to promote energy efficiency. GELcore, which is the joint venture between GE Lighting and Emcore, has certified almost 30 products that meet these performance specifications. These include LED-based traffic lights (see picture), arrow signal confirmation indicators and pedestrian control signs. The ITE produced a set of guidelines for these and other products that meet the US Department of Energy and Environmental Protection Agency standards, under their "Energy Star" program.



Cree raises near-UV LED efficiency record

Cree Lighting Company (Goleta, CA) has demonstrated a near-UV/violet InGaN LED with a 32% external quantum efficiency. This is the highest known external quantum efficiency reported for an LED in the UV-to-blue portion of the wavelength spectrum, and exceeds Cree's previous result of 28% (see *Compound Semiconductor* August 2000, p25). High quantum efficiency in UV and near-UV LEDs is essential for driving phosphors to produce efficient white light sources. Cree's LED emits at 390 nm and has a power output of 21 mW (at a current of 20 mA).

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Ledtronics unveils the latest generation of multicolored LED lamps

Ledtronics (Torrance, CA) has announced the development of a new range of lamps employing the latest generation InGaAlP and GaN-on-SiC LEDs in standard 25 mm Edison screw bases. Drawing just 1.0–1.7 W of power, the DécorLED provides an 11 year life and is available in voltages from 12 to 120 V. Each lamp uses 18 discrete LEDs configured to disperse light in a 270° wide angle or a 30° acute angle. Colors include green (10 cd), white (6 cd), blue (3 cd), yellow (7 cd), red (3.5 cd) and orange (6.5 cd).

The company's SurfLED is a surface-mount LED compatible with infrared and convective reflow soldering and pick-and-place automated equipment. At just 1.6×0.8 mm, the device is suitable for backlighting in cell phones,



New products from Ledtronics include DécorLED lamps with Edison screw bases.

palm pilots and datacom equipment, and has an intensity of 20 mcd. There is also

a super bright variant available that produces 60 mcd (20 mA current).

NITRIDE NEWS

Kyma receives SBIR GaN funding boost

Crystal growth company Kyma Technologies (Research Triangle Park, NC) has received a Phase II Small Business Innovation Research (SBIR) contract for \$750 000 to continue large area GaN bulk crystal growth R&D. Typical substrates for wide bandgap devices include sapphire and two inch SiC. Large area nitride-based wafers would offer manufacturers lower lattice mismatch compared to commonly-used sapphire or SiC substrates, as well as the potential to yield up to four times as many die per wafer by increasing the wafer diameter from two to four inches.

To date, the two year old spin-off from North Carolina State University has sampled two and four inch AlN wafers and is also developing GaN substrates (see *Compound Semiconductor* November 2000, p13). Kyma says it is applying for additional contracts to support these research objectives, with a strong focus on both materials.

In more news, Kyma Technologies has welcomed founder and CTO of RF Micro Devices', William Pratt, and former president and CEO of Integrated Silicon Systems, James Poitras, to its board of directors.

Infineon powers up new range of SiC applications



Infineon (Munich, Germany) is to begin volume production of a new range of SiC Schottky diodes for power applications. SiC enables power devices that block voltages up to 3500 V (more than 10 times that of GaAs) due to a combination of material properties, including a high Schottky barrier, higher electrical

breakdown field strength, and the ability to dissipate heat due to a thermal conductivity comparable to copper. These characteristics result in low leakage currents, low on-resistance, and high current densities, offering higher voltage operation in switched mode power supplies and power factor correction for applications such as PCs, servers and base stations.

The company's new diodes feature blocking voltages of 300 and 600 V variants in compact transistor outline 220 and TO263 surface-mount packages. As a result of the low switching losses, the diodes can operate at high switching frequencies without complex resonant switching circuits, heat sinks and cooling fans. The development of these devices is discussed in detail on page 45.

"An essential advantage of Infineon's SiC technology is that it enables almost loss-free and very fast switching diodes," said Reinhard Ploss of Infineon's Automotive and Industrial business group. "This not only reduces overall losses, but also improves reliability and lowers system costs."

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Rockwell and Kopin collaborate on HBTs

Rockwell Science Center (RSC) and Kopin have agreed to jointly develop InP HBTs for commercial applications. Kopin (Taunton, MA) will develop InP HBT epiwafers, while RSC (Thousand Oaks, CA) will create processing technologies for devices and circuits, and address reliability issues. According to the two companies, InP devices demonstrate superior speed, lower operating voltage, higher

power efficiency and better thermal properties than their GaAs counterparts.

Rockwell and Kopin have a long history of cooperation in the field of HBTs: Rockwell Semiconductor (now Conexant) has been a major customer for Kopin's C-doped AlGaAs epiwafers since the early 1990s. Kopin first began working on C-doped AlGaAs HBTs back in 1989, and recently introduced

its first C-doped InP HBT epiwafers (see *Compound Semiconductor* February 2001, p25).

"InP HBTs are becoming the most exciting frontier for ultra high-speed circuits," said RSC director Derek Cheung. "Our two teams have worked successfully on GaAs HBTs, and we are now combining our resources to move InP HBTs into commercial readiness within a year."

RFMD PAs enable automotive system

RF Micro Devices (Greensboro, NC) has commenced shipping production quantities of GaAs HBT-based PAs for use in Tele Aid, a transport information system developed by Motorola and Mercedes-Benz. The system uses a wireless network to enable data services and information, such as vehicle tracking and positioning by GPS, on-line navigation and emergency assistance. A cellular link provides 24 hour contact with Mercedes-Benz, supplying information on the car itself and indicating the need for roadside assistance or emergency aid. In addition, an automatic collision link notifies emergency units if an air bag deploys. The Tele Aid is a standard feature on all 2001 Mercedes-Benz models.



DAIMLERCHRYSLER

A car full of compound semiconductors: new Mercedes models incorporate a range of features enabled by compound semiconductors. Some European models have 77 GHz anti-collision radar systems; others use an optical databus to connect multimedia and communication devices within the vehicle. This system uses visible LEDs to transmit through plastic optical fiber. LEDs are also found in external lights and directional indicators embedded in wing mirrors, as shown on page 52.

Endwave awarded three flip-chip patents

Endwave, a supplier of RF modules, integrated transceivers, antennas and outdoor units, has received three new US patents for its flip-chip IC technology, bringing the company's total number of patents up to 23. Flip-chip designs minimize the use of resistors, capacitors, inductors, couplers, filters and vias and their associated parasitics that can degrade IC performance. Flip-chip designs are also frequency-independent, allowing the same part to be used for a variety of frequency bands.

The new patents cover several aspects of flip-chip design, including slotline-to-slotline mounted flip-chip technology for millimeter wave circuits. This eliminates the need for expensive ground connections through the substrate. Another patented feature is a coplanar band pass filter that requires no tuning, which thus saves manufacturing/testing time. Finally, the patents include a self-biasing RF amplifier bias that connects coplanar waveguide circuits and eliminates the need for a negative bias.

"These inventions provide Endwave and its customers a unique path to low-cost, high-volume manufacturing of ultra-broadband wireless radios. Flip-chip technology enables us to reduce the size of the GaAs chips, the most expensive component of millimeter-wave radios, by a factor of 5 to 10," said CTO Cliff Mohwinkel.

In more news, Endwave has opened a new design center in Torrance, CA concentrating primarily on the design of millimeter-wave transceivers.

TRW amplifier breaks power density record

TRW (Redondo Beach, CA) has developed an InP-based microwave power amplifier that delivers a record power density of 360 mW/mm at 23 GHz, and a total output power of 400 mW. The device was developed by TRW under contract to the Air Force Research Laboratory, as part of the government's Dual Use Science and Technology program.

"High performance microwave power amplifiers are a key requirement for next-generation digital radios and space-based communication systems," said Dwight Streit, TRW's VP for advanced semiconductors. "Our new InP PA demonstrates not only record power density at least twice that of any other power amplifier

available today, but also provides excellent linearity and power-added efficiency."

"This achievement paves the way for advanced, power-efficient active apertures used in space-based and airborne radars," added Tim Kemerley of the AFRL's Sensors Directorate. "These aerospace radar systems will need highly efficient transmit amplifiers, as well as novel approaches to antenna packaging and integration, to meet requirements for multifunction performance, low mass and affordable cost."

TRW is working to bring InP technology to commercial telecommunication markets this year. Its recently completed high-volume InP production facility is due to be operational by the middle of the year.

GCS signs foundry deals with GTRAN and Celeritek

Global Communication Semiconductors (GCS), a foundry based in Torrance, CA, has announced two foundry deals. GTRAN, a fabless company that designs high-speed devices for wireless and optoelectronic markets, has selected GCS as a foundry partner for its recently developed InP HBT process, which targets emerging 40 Gbit/s SONET markets. Meanwhile, Celeritek, an established GaAs foundry, has signed a three-year agreement with GCS for HBT and PHEMT device wafers for its wireless products.

GCS will supply 4 inch InP HBT wafers, for which it has a production capacity of 500 wafers per week; this will soon be increased to over 1000 wafers per week. GTRAN's InP HBT process exhibits f_t values of 150 GHz and f_{max} values of greater than 200 GHz, making the device suitable for 40 Gbit/s fiber-optic ICs.

According to the company's COO, Deepak Mehrotra, GTRAN already markets a 10 Gbit/s transponder, but decided to develop its own process after a fruitless search for 40 Gbit/s technology. "We decided to put together our own development and process engineering team to come up with a suitable circuit process design that would accommodate the stringent requirements of OC-768 SONET

applications," explained Mehrotra. "We now have the intellectual property required and have transferred the InP HBT design, and our process engineers, to rented space at GCS. We decided it would be best to transfer this technology to a foundry that was sensitive to III-V manufacturing issues." Founded in 1999, GTRAN is based in Westlake Village, CA, and has two product divisions and six design center locations worldwide.

GCS will supply 4 inch GaAs HBT and PHEMT wafers to Celeritek for products such as power amplifiers used in cell phones requiring WCDMA and CDMA standards. Celeritek says the use of GCS as a second source will allow greater flexibility in responding to the wireless market. Under the agreement, Celeritek will outsource "a significant percentage" of its wafer manufacturing to GCS.

"Our stated manufacturing strategy is to outsource a portion of our fabrication work," said Perry Denning, VP and general manager of Celeritek's Semiconductor Division. "We have been working with GCS for over a year now and have been extremely pleased with the quality of their work, and their ability to match our internal process, cycle time and service. It was therefore a natural progression to enter into a contractual relationship."

Knowledge*on plans 6 inch GaAs foundry

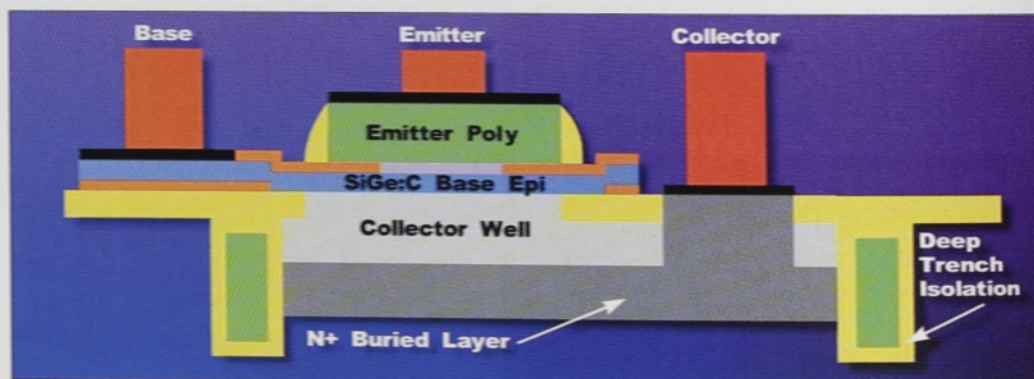
As reported extensively in this magazine, a number of GaAs foundry projects are underway in Taiwan (see *Compound Semiconductor* February 2001, p56), although given the current state of the GaAs industry it remains to be seen how many of these will be successful. Other Asian countries are also planning to enter the foundry business, notably the Korean company Knowledge*on. Formerly known as Optel, the company is an established manufacturer of optoelectronic devices, claiming to be the world's leading supplier of infrared LED chips.

Knowledge*on has now established a GaAs foundry, which should be operational in Q3 of 2001. The fab will offer InGaP HBTs, RFICs and MMIC for wireless (CDMA, GSM, DCS, 3G etc) and fiber-optic (40 Gbit/s) communication applications. The 6 inch production line will be housed in a 35 000 sq.ft facility, and at present Knowledge*on estimates it will have a capacity of 3000 wafers per month.

Correction In a previous issue (see *Compound Semiconductor* February 2001, p56) we discussed a new Taiwanese GaAs foundry project, G-Advanced Semiconductor Manufacturing. We have since learned that following a groundbreaking ceremony last July, the company has disappeared without trace. We apologize for any confusion this may have caused.

New RF process is designed to integrate

Two companies, Communicant Semiconductor Technologies and Motorola have both qualified their own new processes for RF applications that are based on carbon-doped SiGe structures. Motorola's 0.35 μ m HBT process employs a C-doped SiGe base (see figure) and is designed to integrate a variety of active and passive devices on-chip. The device offers a cut-off frequency of 45 GHz and a maximum operating frequency of 90 GHz, at half the current required by current SiGe transistors. Motorola says the addition of carbon provides excellent manufacturing latitude and a low noise figure, for only one additional masking step.



Motorola's latest high-frequency process employs an HBT with a C-doped SiGe base layer and is designed to integrate a variety of devices on-chip.

Communicant Semiconductor Technologies plans to manufacture SiGe:C BiCMOS and Si CMOS wafers at a new \$1.5 billion facility in Frankfurt, Germany. The company will license

technology from two major investors: IHP, a microelectronics R&D center that provides the SiGe:C process; and Intel, which will supply its 0.18 μ m CMOS process.

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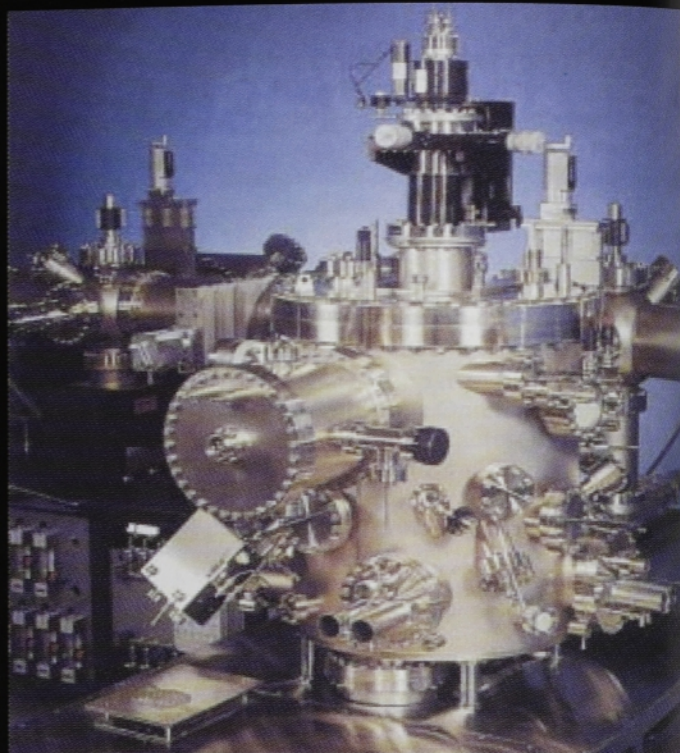
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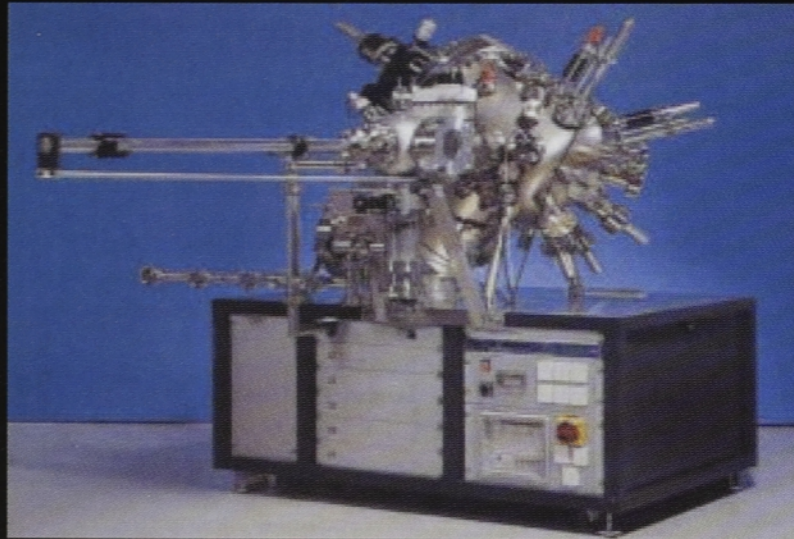
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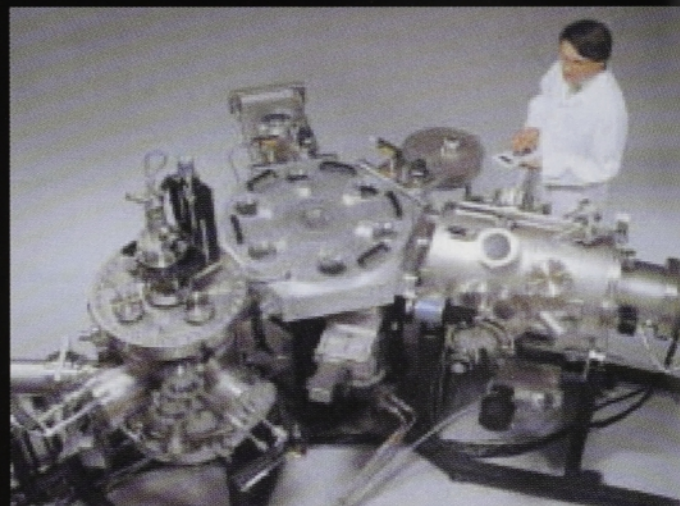
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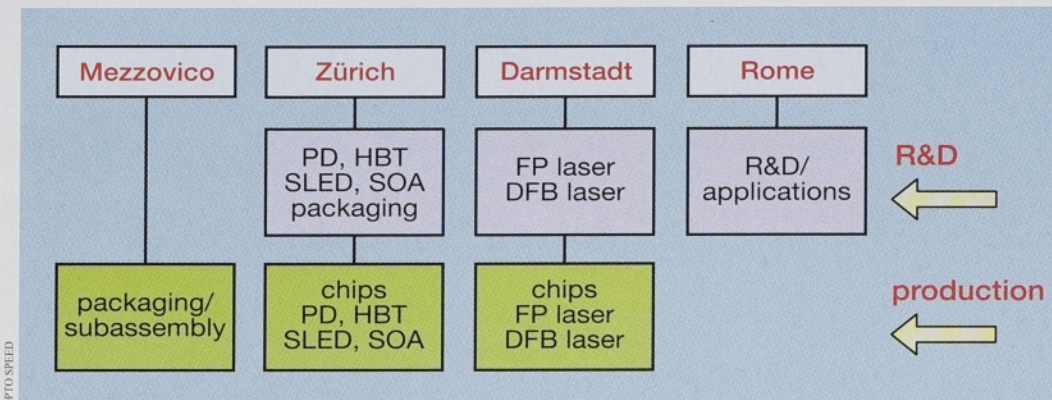
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Opto Speed expansion leads to three new facilities



Organizational chart for Opto Speed, showing the locations of the company's manufacturing sites for different product types.

Switzerland-based Opto Speed is expanding in three locations. The vertically integrated manufacturer of high-speed optoelectronic components is responding to the increasing demand for optoelectronic chips, as used in a variety of applications. The two main markets for Opto Speed are telecom (47% of sales) and datacom (38%) applications, with modest sales (around 14%) into test and measurement applications.

The company has now officially opened its Swiss headquarters in Mezzovico near the Italian border, which includes a 15 000 sq. ft automated manufacturing line for the packaging and testing of optical chips. The company will also open a new manufacturing and R&D center located in Rüschlikon, near Zürich, Switzerland. The 50 000 sq. ft site will include class-100 cleanrooms and a dedicated test facility. Rüschlikon will have an initial annual installed capacity of 10 million optical chips, which is set to increase to 45 million within one year. Opto Speed has also added an R&D operation in Rome, Italy.

"The new Rüschlikon facility includes cleanrooms and equipment for optoelectronic semiconductor production, test, burn-in and qualification, as well as development labs and expanded office space," said president and CEO Roberto Dall'Ara. "This site will enable us to continue our aggressive development, hiring and manufacturing ramp-up."

Background and products

Opto Speed was founded in 1995 as a spin-off of the Swiss Federal Institute of Technology (ETH) in Zurich. It already operates production facilities at both ETH and in Darmstadt, Germany – the latter a result of the acquisition in 1999 of Deutsche Telekom's III-V semiconductor group. The Darmstadt group added transmission laser technology (1310 and 1550 nm FP and 1550 nm DFB devices) to Opto Speed's existing products.

The company manufactures mesa pin photodetectors with high speeds (up to 40 GHz) and low operating voltage (1 V). The single-chip devices can be top or bottom illuminated and have high reliability; 1 × 4 or 1 × 12 arrays are also available. The company's semiconductor optical amplifiers (SOAs) are InP/InGaAs devices with a ridge waveguide structure and tilted facets for low ripple (< 1 dB). They feature > 30 dB gain and > 7 dBm output power.

Opto Speed also makes a range of superluminescent diodes (SLEDs) for broadcast communications in the 1280–1650 nm range. The devices have an output power of up to 25 mW in singlemode fiber, a wide optical bandwidth of 190 nm and a modulation rate of 1.25 Gbit/s. Another product, introduced in 1999, is an InP HBT preamplifier monolithically integrated with an InGaAs pin photodiode; a more recent variant now operates at 40 Gbit/s.

Corning to boost production in Italy

Corning is investing \$150 million in Corning Optical Technologies Italia (Corning OTI), the optical components and devices business it recently bought from Pirelli (see *Compound Semiconductor* November 2000, p25). This will allow the company to significantly increase its capacity for pump lasers, lithium niobate modulators, certain specialty fibers and fiber gratings.

The expansion will follow the relocation of the company's optical components device manufacturing operations from Bicocca to San Donato near Milan. The new facility is expected to be fully operational, and its employment level doubled, by the end of 2001.

Nova Crystals makes room for VCSELs

Nova Crystals, a manufacturer of VCSELs for fiber-optic and datacom applications, has secured new facilities to enable the high-volume production of long-wavelength VCSELs for short-to-long haul, high-bandwidth telecoms. Located in San Jose, California, the 40 000 sq. ft building will expand the company's production floor space fivefold. The acquisition also includes approximately \$10 million in production equipment and a dozen engineers.

"We're already experiencing tremendous demand for our proprietary VCSEL-based products," commented CEO Felix Ejeckam. "This expansion will enable us to meet this rising demand."

1310 nm VCSELs reach 10 Gbit/s

At the recent Optical Fiber Communication conference (OFC), Nova Crystals announced that its long-wavelength 1310 nm VCSEL has been proved capable of operating at 10 Gbit/s. Preliminary devices achieved 7 mW of output power and exhibited single spatial mode and single polarization state output. The company believes these devices will be the first practical VCSEL source for LAN, metro and access markets, and will offer samples to customers during the third quarter of 2001.

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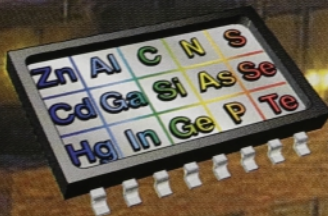
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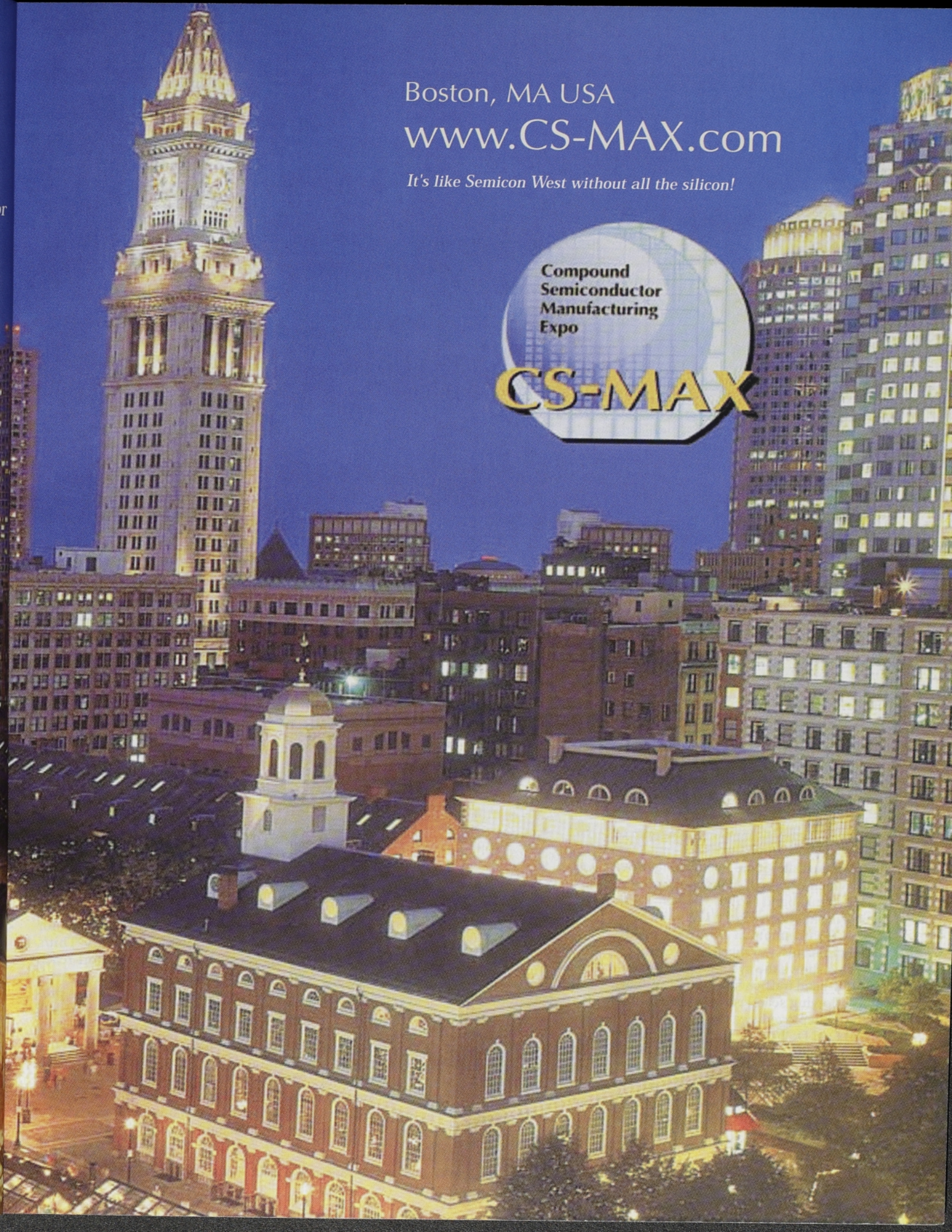
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PerkinElmer teams up with new start-up

PerkinElmer (Boston, MA) is partnering with CENiX, a recent start-up with operations in Pennsylvania and California, to develop 10 and 40 Gbit/s receivers for advanced optical networks and datacom applications. PerkinElmer Optoelectronics is a vertically integrated manufacturer of numerous components, including receivers and detectors for telecommunications and laser diodes for a range of applications. CENiX will incorporate InGaAs APD and PIN photodiodes manufactured by PerkinElmer into its optical subsystem components, which will be manufactured at CENiX's new automated 43 000 sq. ft plant in Pennsylvania's Lehigh Valley.

"This alliance with CENiX represents a significant step in further strengthening our telecom business," said John Engel, president of PerkinElmer Optoelectronics. "We are very excited about partnering with a company who can provide optical component design, development and manufacturing experience."

Xtera demonstrates S-band transmission

Xtera Communications, based in Allen, TX, has used discrete Raman technology to demonstrate the world's first multi-band transmission in the S- (1485–1525 nm) and C-bands (1530–1565 nm). The long-haul and ultra-long-haul optical networking company's eXpander product opens up bandwidth previously untapped by commercial optical networking products which use the C-band and, in some cases, the L-band (1570–1610 nm). The new system allows fiber to carry an additional 96 channels at 50 GHz spacing, with a transmission speed of 10 Gbit/s.

"This shows the system interoperability of S-band traffic with C-band systems, thus allowing seamless upgrades beyond initially deployed systems," said Xtera's COO Carl DeWilde. "In combination, the S-band and C-band will deliver the lowest cost per gigabit per kilometer."

The eXpander demo uses Raman amplifiers from Oplink Communications, and planar lightwave circuits from Lightwave Microsystems.

JDS Uniphase to reorganize following merger with SDL



JDS Uniphase's merger with SDL involved selling its pump-laser facility in Zürich to Nortel Networks.

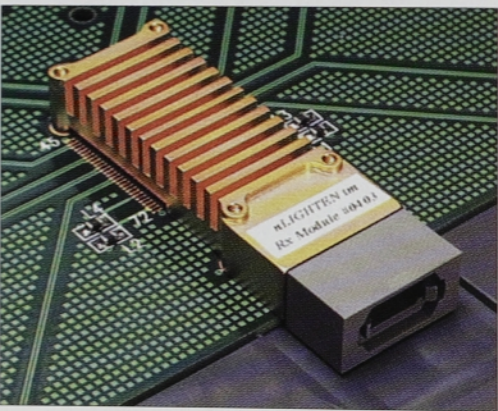
JDS Uniphase has announced plans to reorganize following the finalization of its merger with SDL, which has involved the sale of its pump laser facility in Zürich to Nortel Networks. Two new business groups have been created. One of these, the amplification and transmission busi-

ness unit, will be headed by SDL's CEO and president Don Scifres. This division will consist of several sub-groups at different locations responsible for amplification modules (e.g. Raman lasers and EDFAs), transmission modules (transmitters and receivers) and components. The last category includes 980 nm lasers manufactured by SDL, photodetectors manufactured at the West Trenton facility (formerly Epitaxx) and communications components made by the former Philips Optoelectronics unit in The Netherlands.

Jay Abbe, currently the president and COO of JDS Uniphase, will now lead the WDM, switching and thin-film products business group. This will continue the manufacture of passive products such as arrayed waveguides, MEMS devices and thin-film filters.

"With our increased technological expertise and economies of scale, we will now be able to supply new innovative component and module offerings as well as increased focused efforts for chip-level integration," said Scifres.

Trio will standardize their parallel modules



Gore will standardize its parallel modules along with Agilent and Mitel.

W L Gore, Agilent and Mitel have signed a multi-source agreement to standardize the package and the optical and electrical interfaces for their respective parallel fiber-optic modules. The move ensures access to multiple sources and compati-

bility with other system components. The trio will continue to design, develop and manufacture their products independently, and standardized designs are expected to be on offer later this year.

Parallel fiber-optic transmitters and receivers feature 12 channels operating at 1–2.7 Gbit/s per channel, for an aggregate bandwidth of 12–32.4 Gbit/s. This outstrips single-fiber and copper interconnects and allows network system manufacturers to connect higher bandwidth equipment over longer distances. The modules are designed to meet demand for network capacity in proprietary Tbit/s switch/router links, and very-short-reach OC-192 (10 Gbit/s) connections.

"The performance specifications provide for a robust link budget, and the ball grid array or land grid array interface assures compatibility with high-volume manufacturing lines," said Gore's Pete Widdoes. "Additionally the customers will benefit from the security of supply afforded by the combined capacity of multiple manufacturers."



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AXT to offer VCSELs and 980 nm lasers

AXT has announced that it will begin volume production of two types of laser, 980 nm Fabry Perot edge-emitters and ion-implanted VCSELs, adding to its substrate and nitride LED product lines. AXT recently ceased production of visible laser diodes, but is now leveraging its GaAs laser manufacturing capabilities to introduce these new products. AXT gained these facilities with the acquisition of Lyte Optronics.

Lasers operating at 980 nm, which are used to pump EDFAs, are in heavy demand. AXT's devices exhibit stable singlemode operation with output power up to 200 mW, with threshold currents below 10 mA and slope efficiency better than 0.9 W/A. The company says initial reliability tests have been favorable and long-term tests are currently under way.

The lasers are offered as unpackaged chips or in standard TO-cans, and with either Al-containing or Al-free active regions (i.e. InGaAsP or AlGaInAs). The use of Al-free active regions has been purported to reduce the occurrence of cata-

AXT recently ceased production of visible lasers, but is now leveraging its GaAs laser manufacturing capabilities to introduce new products.

strophic optical mirror damage of the mirror facets under high-power operation.

AXT's ion-implanted VCSELs are designed for applications such as coarse wavelength-division multiplexing (or

CWDM) data communications, in which a number of devices with wavelengths spaced by several tens of nanometers are used for transmission along the same fiber. Devices will be available in the 780–870 nm wavelength range; these have 13 mW output power and are capable of modulation up to 2.1 GHz.

"We continue to leverage our highly efficient manufacturing capabilities in edge-emitters with the introduction of 980 nm technology," claimed AXT's CEO Morris Young.

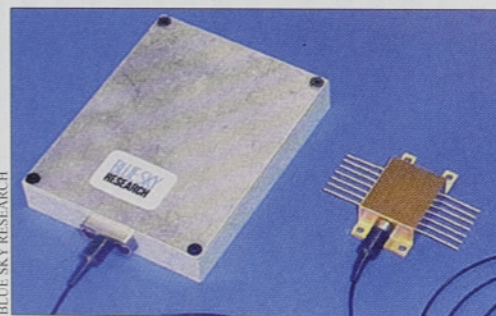
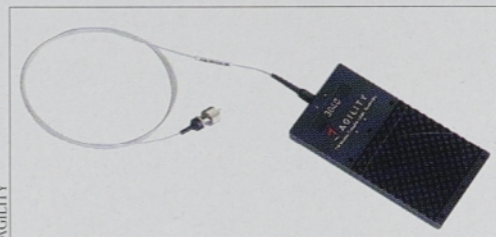
Young added that the CWDM market for VCSELs is growing rapidly. "We have made great strides in the development of our VCSEL technology over the past several months, and continue to invest heavily in this area. AXT is committed to being a leader in the VCSEL arena."

Laser suppliers tune up to standardization

A number of tunable laser suppliers have been hitting the headlines recently, announcing new products, receiving large funding rounds or promoting the development of standards for tunable products. However, all tunable technologies are not the same. While companies such as Agility and ADC (which purchased the Swedish company Altitun) have developed single-chip solutions, other manufacturers – New Focus, Iolon and Blue Sky Research, all based in San Jose, CA – have introduced products based on external cavity designs. In this approach, a standard laser chip is placed within a cavity that can be adjusted in order to tune the output wavelength of the device.

Iolon has received a total of \$69 million in funding during the last eight months to develop and ramp up production of its first widely tunable laser product. Tuning is achieved by a movable mirror that directs light onto different parts of a diffraction grating – the mirror is turned using a small actuator manufactured in MEMS technology. The company claims the device can deliver 20 mW of power, and that it is tunable across a 40 nm wavelength range.

Blue Sky Research has used a different approach – its external cavity does not



Tunable DBR lasers (top) and external cavity lasers (bottom) have both now reached the market.

use mechanical tuning. Instead the device has a micro-etalon wavelength locker that is controlled electronically, providing switching speeds in the microsecond–picosecond range. The device employs relatively low-cost Fabry Perot laser diodes (which are obtained from external sources) and allows narrowband tuning to channel spacings of 50 GHz, with a 25 GHz product in development.

New Focus also claims 20 mW output power for its PowerTune module, which

integrates a high-power laser, a wavelength locker, power control and other control functions and covers the entire C-band (1528–1563 nm). For more details see page 34.

In contrast with the 20 mW products from Iolon and New Focus, Agility's tunable sampled grating DBR laser has an output power of 4 mW. The device has four sections including two DBR gratings; tuning is provided by varying the current to these sections.

The path to standardization

Several efforts are under way to develop standards that will enable customers to design their systems more easily around common tunable laser interfaces. After reports emerged that Agility, Iolon and New Focus had held discussions with the Optical Internetworking Forum (OIF), ADC and Agility announced an initiative to promote the tunable laser industry's initial standards for a 40-pin parallel form factor, electronic interfaces and host-level software commands.

"We believe this initiative will greatly benefit all customers who have a demand for tunable lasers," said Rob Plastow, chief technology officer of ADC's fiber-optics division. "In an evolving marketplace, the ability to provide compatible products with similar interfaces will speed network deployment, while ensuring product quality and reliability."

CD and DVD laser prices fall

Prices for the semiconductor lasers used in optical pickups for CD and DVD drives are falling rapidly in Japan, according to a report in the Nikkei Industrial Daily. Demand for CD-ROM lasers (low power 780 nm AlGaAs-based devices) is falling as major computer manufacturers adopt CD-R/RW and DVD-ROM drives as standard features in their new units. The drives require higher-powered 780 nm lasers, and 650 nm lasers, respectively. As a result, inventory levels for CD-ROM lasers are rising and prices have dropped about 30% since spring 2000 when the lasers were priced at ¥50-60 (43-52 cents) per unit in large volumes. In addition, prices are falling for lasers used in 4× CD-R/RW units as manufacturers compete to make faster (8× and 12×) drives.

Meanwhile, prices for the optical pick-

ups used in DVD and DVD-ROM drives have also fallen, in some cases by more than 10%, since the start of the year. Demand was not as high as expected during the holiday season at the end of last year, due in part to the slowdown in the US economy. The Nikkei Industrial Daily reports that the most common type of optical pickup, which can be used in CD and CD-RW drives as well as DVD drives, is currently selling for ¥1500-1600 (\$12.9-13.7) in large volumes. This is down 12% from the 2000 October-December quarter.

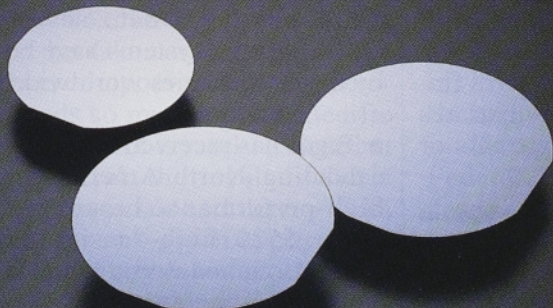
One pickup maker was quoted as saying that some equipment manufacturers have enough inventory to last through to mid-May, which should keep prices down. The situation is markedly different from last summer, when these components were in short supply and OEMs were scrambling to secure supplies in advance.

NEC plans fabless model for spin-off

NEC has fleshed out details of the planned spin-off of its Compound Semiconductor Device Division later this year (see *Compound Semiconductor* February 2001, p4). Effective October 2001, the new company will operate on a "fabless semiconductor company" business model. Manufacturing will initially be performed at current NEC and contractor facilities. Upon divestiture, the new company will be free to pursue new manufacturing relationships.

The spin-off will be headquartered in Kawasaki, Kanagawa Prefecture in Japan, with R&D development facilities in Kansai. First year sales are expected to amount to around \$1.02 billion. NEC will retain full ownership of the new enterprise, with an initial public offering planned within two years.

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Furukawa Electric plans two new plants

Furukawa Electric plans to boost production of components used for WDM systems, citing a continued increase in demand in the medium term despite indications of slowing growth in the US fiber-optic market. To meet this demand, it plans to invest about ¥10.2 billion (\$89 million) to build new production facilities in Japan and Thailand.

Furukawa recently invested ¥3 billion (\$26 million) to set up a wholly owned subsidiary in Thailand, including a pro-

duction facility with 10 000 m² of floor space. This summer, the Furukawa Fitel Thailand unit will start producing fiber-optic components including source and pump lasers, as well as fiber Bragg gratings. The company expects to manufacture 100 000 pump lasers per month, with sales expected to reach \$300 million in 2002. Furukawa will also spend ¥7.2 billion (\$63 million) to build a second facility and an engineering center at its Chiba plant in Japan.

Showa Denko boosts epiwafer production

Showa Denko will invest ¥2 billion (\$17 million) to build an epitaxial wafer production facility at its Chichibu plant in Saitama Prefecture, Japan. The company says demand for InP devices has been surging in recent months. Due to be completed by November, the 32 000 sq. ft facility will increase the company's MOCVD-based epiwafer production by around 10 times compared to one year ago.

MATERIALS & EQUIPMENT

AXT completes substrate supply guarantee program

AXT (Fremont, CA) recently announced the completion of its substrate "Supply Guarantee Program" for 2001, which was implemented last September. Under the program, AXT supplied an agreed amount of wafers to participating customers at predetermined delivery dates and prices in exchange for partial non-refundable payments in advance. A portion of AXT's substrate capacity was allocated

to the program, which was initiated to address concerns over wafer shortages and availability.

To date, AXT has reached agreements with nine customers for GaAs and InP wafers totaling \$91.6 million over the course of 2001. While the program is finished for 2001, AXT will sell substrates under short-term purchase contracts or agreements with no prepayment.

Equipment orders in brief

● **MBE Technology Pte** has placed an order for two **Riber** reactors: one MBE6000 (4 × 6 inch) and one MBE7000 (7 × 6 inch). Three multiwafer systems are already in production at MBE Technology's facility in the Singapore Science Park. To date, seven of Riber's new 7 × 6 inch systems have been ordered by major foundries worldwide.

● **Tegal** has received a repeat order from a leading North American supplier of high-performance broadband networks for a 6520 high-density plasma etch system. Scheduled for installation in June 2001, the system will be used for HBT/HEMT gate mesa and recess etch as well as other compound semiconductor device etching processes.

● **KDF** has received an order for three in-line sputtering tools from a major supplier of components to the fiber-optic communications industry.

● Munich-based **Karl Suss** has received multiple orders for its recently introduced M6000L metal lift-off cluster system (see Product Showcase) from a North American GaAs wafer fab.

● **Ultratech Stepper** has received an order from **Branchy Technology** of Taiwan for a photolithography tool that will be used to manufacture GaAs components, in particular SAW filters.

Aixtron qualifies Mochem's precursors

Mochem (Marburg, Germany) has received qualification of its range of TBA (tertiary butyl arsine) and TBP (tertiary butyl phosphine) precursors using Aixtron's production MOCVD reactors. Mochem says its high-purity Epiproof group V liquid metallorganics have reduced toxicity and lead to fewer waste

products, longer equipment uptime and a capability for low temperature epitaxial growth steps. The company began developing TBA and TBP precursors in 1993 with research funding from the German Ministry of Science and Technology and ongoing research efforts with the University of Marburg and Aixtron.

JMAR receives funding for XRL development

JMAR Technologies (San Diego, CA) has received an additional \$9 million of funding from the US Army Research Laboratory/DARPA to continue development of its X-ray lithography (XRL) source. JMAR was recently awarded \$3.8 million from the same agency to integrate the company's 25 W collimated

laser plasma X-ray source with a lithography stepper manufactured by SAL (South Burlington, VT). The collimator directs the X-rays with a wavelength of 1 nm onto the mask/wafer target. JMAR is to produce a fully integrated XRL system for installation in an established GaAs manufacturing facility.

Axcel buys Temescal evaporation system

Temescal (Fairfield, CA) has shipped a BJD-1800 evaporation system to Axcel Photonics, a recent start-up company that develops and manufactures optoelectronic devices for telecommunications markets. The new system will be housed

at Axcel's new 18 000 sq. ft manufacturing facility in Marlborough, MA. According to director of operations Kurt Linden, the facility will house epitaxial growth systems as well as equipment to manufacture, package and qualify laser diodes.

SDL orders Aixtron MOPVE reactors

SDL, the leading manufacturer of GaAs-based 980 nm pump lasers, has ordered two MOVPE systems. Aixtron, who will deliver the AIX 2400G3 reactors by September, says the systems will be used

in the manufacture of InP-based lasers. These are most likely to be 1480 nm pump lasers for EDFAs and/or 1400–1500 nm lasers for Raman amplifiers. SDL is now part of JDS Uniphase.

MKS Instruments buys On-Line Technologies

On-Line Technologies (East Hartford, CT), which designs and manufactures gas analysis and wafer metrology products based on its proprietary FTIR spectrometer, is to be acquired by MKS Instruments (Andover, MA). MKS Instruments' current portfolio includes Baratron pressure controllers and Mass-Flo delivery products. On-Line's FTIR systems allow measurement of properties such as composition, doping level and thickness, and allow device makers to optimize performance, yield and productivity.

SILICON UPDATE

Quantum cascade lasers light it up

Bob Metzger describes a recent development in SiGe-based IR quantum cascade lasers.

For electronic applications in which performance, cost and system requirements must be taken into account, the silicon versus compound semiconductor debate depends so much on the specific application that there is rarely a clear cut winner. In general, the result is that a wide range of materials and device types may be used for any given application. However, when it comes to optoelectronics, III-V materials are clearly the material of choice, with the availability of a wide range of direct bandgap materials permitting highly efficient radiative transitions across the bandgap.

Unfortunately for silicon, which has an indirect bandgap, large momentum transfers are required for radiative transitions, making this a highly inefficient process. Even with the advent of $\text{Si}_{1-x}\text{Ge}_x$ alloys, the heterostructures formed with silicon usually feature staggered band offsets, so that the electrons and holes are spatially separated, once again making radiative transitions highly inefficient.

The intersubband approach

A potential solution to these difficulties is the one currently being used to fabricate far infrared lasers using a unipolar quantum cascade approach, in which tran-

sitions between quantum well levels within a band (intersubband transitions) are used to generate laser light. Researchers from the Paul Scherrer Institute in Switzerland, the University of Neuchâtel in Switzerland and the ETH (Swiss Federal Institute of Technology) have described the use of intersubband transitions to generate intersubband electroluminescence in a silicon-based quantum cascade structure (G Gehlinger *et al.*).

Unfortunately for silicon, which has an indirect bandgap, large momentum transfers are required for radiative transitions, making this a highly inefficient process.

Implementing a high quality intersubband structure in $\text{Si}_{1-x}\text{Ge}_x$ is considerably more challenging than for InGaAs/InAlAs. This is due to several factors: the large strain resulting from the 4% lattice mismatch between silicon and germanium; the complex valence band structure, which includes coupled heavy and light hole bands, along with larger effective masses; small band offsets that make carrier confinement difficult; and heterointerfaces that are generally optically and

electrically inferior to III-V interfaces.

Despite these challenges, the researchers have fabricated a quantum cascade structure based around an active QW situated between injector and collector wells. A $\text{Si}_{0.68}\text{Ge}_{0.32}$ QW of width 4.0 nm was situated next to four coupled SiGe QWs which formed a mini-superlattice. The main well contains two quasi-bound heavy hole states (HH1 and HH2) separated by approximately 130 meV. The mini-superlattice is designed so that when biased with an electric field of 50 kV/cm, a series of states in the mini-superlattice have a near overlapping energy with the HH1 level, permitting easy tunneling into the QW. In addition, there exists a mini-gap for both heavy hole and light hole states around the energy level of the HH2 state. This quenches transport out of the HH2 state, which in turn increases the probability of a radiative transition between the HH1 and HH2 states.

Laser growth

Growth was by MBE at a relatively low temperature of 350°C to avoid strain relaxation and germanium segregation. TEM examination indicated a coherent strain in the layers with no observed threading dislocations or buckling of >>

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SILICON UPDATE

the interfaces. Square mesas ($420 \times 420 \mu\text{m}$) were fabricated with aluminum contacts at the front and back.

Luminescence demonstration

Luminescence was observed for temperatures as high as 180 K. At a temperature of 50 K, and a current of 250 mA (3.65 V bias), the emission energy was 125 meV, closely corresponding to the expected energy difference between the HH2 and HH1 states, producing a wavelength of around $10 \mu\text{m}$. The full width at half maximum of the EL peak was 22 meV, a value comparable to the narrowest absorption linewidths reported for Si/SiGe heterostructures, indicating that the heterointerfaces were of good quality. However, the EL response to injected current was very weak, indicating very low quantum efficiency. It was suspected that there was poor confinement of holes in the HH2 level since this state lies only 80 meV above the valence band edge, and at high electric fields, the holes could tunnel out through electric-field-induced barrier reduction.

More confinement

In an attempt to improve HH2 confinement (and thereby quantum efficiency), the germanium content of the well was increased from 32% to 41% and the well width increased from 4.0 nm to 4.5 nm. A significantly lower current was required to obtain EL for this structure, and it is estimated (by calibration compared to a known InGaAs/InAlAs LED) that the quantum efficiency of this device was approximately 10^{-5} . This figure is some two orders of magnitude greater than the first structure, while the linewidth was broadened by about a factor of two.

Even though the device only exhibited luminescence, it clearly demonstrated that the cascade intersubband approach, which has been so successful in III-V materials for extending lasing wavelengths into the far infrared, is also applicable to silicon-based devices. Further improvements in device performance and design latitude should be possible by fabricating these structures on relaxed SiGe buffer layers, thereby allowing higher germanium content in the QWs, which will improve hole confinement and quantum efficiency.

Further reading

G Gehlinger *et al.* December 2000 *Science* **290**(22) 2277.

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OADM's set for huge growth

The global consumption of optical add/drop multiplexers (OADM's), an extremely important factor in the increased use of optical communications, will accelerate from \$135.2 million in 2000 to \$3.46 billion in 2005, then expand further to \$29.8 billion by 2010, according to ElectroniCast Corp. The company defines the OADM as a single-fiber unit, i.e. one fiber in, one out. Units will advance from the currently available 16 wavelength fixed-connection modules to 256 wavelength fully reconfigurable units and eventually to 1024 wavelength capacity. To achieve this, the following components are needed by early 2005:

- laser diodes with high powers and precise wavelengths for 50 GHz spacing, covering the nominal 1260–1660 nm band;
- optical fiber amplifier systems spanning the 1260–1660 nm band with uniform high gain and acceptable noise level;

Growth forecast for OADM*

Global shipments (\$ million)	2000	2005
OADM's	135	3460
Optoelectronic components in OADM's	37	798

*Total market value refers to assembled hardware modules only, and excludes software and other system-level costs.

- 1024×(2×2) transparent optical cross-connect switches.

Optoelectronic components such as amplifiers, receivers and transponders comprise just over half of the total OADM component cost, which in turn makes up about half of the OADM value.

"OADM and Components Forecast" is available from ElectroniCast – see "www.electronicast.com".

Broadband drives millimeter wave growth

Over the next five years, the total millimeter wave and high frequency market – including module level equipment and components – is set to grow at 29% per year from \$3.5 billion in 2000 to \$12.4 billion by 2005. ABI cites explosive growth in applications such as LMDS and broadband satellite systems. In addition, automotive applications such as collision warning radar will also gain in importance. Shipments of these systems, which use GaAs MMICs operating at 76 GHz, are expected to exceed a total of 1 million units in trucks and passenger cars within five years. In the near term, LMDS will be the key market driver. While only accounting for 9% of the market at present, this

application is expected to grow at a rate of 30% over the next five years. High expectations still prevail for broadband satellite systems, says ABI. Although MMDS and fixed wireless systems operating at 3.5 and 5.8 GHz could temper satellite sales, total shipments of broadband customer premise equipment are still expected to exceed 2 million units in 2005. Driving these applications will be further advances in high frequency GaAs MMICs. The market for these devices will exceed \$200 million in the next five years.

"Millimeter Wave: Broadband, Automotive Radar and Semiconductors" is available from ABI – see "www.alliedworld.com".

Free space optics firms face demand surge

Free space optical technologies are expected to result in a \$1 billion market early in 2003. According to Allied Business Intelligence (ABI), after more than a decade of low growth, free space optical vendors will face an onslaught in demand. Free space optics employs transceivers to send modulated data through the atmosphere, relying on line of sight to make connections between hubs and customer premises.

"A major shift is underway in the free space optical market," says Andy Fuertes, ABI's VP of Communications Technologies. "While these technologies were used for years in niche applications, they're ready for the delivery of broadband capabilities in mainstream carrier networks."

Deployments are expected to be in urban environments, a market the technology will share with LMDS. Traditional applications are also expected to grow, but the carrier/access market will overshadow all other segments of the market within five years. "The leading applications for free space optics in 2000 were wireless bridges," adds Fuertes. "However, in 2005, carrier/access applications are expected to account for over 70% of the market."

"Free Space Optics: Technologies and Opportunities in the Carrier Class Network" is available from ABI – see "www.alliedworld.com".

Year	FSO transceiver shipments worldwide (\$ millions)
2000	118.8
2001	492.0
2002	885.6
2003	1536.1
2004	2659.5
2005	4400.3

North American opto markets to expand

The North American market for optoelectronic components, which generated revenues of \$1.97 billion in 1999, is set to grow to \$10.11 billion in 2006, according to Frost & Sullivan. The study identifies LEDs, photodetectors and laser diodes as

the fastest-growing segments, while an important market also exists for IR optocouplers. Driving this expansion are developments in high brightness GaN-based blue and green LEDs, which have greatly expanded the scope for applications in automotive, video displays, signage and traffic signals. Also, InP-based laser diodes are widely used as the primary light sources in the fiber-optic communications

market, and vertical emitters are providing a highly manufacturable, low-cost light source suited to both telecom and datacom applications. The photodetector segment in particular is expected to produce high returns by integrating photodetectors with laser diodes in transceiver modules.

"North American Optoelectronics Markets" is available from Frost & Sullivan – see "www.frost.com".

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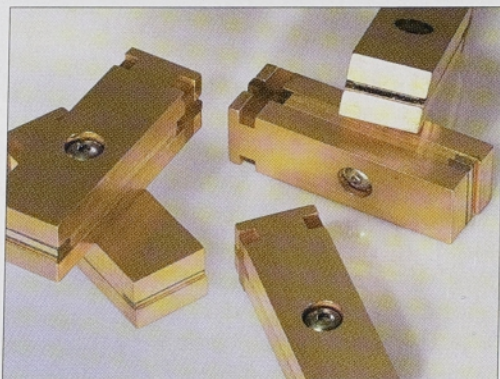
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OPTO PRODUCTS

Spectra-Physics offers new 50 W laser bars

Mountain View, CA. Spectra-Physics Semiconductor Lasers (formerly Opto Power) has introduced a new line of 50 W laser bars. The Prolite series is offered in the 800–830 nm wavelength range and is designed for hair removal and for pumping solid-state media with high reliability and long lifetime (more than 10 000 hours at rated power).

The company's new Raman fiber laser, the Streamline RL, consists of a rack-mounted box containing a single 35 W semiconductor laser-bar laser source, the fiber laser, a cascaded Raman

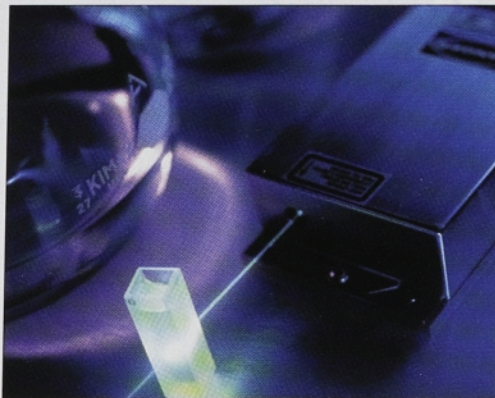


cavity and all associated power and control electronics. Delivering more than 5 W of randomly polarized power from a singlemode fiber, the turnkey system is offered at wavelengths of 1450, 1455 and 1480 nm. The product is designed for telecom component development and Telcordia reliability testing.

www.spectra-physics.com

Coherent laser focuses on argon applications

Santa Clara, CA. Coherent Laser Division has developed a prototype 488 nm laser. The device is targeted at applications dominated by air-cooled argon lasers, from DNA sequencing through to printing and photo processing. Currently in beta testing, the OPSL-488 is an optically pumped 976 nm VCSEL-type structure grown by MBE, with a frequency doubled element



to produce 20 mW at 488 nm.

Coherent has also introduced a diode-pumped UV laser producing 4.5 W of power at 355 nm. The AVIA device is pumped by two field-replaceable Al-free active area diode modules, also manufactured by Coherent.

www.coherentinc.com

Vishay releases set of multimedia products

Malvern, PA. Vishay Intertechnology has released several new products. The TSOP7000 IR receiver module combines a photodetector and pre-amplifier operating at a 455 kHz carrier frequency for use in multimedia end products. The device operates at up to 20 kbit/s over transmission distances of up to 20 m. A new range of optocouplers feature a thin 2 mm profile and consist of a phototransistor optically coupled to a GaAs IRED. Intended for current isolation, the eight new TCMT11xx Miniflat optocouplers are designed for PCMCIA cards, notebook modems, telecommunications products and programmable logic controllers.

www.vishay.com

WIRELESS PRODUCTS

Infineon launches a Tri-band PA module

Munich, Germany. Infineon has designed a new PA module for mobile phones used in 900, 1800 and 1900 MHz bands, enabling users to roam between GSM, PCN and PCS networks. The

CGM20GTriB is based on the company's GaAs MESFET process and employs a low-temperature co-fired ceramic (LTCC) substrate. The maximum output power of 34.5 dBm for GSM and 32.0 dBm for PCN/PCS (supply voltage of 3.2 V) is achieved for an input power of only 3 dBm.

The CGM20GTriB is based on the CGM20G, a dual-band GSM/PCN PA module that supports data rates of 57.6 kbit/s in the uplink – four times greater than standard GSM phones. The CGM20GTriB is sampling now and will be available in high volume by the middle of 2001.

www.infineon.com

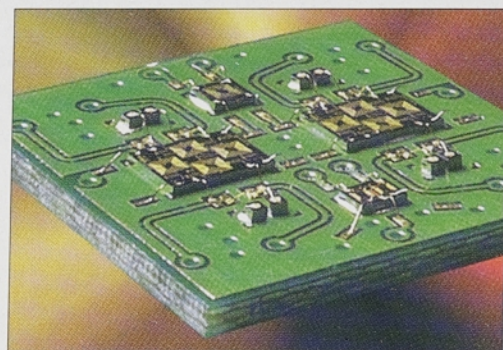
Qualcomm delivers W-CDMA solution

San Diego, CA. Qualcomm CDMA Technologies has introduced a W-CDMA power amplifier module for IMT-2000 (1920–1980 MHz) applications. The PA5200 contains all components including Mobile Station Modem baseband, transmit and receive processors. Based on RFMD's GaAs HBT process, the module is offered in a $6 \times 7.5 \text{ mm}^2$ 13-pin land grid array package and includes bias control and compensation. The module delivers 27 dBm linear output with 26 dB gain.

www.qualcomm.com

MCM modulator from Alpha aids integration

Haverhill, MA. Alpha has launched an eight-chip vector modulator multi-chip module (MCM) for integration into base stations and 2.5 G data transmission systems. The modulator allows 360° of



phase control and a large linear amplitude adjustment range. Mixed technologies can be integrated to cover the AMPS through the W-CDMA range with less than 15 dB insertion loss, and IP3 intercepts of +22 dB with switching speeds of less than 10 ns.

www.alphaind.com

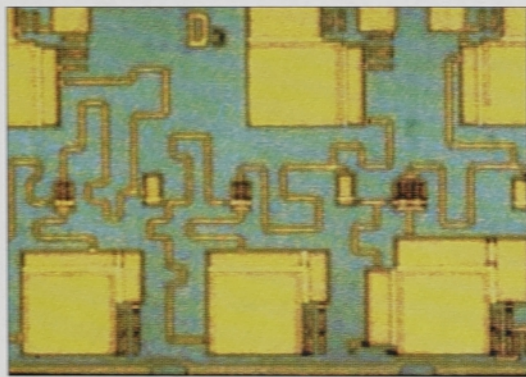
Anadigics amplifier improves the picture

Warren, NJ. Anadigics has introduced a high-performance balanced linear amplifier targeting residential gateway, set-top box and other digital interactive cable devices. The ABA3100 is a single supply GaAs MMIC circuit that delivers 12 dB gain across the 50–860 MHz CATV bandwidth, with an IP2 of +60 dBm. Noise of less than 3.2 dB allows the device to serve as an LNA that can compensate for loss of signal in digital set-top boxes. Other applications include base stations, driver amplifiers and CATV drop amplifiers.

www.anadigics.com

Fujitsu expands LNA MMIC product line

San Jose, CA. Fujitsu Compound Semiconductor has expanded its LNA MMIC line with two new millimeter-wave products. Designed for low noise and high dynamic range applications such as point-to-point or point-to-multipoint radio links and LMDS, both devices offer an output power of up to



9 dBm and 18 dB power gain. The FMM5703X operates from 24 to 32 GHz and the FMM5704X covers the 36–40 GHz frequency range.

www.fcsi.fujitsu.com

Raytheon unveils a 5 GHz radio chipset

San Jose, CA. Raytheon has released Tondelayo, a 54 Mbit/s radio chipset based on the IEEE 802.11(a) standard for high-speed wireless networks in the 5 GHz UNII band. The chipset includes a power amplifier/switch module, together with RF, IF and baseband chips. Volume production and delivery are planned for the third quarter of 2001.

The RTPA-5250 PA/switch was developed using Raytheon's 0.5 μ m GaAs PHEMT process and features T/R and antenna selection switches in addition to the amplifier gain stages, providing lower loss, an improved noise figure and fewer parts. The RTCV-5500



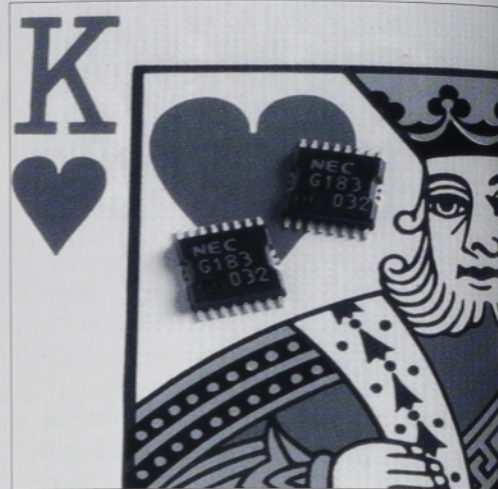
LNA up/down converter and RTIF-5500 IF converter ICs are SiGe-based and provide 73 dB of receive gain, 60 dB of programmable attenuation and 7 dB transmit attenuation. The baseband IC was developed in CMOS.

Raytheon named the chipset in memory of Hollywood actress Hedy Lamarr, who starred as the character "Tondelayo" in a 1942 movie, and who is also credited as the original patent-holder for Spread Spectrum technology.

www.tondelayo.com

NEC's GaAs switch aids down-conversion

Santa Clara, CA. CEL has announced a 4 × 2 GaAs switch for down-conversion used in DBS receiver applications. Manufactured by NEC, the UPG183GR provides four independent IF input



channels that can be internally switched to one of two output channels. Operation is in the 950 to 2150 MHz range, with an insertion loss of 7 dB at 50 Ω for a 26.5 dB channel-to-channel isolation.

www.cel.com

Agilent releases new E-PHEMT products

Santa Clara, CA. Agilent has introduced a new small-signal E-PHEMT, the first in a family of transistors for GSM and W-CDMA systems and other applications up to 6 GHz. The ATF-54143 eliminates the negative voltage supply, and can be used as LNAs in applications that benefit from the space and power savings afforded by a single positive supply voltage. The noise figure is typically 0.45 dB at 2 GHz, increasing to 0.9 dB at 5 GHz.

www.agilent.com

RFMD offers mixer for handset market

Greensboro, NC. RFMD is offering a new dual-band LNA/mixer for the emerging TDMA/GSM handset market. The RF2492 is a complete receiver front-end that has dual IF outputs which interface with two independent IF SAW filters, supporting TDMA and GSM/GPRS where 30 kHz and 200 kHz IF bandwidths are used. The RF2492 provides 24 dB cascaded gain and 2.9 dB cascaded noise figure. Production quantities will be ready for shipment in the second quarter of 2001.

www.rfmd.com

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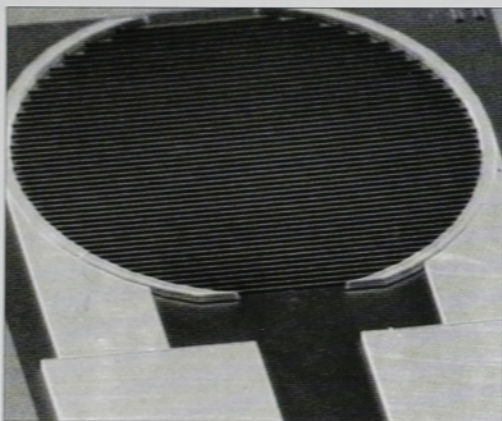
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FIBER PRODUCTS

OptoLynx offers high-speed photodetector

West Lafayette, IN. OptoLynx has released a line of high-speed GaAs and InGaAs MSM photodetectors along with a series of GaAs PINs. Data rates of 10 Gbit/s are easily achievable with these devices. Photodetector active area, capacitance and responsivity will vary with bandwidth and application.

The devices are available as single element detectors or in array form. Applications include serial and parallel Gigabit Ethernet, Fibre Channel, monitor



diodes, POF, backplanes, etc. InGaAs PINs are in development, with amplifier circuits and monolithically integrated photoreceivers to follow. Custom designs and configurations are available. www.optolynx.com

OCP launches line of DWDM transmitters

Chatsworth, CA. Optical Communication Products (OCP) has unveiled a family of DWDM optical transmitters for metropolitan-area networks. The DWTX-48 series lasers are designed to work from 100 Mbit/s to 2.5 Gbit/s and meet or exceed SONET/SDH standards for DWDM OC-48/STM-16 Long Reach 1550 nm (80 km) specifications. They can also be used to transmit data in Fibre Channel, Fast Ethernet and Gigabit Ethernet formats. The devices are housed in a low-profile 24-pin package and operate from a single +3.3 V supply. www.opc-inc.com

Vitesse ICs improve the capability of fiber

Camarillo, CA. Vitesse has introduced 10 products (see table), including laser drivers, limiting amplifiers and TIAs for transceivers and transponders used in OC-48 SONET/SDH DWDM systems operating at up to 3.125 Gbit/s, as well as Gigabit Ethernet and Fibre Channel.

"The designers of communications equipment need to optimize a fiber's capability by having a longer module reach, excess margin on the data eye opening and a low dispersion penalty," said Vitesse's Ray Milano. "These new devices provide this and more in low-cost packages [or die form], that are guaranteed to run at today's higher required temperatures."

www.vitesse.com

Something for everyone: Vitesse's new 3.125 Gbit/s devices

Part	Function	Supply voltage	Package type	Key features
VCS7807	2.125 Gbit/s MSM diode and TIA	3.3 V	TO-46, TO-56 or die	Excellent receive sensitivity
VCS7709	1.25 Gbit/s PIN diode and TIA	3.3 V	TO-46, TO-56 or die	Excellent receive sensitivity
VCS7938	Laser diode driver	3.3 or 5 V	48-pin TQFP or die	Automatic power control (APC), slow start mechanism
VCS7939	Laser diode driver	3.3 or 5 V	32-pin TQFP or die	APC
VCS7940	Laser diode driver	5 V	32-pin TQFP or die	APC plus 100 mA modulation current
VCS7959	Limiting amplifier with CML outputs	3.3 or 5 V	16-pin TSSOP or die	Loss of signal detect (LOS)
VCS7960	Limiting amplifier and laser diode driver with CML outputs	3.3 V	48-pin TQFP or die	APC plus LOS
VCS7961	Limiting amplifier with PECL outputs	3.3 or 5 V	16-pin TSSOP or die	LOS
VCS7962	Limiting amplifier and laser diode driver with PECL outputs	3.3 V	48-pin TQFP or die	APC plus LOS
VCS7969	TIA and limiting amplifier	3.3 or 5 V	16-pin TSSOP, TO-46 incl. PIN detector or die	No external components required

Agilent DFB laser modules reduce costs

Palo Alto, CA. Agilent Technologies has announced the development of a new family of 20 mW (+13 dBm) DFB laser modules designed to cut costs and increase throughputs in the R&D and manufacturing of optical amplifiers and DWDM systems. The 81663A offers full remote control, compatibility with Agilent compact tunable lasers, return loss and DFB source modules, single and dual-channel power meters and optical test mainframes, and the ability to install a maximum of 17 DFB modules in a single mainframe.

www.agilent.com/comms/DFB

New Focus unveils widely tunable laser

San Jose, CA. New Focus has launched what it says is the industry's first widely tunable laser. Designed to provide dynamic bandwidth allocation and ease laser inventory logistics in telecom and metro network applications, PowerTune integrates high-power laser, wavelength locker, power control and other control functions into a module capable of 20 mW (+13 dBm) over the entire C-band (1528–1563 nm). New Focus plans to deliver PowerTune samples to DWDM systems customers in April, with production slated for late 2001.

www.newfocus.com

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Components market reaches \$18 billion

The market for compound semiconductors has more than doubled in two years to be worth \$18 billion. Tom Hausken of market research firm Strategies Unlimited explains why.

The market for components based on compound semiconductors reached nearly \$18 billion in 2000 – more than doubling in just two years. Although the industry is still dwarfed by the market for components based on silicon, this is a remarkable increase. And while growth is slowing down from these extraordinary levels, sales in 2001 are expected to show a strong increase.

Figure 1 presents the total market for compound semiconductor components for the last seven years. The overall market grew nearly 60% from 1999 to 2000. The market is still dominated by optoelectronics – 2000 sales hit \$14.2 billion, a growth of 67% compared with 1999. Electronics represents \$3.6 billion in sales, a growth of 34% since 1999.

Demand in the communications sector, both wireless and fiber optic, led to most of the growth last year (see figure 2). Communications applications amounted to more than 60% of the market for compound semiconductor products. The market for the visible LEDs used in lamps and displays is also growing rapidly, making up more than 16% of the total. The remaining applications include laser diodes for optical storage (DVDs and CDs), office machines, industrial, medical, aerospace and solar panels.

Optoelectronics

Figure 3 presents a breakdown of the sales in 2000 of optoelectronic components by the type of device. This excludes image sensors and detectors based on silicon rather than compound semiconductors. The market is a mixture of high-volume and low-volume products. On the high-volume and low-price end are lasers for optical storage and visible LEDs. On the relatively low-volume but high-priced end are telecom modules.

Telecom The telecom components market (lasers and detectors) had the most promi-

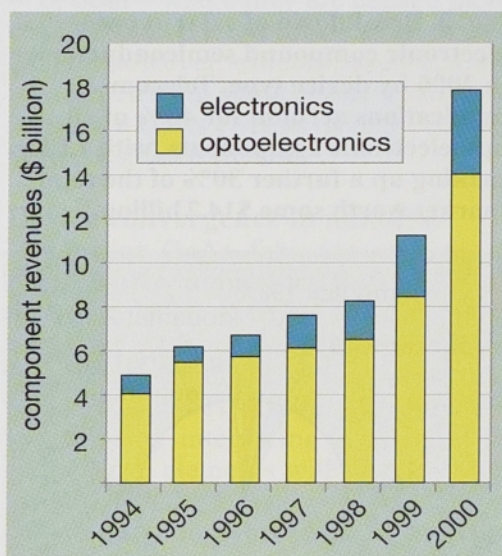


Fig. 1. The market for compound semiconductors grew by nearly 60% from 1999 to 2000, reaching almost \$18 billion. Optoelectronic components remains the dominant sector.

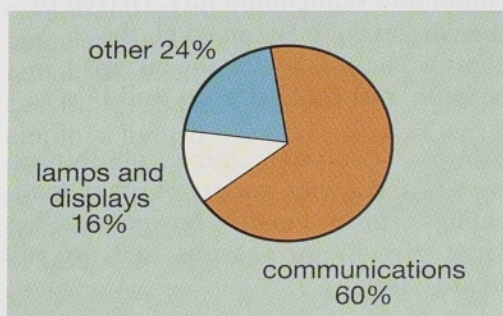


Fig. 2. Breakdown of the 2000 market for compound semiconductors. Most components were used in fiber-optic and wireless communications.

nence in 2000, growing more than 160% to \$6.3 billion. While the overall unit sales of telecom products are still lower than in other sectors, the unit sales of some products have swelled by orders of magnitude. And although prices of individual products decline rapidly, innovation happens so quickly that the mix of products rapidly evolves to higher-

performance products that bring high prices. One of these developments is the phenomenal success in 2000 of 10 Gbit/s transmission, leading to surging sales of expensive components for transmitters and receivers. An emerging development is wavelength tunable lasers that enable flexible provisioning of wavelengths in all-optical networks.

Another key development is the integration of the optoelectronics with ever more electronics and passive optical devices. This integration removes a design and manufacturing burden from the customer, and reduces the physical footprint of the overall ensemble of devices. As the industry migrates to the use of these modules over discrete components, the selling price rises with the value of the module, even as the prices of the individual sub-components fall dramatically.

Datacom The market for so-called datacom components grew 31% to \$1.1 billion in 2000. The datacom market differs substantially from the telecom market even though both are used for data communications. The datacom market is one of transceivers chiefly designed for Ethernet or Fibre Channel protocols for short-range links, usually at short wavelengths (850 nm). The transceiver product, while now evolving to data rates as high as 10 Gbit/s, represents little integration with the surrounding elements on the board. The end user is an enterprise rather than a carrier, and the all-round emphasis is much more on cost than performance.

The mix of datacom products is migrating toward higher value – mainly due to increasing data rates – but overall sales are more subject to falling prices. Consequently, while datacom transceivers represent higher unit sales than pairs of telecom sources and detectors, revenue and growth in revenue are less in the datacom market.

Datacom suppliers have often threat-

ened to offer a "disruptive technology" to the telecom sector by introducing low-cost manufacturing principles into the high-end communications business. The convergence is not simple: greater aggregation of data, longer distances and carriers' demands for very high reliability drive the performance requirements on each component to the very limit of today's technology.

Put another way, telecom products must exhibit virtuosity in sheer performance, while datacom products must exhibit virtuosity in manufacturing. What is now happening is that the two sectors are naturally migrating closer using principles borrowed from each other. For example, datacom suppliers are looking toward long wavelengths and even WDM, while telecom suppliers now have the sales volumes to implement lower-cost manufacturing methods.

It is becoming impossible to identify some products as fundamentally datacom or telecom. This development is not so much disruptive as it is a matter of the industry maturing to reach the next stage of volume production.

Visible LEDs The visible LED market grew 24% in 2000 to \$2.9 billion for applications in lamps and displays. The strongest contribution is from high-brightness LEDs, which now form a rapidly growing market, with such emitters appearing in car tail, turn and brake lights, exit signs and green and red traffic signals. Large-screen displays, such as the one used at Times Square in New York City, are becoming more prominent. These displays offer brilliant color resolution even in bright daylight.

High-brightness LEDs are also seeing strong growth from applications as backlights for the liquid-crystal displays (or LCDs) in cellular phones and car stereos.

Other lasers Laser diodes used for non-communication applications grew 60% to \$1.5 billion in 2000. These are used for a wide variety of applications including optical storage (such as various types of DVDs and CDs), laser printers, barcode scanners, laser pointers, materials processing and instrumentation.

Infrared LEDs The infrared LED business grew a healthy 22% in 2000 to \$1.4 billion. Infrared LEDs are used in remote-control units, rotary encoders for

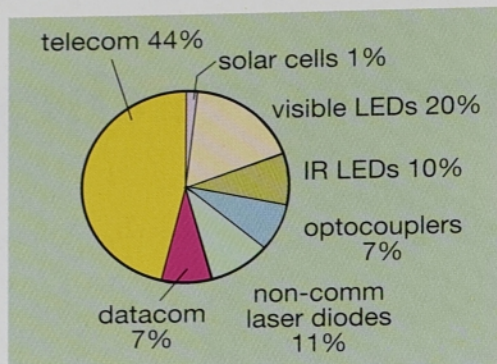


Fig. 3. Breakdown of sales of optoelectronic compound semiconductors in 2000 by device type. Telecom applications account for 40% of all optoelectronic components, with LEDs making up a further 30% of the total market worth some \$14.2 billion.

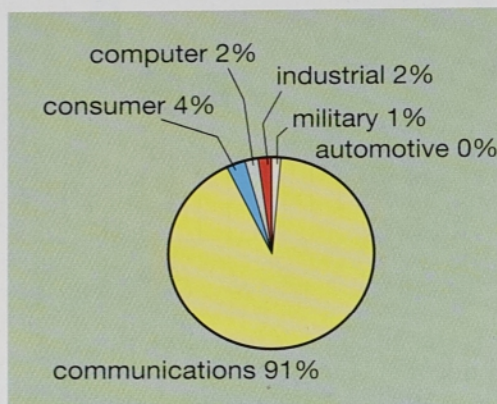


Fig. 4. Applications in 2000 of electronic components manufactured using compound semiconductors. Driven by the wireless handset market, the comms sector is by far the largest consumer of GaAs devices and ICs.

printers, computer mice, photointerrupters and a wide variety of other applications. This is a mature business but has large growth for reasons that are not totally clear.

Optocouplers Sales of optocouplers also grew at 22% to reach \$960 million in 2000. These devices are used to electrically isolate two circuits from each other. The market is characterized by continuing pricing pressure and volume production. There is a persistent movement toward surface-mount packages and simpler configurations in 4-pin packages. Optically coupled solid-state relays (OCSSRs) are increasingly replacing electromechanical relays for a variety of applications in the areas of communications, modems and industrial instrumentation.

Solar cells Sales of compound semiconductor solar cells were practically flat in 2000. These solar cells are mainly used in satellite energy panels for their efficiency and durability (due to higher radiation hardness) compared with silicon solar cells. This business grew rapidly from the mid-1990s and, after dropping off with the brief lull in satellite deployments, is now expected to grow modestly again in the coming years.

Electronics

Compound semiconductor electronics is still almost entirely based on GaAs, although there is emerging business in InP, SiGe, SiC and GaN. At \$3.6 billion, and expected to grow 19% to \$4.3 billion in 2001, this market is holding its own by filling niches that silicon cannot, although silicon is still pushing its performance to ever higher data rates.

Figure 4 presents a breakdown of the market for compound semiconductor circuits by application. Communications dominates the market, with a 91% share in 2000. Of that, 69% is for wireless handsets and 18% is for the circuits used to support fiber-optic transmission. Emerging applications in communications include wireless LANs and fixed wireless radios for broadband and Internet access. Other markets for compound semiconductor electronics include cable and satellite TV terminals and modems, together with computing, industrial and military/aerospace applications.

Figure 5 shows the forecast for worldwide cellular handset shipments. Each handset uses multiple GaAs ICs and field-effect transistors (FETs) as power amplifiers, receivers and RF switches. Sales in 2000 were up 43% on 1999's figure to 400 million units. China and other non-US markets offer significant growth for handset sales, as does the commercialization of new Internet-enabled 2.5G and 3G mobile phones.

For fiber-optic systems, compound semiconductor ICs are used as laser and modulator drivers, receivers, serializer-deserializers (mux-demux) and crossbar switches. These circuits must be able to operate just beyond the nominal telecom line rates of 2.5, 10 and, soon, 40 Gbit/s. At 10 and especially 40 Gbit/s, device and package design enters a different realm, one more familiar to engineers who have worked in the military industry than to conventional circuit designers. While unit

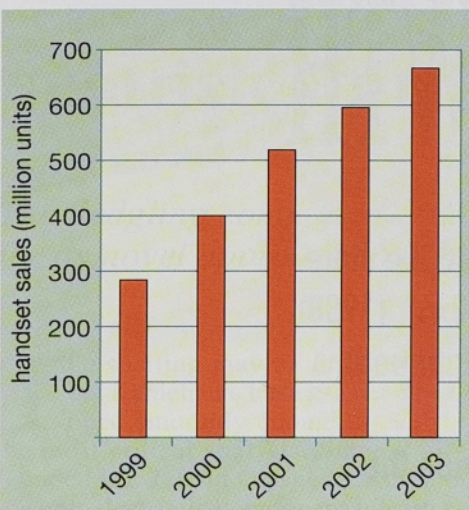


Fig. 5. Wireless cellular handset shipment forecast: each handset uses multiple GaAs ICs and FETs as power amplifiers, receivers and RF switches.

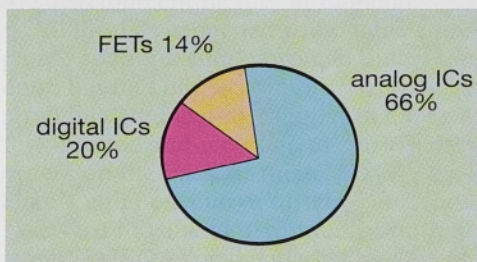


Fig. 6. Sales of electronic compound semiconductors in 2000 by device type. Analog ICs for the wireless industry account for 66% of the \$3.59 billion market, while the market share of digital ICs is growing rapidly.

sales in this market will remain orders of magnitude below those for wireless handsets, the value and growth rates are both very high.

It appears that heterostructure bipolar transistors (HBTs) based on InP will be the choice technology for new 40 Gbit/s telecom systems. InP HBTs outperform GaAs HBTs, but at the moment few suppliers are prepared to offer products at this data rate.

Figure 6 presents a breakdown of the compound semiconductor electronics market by device type. While analog ICs for the wireless industry remain the dominant device type at 66% of the market, the market for digital ICs is growing rapidly. Sales of discrete FETs are relatively static, and are expected to decline slightly in the years ahead.

Transistors based on epitaxial sub-

strates now generate more revenue than those that are based on ion-implanted substrates. HBTs, pseudomorphic high-electron mobility transistors (PHEMTs) and epitaxial MESFETs account together for about 54% of shipments, with ion-implanted MESFETs and diodes making up the remainder.

The price of epitaxial wafers has been declining. They can now provide higher performance or lower voltage operation – or both – where they are needed more cost effectively. At data rates below 2 GHz, however, silicon-based ICs are now penetrating applications where ion-implanted GaAs circuits have previously been considered superior.

Device convergence in modules

The major GaAs fabs are moving to 6 inch wafers to increase the number of dice per wafer, thereby reducing chip cost. Chip sizes are likely to remain about the same over the next few years, but packaged devices will incorporate more functions by integrating GaAs, silicon and passive elements within multi-chip modules (MCMs).

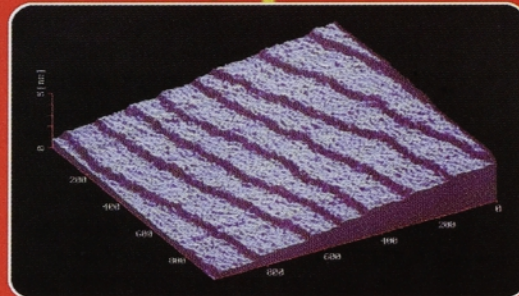
This move to hybrid integration mirrors what is occurring in optoelectronics for telecom applications. For years, optoelectronics researchers aimed for the holy grail: devices that monolithically integrated optoelectronic sources and detectors with electronic circuits onto a single compound semiconductor chip. Such optoelectronic integrated circuits (OEICs) remain impractical for commercially successful products. Today the industry employs hybrid integration: optimizing manufacturing processes for each type of device then integrating the chips on a common platform.

Such an integration of dissimilar sub-components, each optimized for best performance at lowest cost, has proven more effective than seeking monolithic integration onto a single chip. While customers will demand more of these compact and integrated modules, the nature of hybrid integration is that the sub-components will continue to be manufactured separately for years to come.

Tom Hausken is a senior analyst for fiber-optic components at Strategies Unlimited, a market research company based in Mountain View, CA. See "http://www.strategies-u.com" for further information.

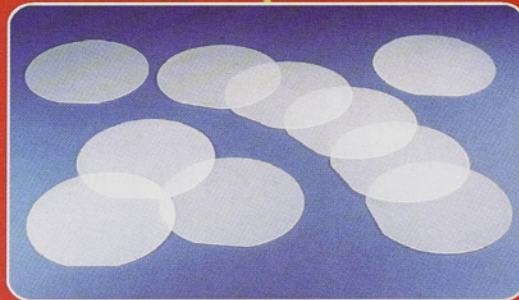
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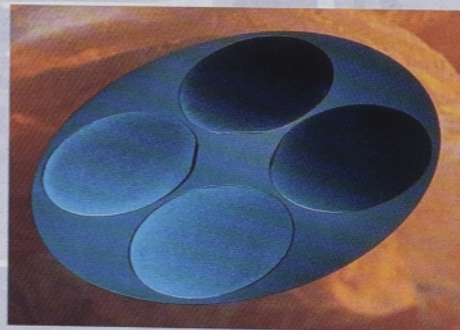
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Scottish start-up takes a hybrid approach

The fledgling company Kamelian has gathered venture capital and technical enthusiasm for its novel approach to next-generation optical networks. Peter Gwynne reports.

The spelling may be idiosyncratic but Kamelian's business has developed smoothly enough to satisfy the most critical analysts. Since it was founded last July in Glasgow, Scotland, the optoelectronic component manufacturer has raised close to \$20 million in venture capital. The firm has also hired more than 20 people, and has hatched plans for a manufacturing and engineering development facility in England.

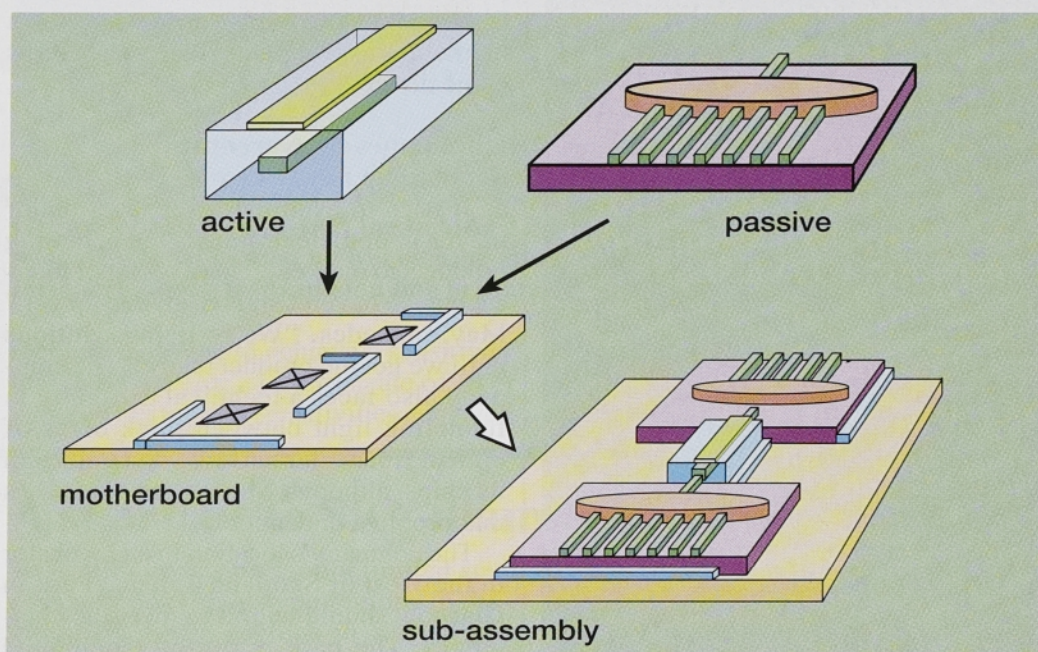
All this has happened without the company sending a single product out of the door, but that day is coming. "We'll start providing engineering samples in the next few months and we hope to start taking orders on the back of them," says Kamelian's chief executive officer Paul May. "We will have a semiconductor optical amplifier [SOA] on the market by the end of this year."

The company sees its future in integrated optical chips for next-generation optical networks. It will develop and manufacture its SOAs from indium phosphide, with the objective of integrating those active chips with other vendors' passive devices, notably arrayed waveguide gratings (AWGs). The integration will produce products for dynamic functions such as switching, the conversion of wavelengths and signal regeneration.

The products promise to satisfy the demands of systems integrators such as Alcatel, Lucent, Marconi and Nortel for components with higher functionality for their networking equipment. Analysts forecast that this niche of the optoelectronics market will be worth at least \$10 billion by 2003.

The early bird

Kamelian hopes to claim a good slice of that market by introducing its new technology early. "We feel we've put our stake in the ground," says May. "No other start-ups have become visible doing III-Vs and combining them with passive



Kamelian's approach: customized active components such as SOAs are integrated into a silicon microbench with outsourced passive components. The resulting hybrid modules are potentially highly scalable and of low cost.

components." To stay ahead of the game Kamelian has ambitious plans for growth. It intends to expand to 80–100 staff by the end of this year. "It's pretty aggressive but manageable growth," May asserts.

The venture capital to enable that growth comes from two main sources. An infusion of \$1.5 million from 3i Group, a major European investor in growing businesses, helped to set up the company, and last December the same venture capital firm added another \$8 million. "Kamelian is a very exciting business with superb technology, an outstanding management team and the potential to become a key player in a fast-growing market," explains Andrew Dawson, an investment director with 3i's Scottish Division. At about the same time Lightspeed Venture Partners, an American venture capital company that concentrates on optical products and systems, contributed \$8.5 million. "We were attracted to Kamelian because of its plat-

form technology," says Chris Schaepe, a founding general partner of Lightspeed. "It has the potential to enable the key building-blocks of next-generation optical networks supporting intelligent wavelength provisioning and management."

Cutting the complexity

Kamelian's technology strategy uses SOAs, which are effectively laser diodes operating below threshold, to amplify, switch or convert optical signals to different wavelengths. These active optical chips offer greater functionality than passive chips that require no electrical power. But May does admit, "Going all active would be very complex."

Kamelian's hybrid approach reduces that complexity while maximizing the benefits from its active chips. Hybrids envisioned by the company include reconfigurable wavelength add-drop multiplexers, which selectively pass or drop

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wavelength channels, permitting data to be added to any vacant channel; wavelength converters that transform data on an input channel from an input to an output wavelength; and 2R regeneration that amplifies and reshapes data pulses on a single channel.

May foresees three potential markets for these products. First are the long-haul providers of communications networks, such as Nortel and Lucent. Next come providers of metro services around cities. Finally, he says, "Last-mile access is a market for us, but in the future when costs come down."

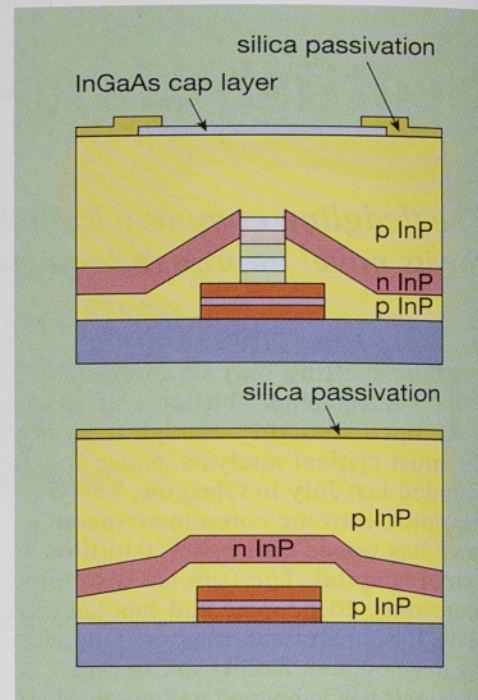
Challenges to overcome

The start-up faces a number of challenges as it tries to establish itself as a major player in optoelectronics. One is getting products to market. "There's a lot of interest but we haven't signed anyone up yet," May concedes. "We're being cautious until we get the product ready." The company also faces a technical difficulty in funneling light between thick cores of optical fibers and narrow waveguides in its chips, although May asserts that it has that problem under control.

The company's location in an incubator in the West of Scotland Science Park in Glasgow should help it to meet the challenges. The park is run by Compound Semiconductor Technologies (CST), an optoelectronics company founded in 1998 by Glasgow University, Strathclyde University and three regional funding groups. CST offers optoelectronic III-V foundry services that can significantly reduce the time, cost and risk of developing new products (see *Compound Semiconductor* Sept/Oct 2000, p26).

Kamelian has already used CST's facilities to establish its manufacturing process. The company now has plans to establish its own manufacturing facility in Oxford, home to England's oldest university and in recent years a center for technology start-ups. The 25 000 sq.ft plant is scheduled to start up before June and to move to full production by late summer. "We'll be growing our own material and manufacturing it at Oxford," explains May. "But CST will allow us to continue to use its site as the effective pilot plant for new technologies."

The Oxford facility will also help with corporate recruiting. "We will have two centers of possible recruitment," May explains. "Scotland is very strong in pro-



Schematic of an SOA after overgrowth, capping and passivation, showing (top) an active section and (bottom) a passive section of the device.

ducing optoelectronic engineers out of the universities. And we have already had situations in which being in Oxford helped us to get the right people."

Kamelian's staff certainly have some impressive résumés. May helped to found Cambridge Display Technology, while chief operating officer Tim Bestwick was previously director of technology strategy for Bookham Technologies, a producer of passive chips. David Sibbald, who set up a network software business that he sold to Cisco Systems last year, is Kamelian's non-executive director. And Ivan Andonovic acts as both the chief technical officer of Kamelian and the professor of broadband networks at nearby Strathclyde University, the source of the company's underlying technology.

One last question: where does "Kamelian" come from? "Some of our future products will change signals from one optical channel at a particular wavelength to another, like a chameleon," May explains. "The real spelling of chameleon is a bit difficult for some people. 'Kamelian' had some significance and was a relatively meaningful name."

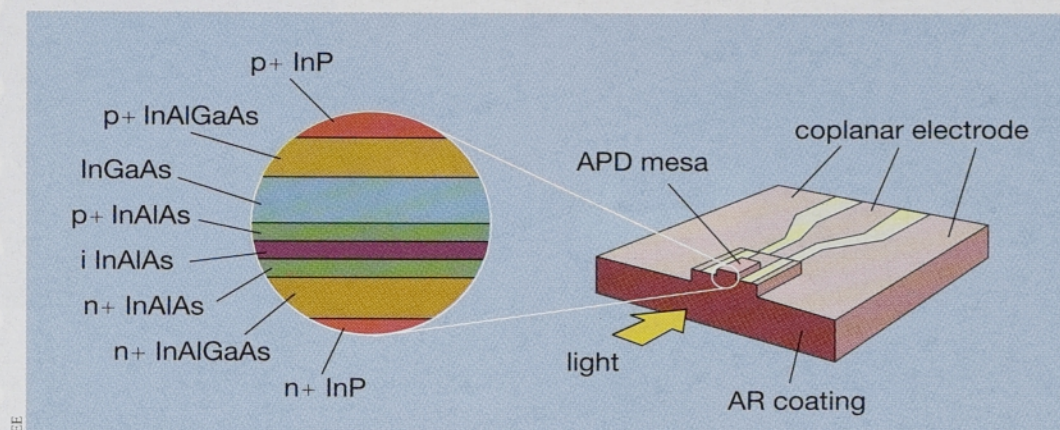
Peter Gwynne is a freelance technology writer based in Massachusetts.

NEC develops new avalanche photodiodes

A team made up of T Nakata and colleagues at NEC Corporation, Japan are currently developing waveguide avalanche photodiodes (APDs) to address the high sensitivity and low operation voltage requirements of receivers in optical networking components.

The waveguide design is normally used with high-speed 40 Gbit/s pin photodiodes because it enables high quantum efficiency and high-speed operation simultaneously. The waveguide structure is also combined with a thin 0.1 μm InAlAs multiplication layer, which should provide a high gain-bandwidth product.

The InAlAs waveguide APD has achieved a low operation voltage of 15 V, quantum efficiency of 76%, multiplied dark current of 40 nA @ $M=10$, bandwidth of 32 GHz and a gain-bandwidth product of 180 GHz. A 10 Gbit/s APD



Grown by MBE on Si-InP, the InAlAs APD waveguide mesa measures some 6 μm wide. It was fabricated by wet etching and passivated with SiNx. The electrodes form a coplanar transmission line to match the impedance of 50 Ω .

receiver managed to achieve a sensitivity of -28.8 dBm (for a bit-error rate of 10^{-9}) – one of the highest sensitivities achieved

for such a device.

The researchers describe their findings in *Electronics Letters* **36(24)** p2033.

Phototransceiver has QD microcavity LED

Densely packed two-dimensional arrays of phototransceivers that detect, process and transmit image signals with high sensitivity and low power consumption are desirable for image-sensing applications. In an article in *Electronics Letters* **36(23)** p1955, O Qasaimeh *et al.* from the University of Michigan and the University of Texas describe a low-power monolithically integrated phototransceiver consisting of a modulated barrier photodiode (MBPD) and an $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$ self-organized quantum dot (or QD) microcavity LED.

As a light emitter in the phototransceiver circuit, the QD microcavity LED promises narrowband resonant emission, directional output and nearly singlemode operation. In addition, a high wall wall-plug efficiency can be obtained at low operating currents.

The MBPD exhibits a responsivity of 1.8×10^3 A/W for 630 nm excitation. At an output wavelength of 980 nm, the phototransceiver features an optical gain of 18 dB and power dissipation of 110 μW . The input required for both receiver and detector is just 10 nW.

A shortcut to SiC–diamond heterostructures

To date there has been only limited success in producing n-type regions in diamond or p-type regions in SiC, while n-type doping of SiC by nitrogen implantation and p-type doping of diamond with boron are well-established processes.

One way around this problem is to combine these two materials in order to exploit this complementary behavior for fabricating p-n heterojunctions or n-type regions in insulating diamond, and preliminary experiments have shown that ion-beam synthesis could be a suitable way to produce SiC–diamond hetero-

structures in microscopic regions.

Writing in *Applied Physics Letters* **77(2)** p226, V Heera *et al.* at Forschungszentrum Rossendorf, Dresden report two ways of achieving these heterostructures: diamond formation by high-dose carbon implantation in crystalline SiC, and SiC formation by high-dose silicon implantation in natural diamond. Implantation is carried out above 700 $^{\circ}\text{C}$ in order to avoid implantation damage, and epitaxial nanometer-scale spherical diamond or plate-like SiC precipitates are formed inside the host crystals.

MOSHFET features the best of both worlds

GaN-based HFETs have become important in high-power microwave electronics due to the extremely high sheet carrier density and high mobility of the 2D-electron gas at the AlGaN/GaN heterointerface, which leads to record microwave power densities up to 9.8 W/ mm^2 . A novel AlGaN/GaN metal-oxide-semiconductor HFET (MOSHFET) combines the advantages of the AlGaN/GaN heterointerface and a MOS device structure.

G Simin and colleagues at the Uni-

versity of South Carolina, writing in *Electronics Letters* **36(24)** p2043, describe a large-periphery multigate MOSHFET capable of switching high power densities of up to 7.5 kW/ mm^2 . This new device features an on-state channel resistance as low as 75 m Ω per mm^2 , which is two to three times less than that reported for buried-channel SiC FETs, and twenty-five to a hundred times less than the on-state channel resistance of SiC induced-channel MOSFET switches.

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SiC Schottky diodes reach the market

The challenges facing the development of silicon carbide Schottky diodes for power applications are discussed by **Roland Rupp** and colleagues from Infineon Technologies.

SiC technology and device development are moving forward rapidly. Impressive results with SiC devices are regularly reported in this magazine; see for example C Weitzl *et al.*'s article on the material's high-frequency applications (*Compound Semiconductor* May 2000, p45). On the other hand, total sales of SiC devices worldwide are – to the best of our knowledge – still close to zero with no significant upward momentum.

The reasons for this are threefold. First, most of the existing devices are aimed at cost-insensitive niche markets like military applications or solar-blind UV detectors where the performance advantage is the key. Second, ultrahigh voltage applications, where high current ratings are required, cannot be addressed with SiC yet due to its high substrate defect density. Finally, semi-insulating substrates are needed for the high-frequency applications where SiC is truly the enabling technology. These are very expensive even compared with standard SiC substrates.

Due to the low market volume of SiC devices, all manufacturing is done in a "laboratory production" style, and cost-effective production lines have not been built. To relieve this deadlock, we tried to determine the necessary preconditions for a mass market for SiC power devices. These are as follows:

- The device should be as simple as possible to reduce the barrier to industrial volume production.
- It should minimize the processing steps specific to SiC.
- The required chip area (i.e. current rating) has to be low due to yield-limiting micropipe defects in the substrate.
- High application competence is required to be able to convince potential customers that they can save money despite the high cost of the SiC device compared with a competing Si device.
- The target market really has to be a mass market in order to allow a return of

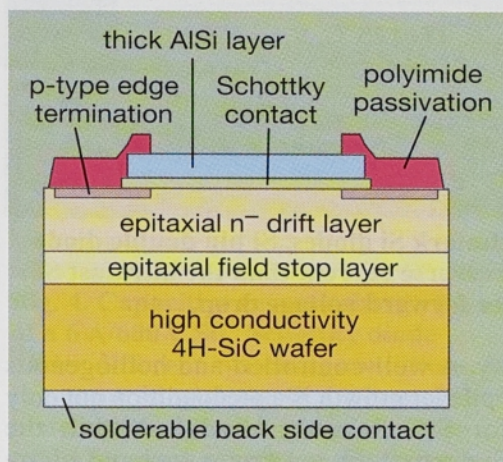
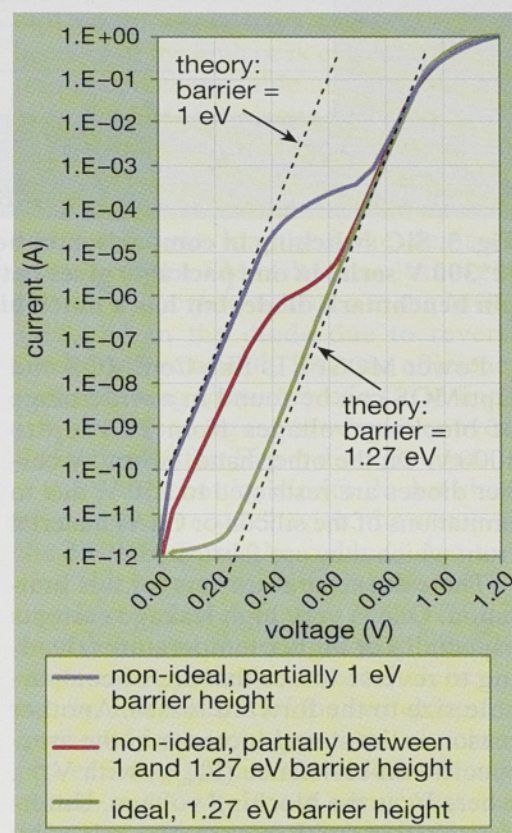


Fig. 1 (above). Basic structure of the newly developed SiC Schottky diode. **Fig. 2 (right).** Forward current vs forward voltage for SiC Schottky diodes which have a different metal-semiconductor interface quality. The green curve represents a Schottky diode with a nearly perfect interface, while the dark blue curve represents a Schottky diode where the barrier is reduced to about 1 eV in a significant part of the interface.



the development expenses.

The device we identified fulfilling all these requirements is the SiC Schottky diode for voltage levels of 300 and 600 V.

Market forces

System miniaturization is a trend in electronics that is mainly – but not only – driven by the increasing amount of portable applications. The power supply of these items is still a dominating part concerning the dimensions and weight of the whole system. For example, in a typical portable computer the power supply accounts for more than 10% of the system's total weight. Therefore all manufacturers of switch-mode power supplies (SMPSs) have defined roadmaps to increase the power density of their products.

There are two major approaches to

realizing these roadmaps. The first is to reduce the size of passive components by increasing the switching frequency at constant efficiency and/or reduce the size of the electromagnetic interference EMI filter through low noise generation. The second is to reduce power losses and correspondingly the cooling effort, reducing the need for a heat sink and fan.

This results in a specific requirement for the main power semiconductor components: a significant reduction of switching power losses. This is why unipolar semiconductors such as MOSFETs and Schottky barrier diodes are replacing bipolar devices. The beauty of unipolarity is the absence of stored charge carriers and, therefore, theoretically instantaneous switching transients limited only by small parasitic capacitances.

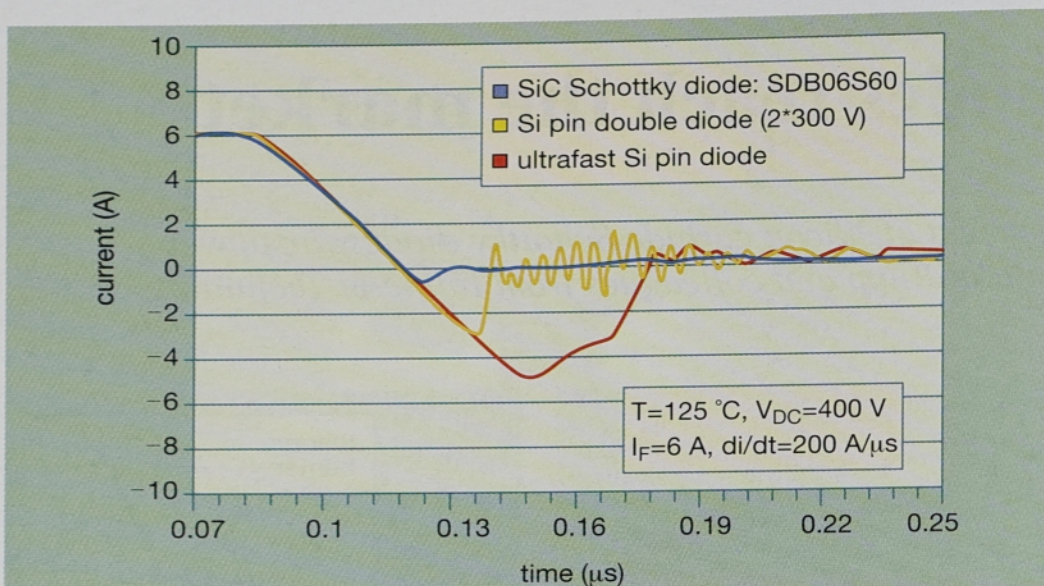


Fig. 3. SiC switching in comparison to benchmark Si diodes. Si pin double diode (2*300 V serial in one package) gives better reverse current than the ultrafast Si pin benchmark diode, but has a much higher forward voltage drop.

Power MOSFETs like CoolMOS and OptiMOS can be found in a wide range of blocking voltages from 20 V up to 1000 V. On the other hand, Schottky barrier diodes are restricted to 250 V, due to limitations of the silicon or GaAs material from which they are fabricated.

There are several reasons for this limitation. One is very high leakage currents especially at higher temperatures, leading to reverse losses that are of comparable size to the forward losses. Another reason is the strong increase in the area-specific on-resistance ($R_{on,A}$) with $V_b^{2.5}$, where V_b is the blocking voltage. Unfortunately this problem cannot be solved by simply increasing the chip area since this also increases the reverse losses.

The input stage of an off-line SMPS usually requires devices rated in the range 500–600 V. Thus a strong and unsatisfied need exists for Schottky barrier diodes capable of working in this voltage range.

Cost-effective SiC Schottky diodes

As mentioned above, a SiC Schottky diode is the SiC device with the simplest technological process for manufacturing. Figure 1 shows a schematic of the device layout. The whole device can easily be produced with a 3–4 mask layer process. There are three major functional items in this device:

Drift region The epitaxially grown drift region is responsible for the maximum blocking voltage and the on-state resistiv-

ity. A well-controlled and homogenous epilayer growth is a precondition not only for SiC Schottky diodes. Within the Siemens/Infineon group we have a long history in developing epitaxial processes for SiC. The tool we are using today is a multiwafer reactor for six 2 inch wafers (Rupp *et al.*), while another reactor suited for seven 2 inch or five 3 inch wafers is in preparation (Vrob'ev *et al.*). To adjust the trade-off between forward and reverse characteristics, the thickness and doping tolerance in the drift region have to be kept small.

Our diodes are dimensioned for an average electrical field of 1.75 MV/cm. So it is clear that deviations in the +10% range for doping and –10% for thickness are already relevant for the reverse yield. Deviations in the other direction are conflicting with the forward performance; we have to be very stringent here as well, because we have to keep the area of the SiC devices small due to the still extremely high costs of the base material and the large intrinsic defect density (micropipes) in the order of 20/cm².

Guard ring The edge terminating guard ring determines the maximum blocking voltage at a given drift layer doping and thickness. The guard ring is generated by an acceptor ion implantation with subsequent annealing. Exact control of the annealing conditions is required to achieve the right concentration of electrically activated acceptors in the implanted

area. Deviations in either the positive or negative directions lead to a reduced blocking capability (Mitlehner *et al.*).

The semiconductor-metal junction This is responsible for the rectifying barrier and the leakage current of the diode in reverse direction. The biggest challenge is probably to get a reproducible and homogenous Schottky barrier between the SiC and the metal contact. Any kind of surface inhomogeneities usually lead to local barrier reduction and leakage current “hot spots”. These can never be prevented completely. Sources of such inhomogeneities are surface impurities, locally differing reconstruction of the SiC surface and an inhomogeneous structure of the Schottky metal (i.e. epitaxial areas next to nearly amorphous regions).

The effect of local barrier reduction on the forward characteristics of a Schottky diode is shown in figure 2. Here a diode with a nearly ideal barrier is compared with two others that have a certain amount of defects at the metal–semiconductor interface. As described in several papers (e.g. Defives *et al.*), at low forward voltage the areas with the lower barrier dominate the I-V curve. At higher forward voltage the areas with the higher barrier take over, because they are represented by a much larger part of the total interface. This results in a typical appearance of the log I vs. V_F plot showing two or more separate linear branches each representing one specific barrier. The “perfect” diode, on the other hand, has only one linear region stretching over many orders of magnitude.

One would expect from figure 2 that diodes 2 and 3 will not exhibit a suitable blocking behavior, but this is not necessarily the case. As described by Tung *et al.*, and discussed by Treu *et al.* in the specific case of SiC, such areas with lower barrier can be shielded under reverse bias by the space charge region of the surrounding high barrier regions, provided they are small enough (i.e. they have a diameter less than the depth of the space charge region). This is similar to the effect intentionally used in merged p-n Schottky diodes (Dahlquist *et al.*) to reduce leakage current.

For a production process with reasonable yield, it is essential to keep all the unavoidable imperfections of the metal–semiconductor interface small enough that they cannot generate excess leakage

current. In fact, we get a much better yield for our Schottky diode production than one would expect from the $\log I$ vs. V_F plots for the diodes.

High volume production

Besides this basic understanding of the SiC Schottky diode, it was important for us to build a production line with a capacity in the order of several million devices per year. The line must be flexible enough to react to the highly unpredictable speed of market development, and must also minimize costs.

The last point is especially important, because SiC devices already suffer from very high substrate cost as a barrier to market entry. Therefore it was our aim at Infineon to minimize the investment dedicated to SiC. We have been able to adjust our technological process so that we can mostly use standard 6 inch Si tools, with very few exceptions such as SiC epitaxy.

We believe that there will soon be a demand for large volumes of the new SiC Schottky diode because it exhibits the following properties.

A widely expanded voltage range

SiC Schottky diodes offer a very low specific on-resistance with high rated voltages. Unlike Si and GaAs Schottky diodes, there is only a moderate increase in leakage current with increasing temperature (Treu *et al.*). The area-specific differential on-resistance of a 600 V SiC Schottky diode increases from about $0.9 \text{ m}\Omega\cdot\text{cm}^2$ at room temperature to $1.8 \text{ m}\Omega\cdot\text{cm}^2$ at 150°C . This positive temperature coefficient makes the Schottky diode well suited for paralleling without the risk of thermal runaway.

When switching a Schottky diode off there is no need to remove excess carriers from the n-region as there is for p-n diodes. Hence no reverse recovery current will show up. Instead only a displacement current for charging the junction capacitance of the diode can be observed (see figure 3). The current transient depends only on the external switching speed up to very high frequencies.

The charge transported by this current is very low compared with the reverse recovery charge (Q_{rr}) of pin diodes. Due to the different origin of this charge we have named it capacitive charge (Q_c).

Q_c and the switching power losses of SiC Schottky diodes are not only ultra-low. Compared to Si ultrafast diodes,

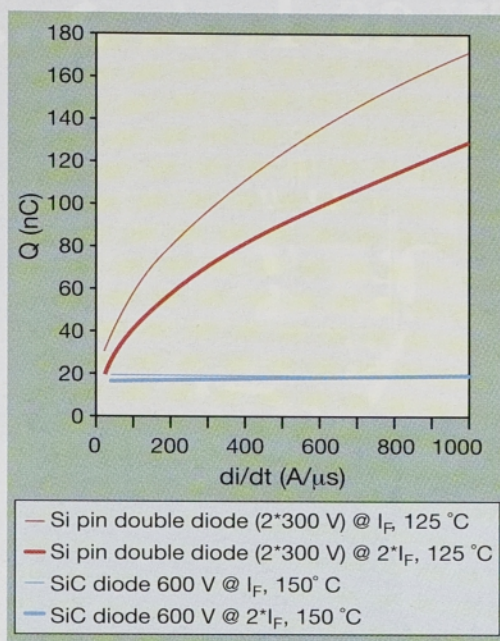


Fig. 4. Capacitive reverse charge (Q_c) of a 6 A/600 V SiC Schottky diode under different switching conditions. It is compared with the Q_{rr} -values of the benchmark silicon solution (I_F is the rated forward current of the device).

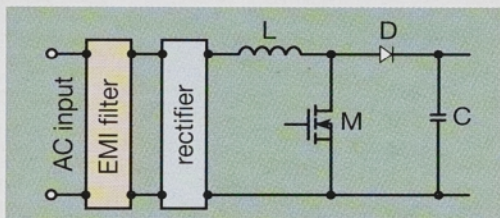


Fig. 5. Power factor corrector (PFC) with a boost converter. The semiconductor switch and the diode D need a blocking capability of 600 V for wide input range usage. The diode D is one application of a SiC Schottky diode.

where losses depend strongly on dI/dt , current level and temperature, they are more or less independent of these boundary conditions (figure 4). A dependence of Q_c on these parameters cannot be seen at the same scale as with a benchmark Si diode approach. Again this is due to the capacitance-like behavior of this device in reverse direction.

Active power factor correctors

As always when trying to replace a cheap and highly current-overload-stable bipolar device with a unipolar device, the most striking argument is the need for high switching frequencies. There is one mass-market application in which this need is especially pronounced: the active

power factor corrector (PFC), an example of which is shown in figure 5.

The use of power factor correctors is growing strongly worldwide, driven by legal requirements. Boost converters are usually chosen to realize active power factor correction. They can be driven in discontinuous current mode (DCM) or continuous current mode (CCM).

The DCM solution does not require an ultrafast diode like the SiC Schottky diode, but has several drawbacks: all circuit components have to be oversized because of the high peak currents, the system becomes unstable at light load and complex EMI filtering is necessary.

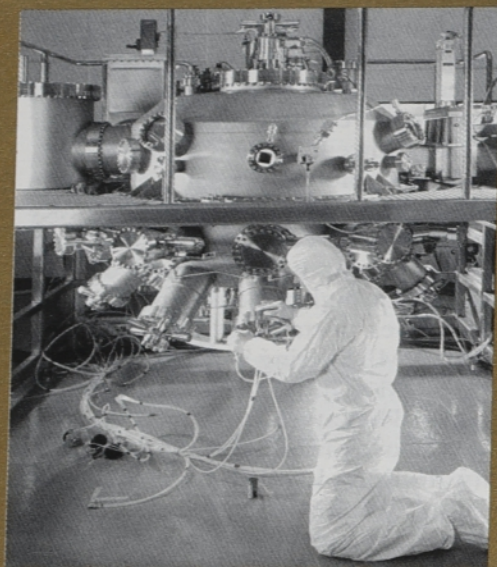
The CCM solution lacks these disadvantages. The circuit components don't have to be oversized, the system operates stably at light load and the demands placed on the EMI filter are less rigid. However, the power losses in the MOSFET and in the diode due to reverse recovery dramatically limit the efficiency and switching frequency of a CCM boost converter (see figure 6) when a conventional or ultrafast Si p-n diode is used.

As SiC Schottky diodes do not show reverse recovery behavior, the stress on the MOSFET will be reduced due to a very low current spike during the turn-on transient. A less expensive MOSFET can be chosen and the entire system can be made more reliable. The efficiency is nearly independent of the switching frequency due to very low total switching power losses (figure 6), which is ideally suited to CCM. Boost converters can therefore operate at much higher switching frequencies. Reducing the boost inductors opens up new horizons in power density. This also has a strong impact on the cost of the inductor.

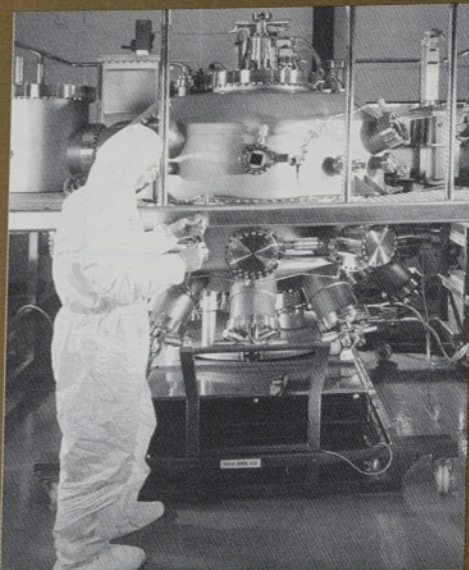
EMI challenges at high frequency

The EMI norm regulation begins at 150 kHz, so the main harmonic of the boost converter can be well inside this range. One would suspect complications achieving the EMI norm in case of higher switching frequency, but this concern is unfounded. Typically current-compensated double choke inductors have a maximum impedance (i.e. highest damping efficiency) in the frequency range from 300 kHz to more than 1 MHz. The main and higher harmonics of a boost converter running at 300–500 kHz will be filtered with the maximum efficiency, so the increase in switching frequency to 300–

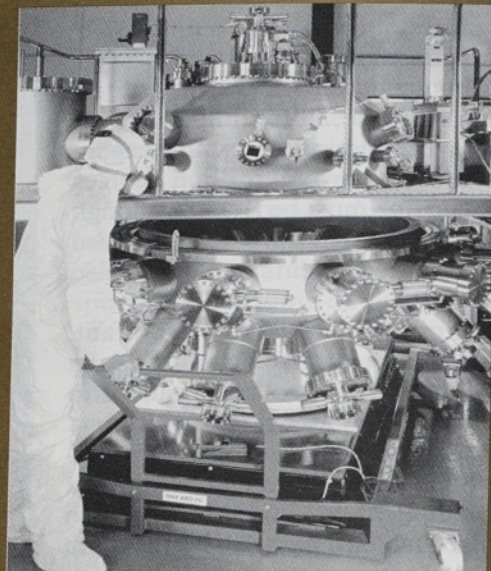
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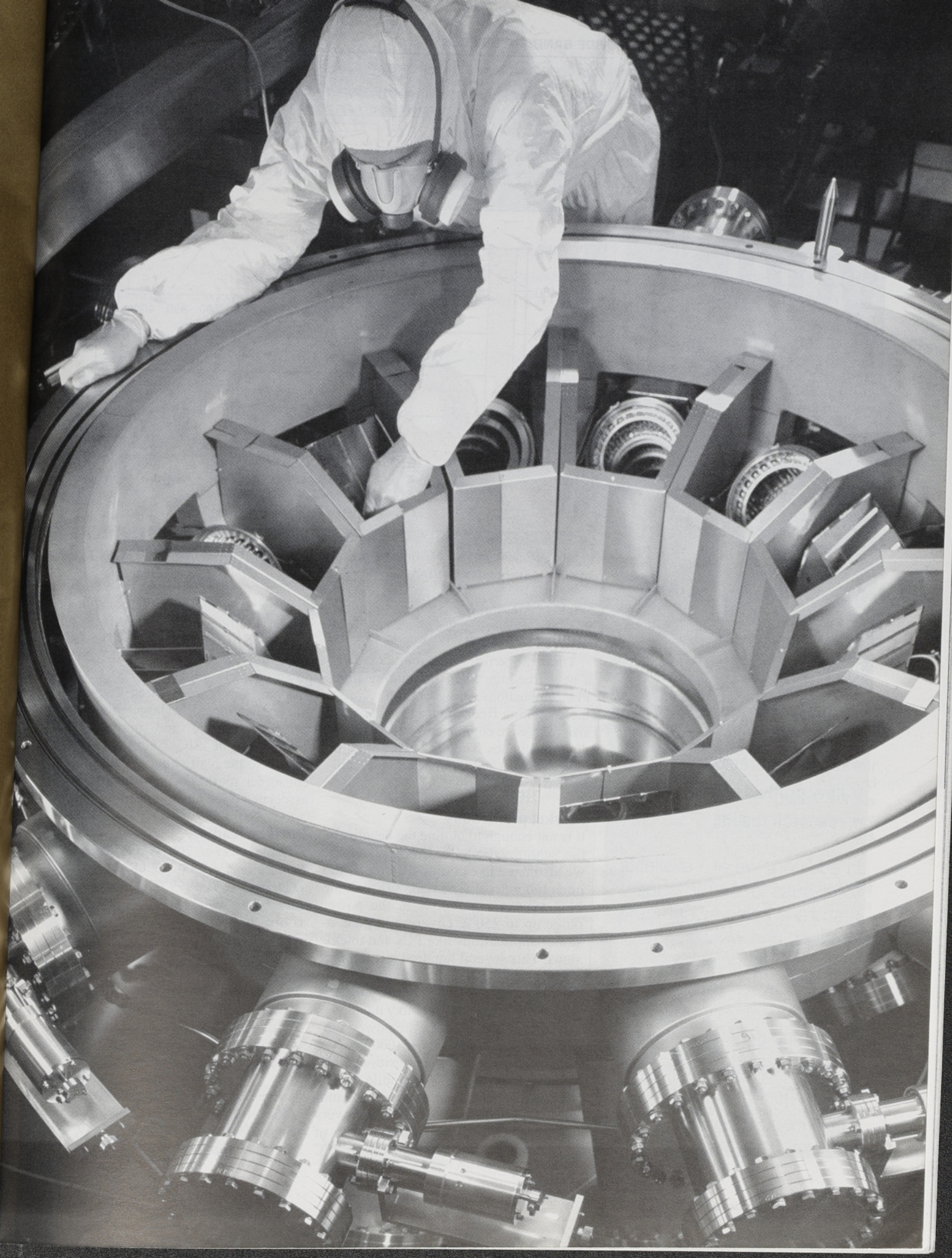


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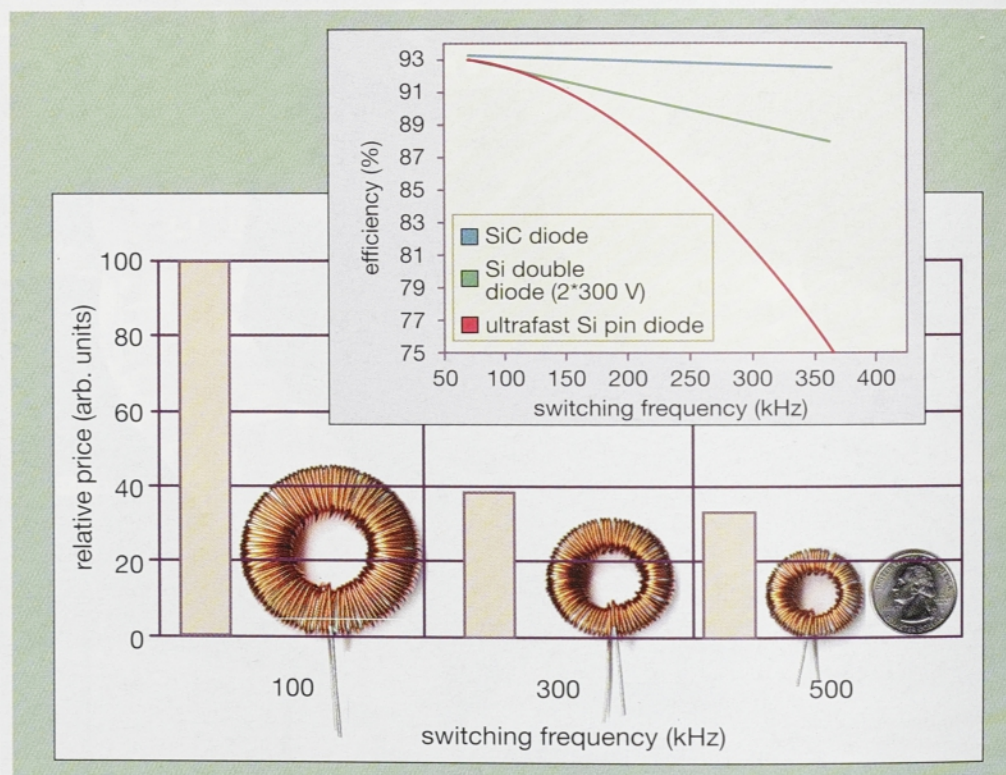


Fig. 6. Efficiency of a PFC boost converter (top) and inductor size and price vs the switching frequency (bottom).

500 kHz does not cause a need for additional EMI filtering and electrical noise can even be reduced.

These properties give circuit designers a new freedom when optimizing their PFC applications. Designers can increase the switching frequency, and reduce the size of passive components and semiconductor switches. They can also shrink or eliminate heat sinks and increase reliability and power density.

Market predictions

It is not enough to outline the benefits of the Schottky diode for this application; we also have to examine the size of the potential market. The real high-volume PFC market segment is in the power range up to 250 W covering large consumer applications like PCs and televisions. This several hundred million part per year market is extremely cost sensitive, making it an unlikely entry market for an expensive SiC Schottky diode.

On the other hand, in the power-supply range from 200 to about 1000 W many high-end applications are positioned like servers, base stations for mobile phones and infrastructure for terrestrial communication. For this market reliability is very important. If one can reduce the risk of failure of the MOSFET switch in the PFC

stage by replacing a conventional diode with an SiC diode, this will justify the still high price of the new diode. The same holds true in applications where high power density or ruggedness towards overtemperature are required. These high-end applications offer large-enough volumes to initiate and ramp up the production of SiC Schottky diodes. Access to the really huge volumes of the consumer market will follow with the associated price reduction.

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R Rupp, H Kapels, C Miesner, M Treu, I Zverev and M Krach are with Infineon Technologies AG, PO Box 800949, D-81541 Munich, Germany.

Lighting the future with LEDs

*The market for high-brightness LEDs already exceeds \$1 billion, and it will continue to grow at an impressive rate as prices fall and performance improves. These were the themes of the recent Strategies In Light conference in San Francisco, writes **Tim Whitaker**.*

High-brightness LEDs are finding an increasing range of uses – LCD backlights for cellular handsets, traffic signals, displays, automotive applications, signage and illumination, to name a few. Speakers at the Strategies in Light conference, held on 8–9 February in San Francisco, discussed these market segments and the demands they place on LEDs. Representatives of the major device manufacturers were also there, making for an interesting panel session that brought Nichia, Toyoda Gosei and Cree together in a rare out-of-court meeting.

Breaking the \$1 billion barrier

Opening the conference, Bob Steele of Strategies Unlimited revealed that the market for high-brightness (HB) LEDs exceeded \$1 billion in 2000. Sales grew 41% since 1999, reaching \$1.2 billion (see figure 1); the market grew by an astonishing 58% annually over the previous five years. Growth will continue in the next five years, but at the less spectacular rate of 22%. Steele predicts that the HB-LED market will be worth \$3.25 billion in 2005.

At \$1.7 billion in 2000, sales of conventional-brightness LEDs still exceed HB-LEDs, but the conventional market is growing much more slowly. According to Steele, “high brightness” is determined by the quantity and efficiency of light output: HB-LEDs usually have luminous intensities of hundreds of millicandela (mcd) for standard 5 µm lamps, although this value is lower for surface-mount devices where the viewing angle is larger. The various materials used for HB-LEDs are AlGaAs (red), AlInGaP (yellow-green to red) and InGaN (blue, green and white), although many AlGaAs and AlInGaP LEDs do not fall into the high-brightness category. Conventional LEDs include GaAsP (yellow to red) and GaP (green to red) devices.

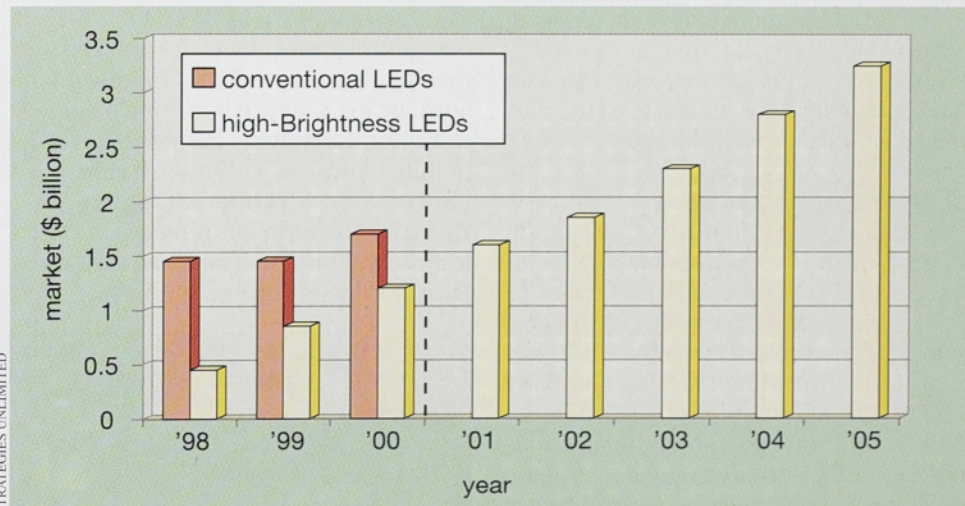


Fig. 1. The market for high-brightness (HB) LEDs is expected to grow at a compound annual rate of 22% over the next five years, reaching \$3.25 billion in 2005. HB-LEDs are defined as AlGaAs, AlInGaP and InGaN devices having luminous intensities over 100 mcd for standard 5 mm lamps. Market figures are for components (not chips) and include lamps and displays.

Steele split the market by application as shown in figure 2, and gave further information on the segments as follows.

Signs The total sign market for HB-LEDs (both single and full color) approximated \$380 million last year. The market for HB-LEDs in full-color signs grew 30% to reach \$180 million. Most of these are outdoor signs, the largest segment being sports stadia.

Traffic signals More than 8% of conventional traffic signals in the US have now been replaced with LEDs. More than 350 000 replacements were made in 2000, and almost half of these were for green lights: in 1999, a very small fraction of LED signals were green due to the high cost of green LEDs. The traffic signal market was worth \$36 million in 2000.

Automotive applications This market totaled \$260 million. It includes exterior

lighting for automobiles, such as center high-mounted stop lights (CHMSLs) and turn signals (see figure 3); truck and bus exterior lighting; and interior lighting like map lights and instrument panels. This last market now exceeds \$180 million.

Brake lights The market for HB-LEDs in CHMSLs had a value of more than \$60 million in 2000, while the cost of each fixture has fallen from \$50 in 1989 to around \$7. Approximately one-third of all new cars and light trucks (including SUVs) feature LED-based CHMSLs, and penetration in Europe is close to 70%.

Mobile handsets Single-color LED backlights for monochrome displays in mobile handsets, and white backlights for full-color displays, have become a major market for HB-LEDs, especially in Asia. Steele estimated that more than 25 million handsets with full-color displays were produced in Japan in 2000.

Illumination LEDs These have not penetrated the illumination market to any significant degree, although there are several near-term applications including decorative, architectural and retail display lighting, flashlight bulbs and machine vision.

In conclusion, Steele pointed out that HB-LEDs will enjoy a multi-billion dollar market without significant penetration of the illumination segment, although that is a desirable long-term goal. The performance of devices is improving, prices are falling, existing applications are growing rapidly and new ones are emerging. Although new suppliers are entering the market, barriers are high due to technological and legal (patent) issues.

LEDs replace neon signs

The electric sign industry, valued at \$5.4 billion in 1999, is dominated by fluorescent (48%) and neon (41%) technologies. The latter category has the highest potential for replacement by LEDs according to Jim Sloan, whose company Sloan LED is a supplier of LED lighting systems for signage applications. LEDs have a number of advantages over neon including low voltage operation, absence of start problems in cold temperatures, ruggedness and long life. Around 64% of neon signs are channel letters (see figure 4a): these are standalone letters mounted on the outside of retail establishments and suchlike. The second-largest category, says Sloan, is perimeter or border accent lighting (see figure 4b), used both internally and externally.

Sloan mentioned several problems with using LEDs in signs. One is heat – temperatures inside sign cabinets can exceed 75 °C, so it is important to keep the temperature of the LED junction below its maximum rating. Outdoor signs must also be weather resistant, and it is necessary to match the LED color to the lens color (which can be proprietary in the case of large businesses). Furthermore the neon-sign industry is put off by the high initial cost of LEDs, the fact that many sign-makers have invested in their own neon shops, and the number of different designs put forward by LED manufacturers.

Traffic signals

The California Department of Transportation (CalTrans) has already installed 50 000 traffic-signal modules, specifically red stoplights and pedestrian “hand” sig-

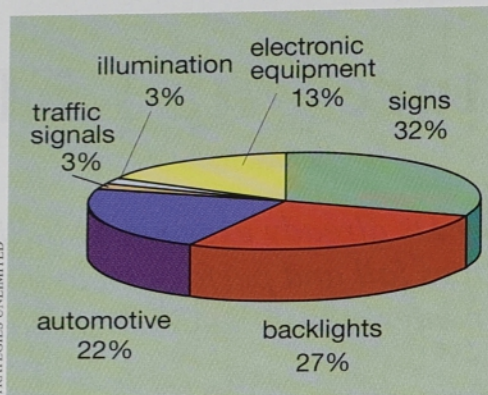


Fig. 2. Breakdown of the 2000 HB-LED market by application; the market totaled \$1.2 billion. Signs are mostly for outdoor use and are both single and full color. Backlights are mostly used in mobile handsets. Automotive refers to both exterior and interior lighting. Electronic equipment refers to indicator lights such as those used on Sony's PlayStation2 game console.



Fig. 3. Showing the way: LED indicator lights are embedded in the wing mirrors of this new Mercedes-Benz car.

The performance of high-brightness LED devices is improving, prices are falling, existing applications are growing rapidly and new ones are emerging.

nals. According to CalTrans' Gonzalo Gomez, the goal is reduced energy consumption: exchanging a 155 W lamp for a 10 W LED module uses 60–65% less energy for a red signal, and 85–90% less if all colors are replaced. The program has already resulted in a load reduction on the power grid of 4 MW, equaling \$2.5 million in energy savings. Another 160 000 modules will be installed by June.

When asked to comment on reliability, Gomez stated that there have been a few failures, although many fewer than when using incandescent lamps. Fortunately the

manufacturers provide a warranty to cover failed LEDs, except (quite understandably) when the failure is due to someone shooting out the signal. Regarding cost, Gomez stated that the price of a red module has fallen from \$180 three years ago to around \$65.

Truck lighting

According to Brad Van Riper, the vice-president of R&D at Truck-Lite, lighting failures are the most frequent maintenance problem experienced by truck fleets. Despite their high cost, LEDs are very well suited for use in signaling and marking devices on trucks since they are highly resistant to shock and vibration, draw very low currents, have long lifetimes and a rapid illumination rate. Van Riper also pointed out that it can take 20–30 minutes to troubleshoot and repair a failed light on a truck, resulting in a cost of \$50–60. The cost to replace standard lights with LEDs (around \$150) can be recovered over the life of the vehicle.

Interior automotive

John Roberts of Gentex described his company's binary complementary white (BCW) approach to LED lighting, which combines the output from amber AlInGaP and blue-green InGaN LEDs (for more details, see *Compound Semiconductor* March 2000, p43). In 2001, Gentex will supply an estimated 300 000 BCW pods to General Motors, Ford, DaimlerChrysler and others. Gentex adopted the BCW approach in 1998 largely because phosphor-converted (PC) white LEDs were not available at that time. However, the BCW technology also has the potential to offer high luminous efficacy because it relies primarily on AlInGaP LEDs, providing cost and performance advantages. Also the output color of the lighting fixture can be controlled and adjusted electronically, rather than being fixed earlier in the manufacturing cycle as is the case with PC LEDs.

Displays

Most professional sports teams in the US have – or soon will have – large-format outdoor LED video displays, says Tony Van de Ven, CEO of LED display manufacturer Lighthouse Technologies. There is also a rapidly growing market for indoor applications following the introduction of displays with a pixel size of 10 mm – previously the resolution was



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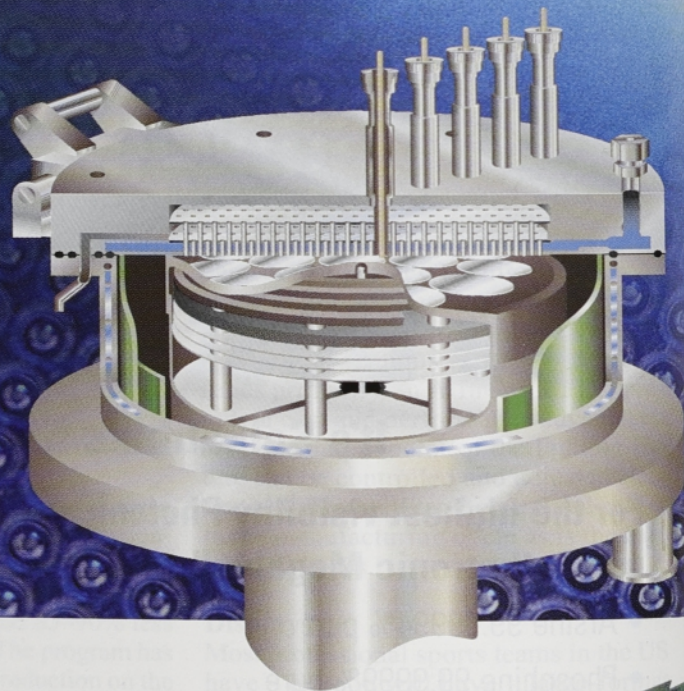
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too coarse for indoor use. The displays manufactured by Lighthouse contain pixels consisting of three LED chips (red, green and blue) in a surface-mount package; these are combined in 16×16 modules with drivers on the back surface and integrated heat sinks. The modules are combined into panels, several of which make up the display.

Van de Ven explained that while Lighthouse is a heavy user of LEDs, consuming around 1.5 million chips per week, the company does not experience constraints on its chip supply. He also noted that the price of blue and green LEDs at the high-performance end of the market has hardly reduced, although the price of AlInGaP chips has fallen, largely due to the growth in capacity in Taiwan. Chip-cost accounts for almost half of the total cost of Lighthouse's displays.

Other issues facing the market include the need to improve LED efficiency in order to reduce the heat that must be removed from the display. Also, said Van de Ven, brightness and color control need to be improved; blue and green InGaP-based LEDs typically have a variation in wavelength of ± 7 nm, so every pixel must be actively controlled to ensure a consistent output. Trends for the LED video display industry include higher brightness, higher resolution (Lighthouse recently introduced a 5 mm product) and, of course, lower cost. The 10 mm display costs around \$3 per pixel, or \$30 000/m².

Lighting

Although general illumination offers a huge potential market, current niche lighting applications are developing fast. Several examples were shown by Katharina Keller of Zumbotel Staff, a European manufacturer of luminaires (a luminaire is a complete lighting system). Keller showed indoor and outdoor lights for orientation and guidance, as well as architectural feature lighting.

According to Leonard Hordyk and Brent York of optoelectronic lighting manufacturer TIR Systems, the lighting industry is rapidly adopting LEDs. However, both the lighting and the LED industries need to find common ground and standards. Of equal importance is the convergence of many technologies to make lighting units – optics, power conversion, drive and control electronics and housings, as well as the LEDs themselves.

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Fig. 4. Signs of the times: LEDs could in time replace the neon used in signs for (a) channel letters and (b) the border lighting on buildings.

The future market for high-brightness LEDs will prove to be very valuable, provided device manufacturers meet the challenges presented by each of the different market segments.

program for solid-state lighting was discussed by Steve Johnson of Lawrence Livermore National Lab (for an overview see *Compound Semiconductor* February 2001, p50). A similar program – The 21st Century Lighting Project – is running in Japan and was discussed by Tsunemasa Taguchi. A performance target for white LEDs of 120 lm/W has been set for 2010. Taguchi described a prototype streetlight using white LEDs, which consists of 700 LEDs in a case measuring 28×13 cm². The brightness of the unit is normally 80 lux, but it can sense a person's approach and increase its brightness to 660 lux for a power consumption of 56 W. The LED lamp is 46 times brighter than an incandescent bulb with the same power consumption, although it does cost around ¥1 million (\$8500). However, the unit uses solar cells to store power in batteries, allowing it to operate without an external power supply.

So are LEDs suitable for general illumination? Not yet, reports Nadarajah Narendran of the Lighting Research Center (LRC). LEDs suffer from a high initial cost compared with traditional lighting sources and only a small number of lumens are available from conventional packages. Furthermore Narendran's studies indicate that reliability is not as good as publicized, and there is significant lumen depreciation – white LEDs exhibited lifetimes (defined as the time taken for the relative light output to halve) of less than 10 000 hours (see figure 5).

Tales from Taiwan

An overview of Taiwan's booming LED industry was given by B J Lee, the president of Epistar – a supplier of chips and epiwafers. Lee stated that Taiwanese companies have roughly one-third of the overall market for LED lamps by volume, and a 21% share by revenue. AlGaInP and InGaP LEDs are growing the fastest: Lee believes that between 1999 and 2000 the worldwide AlGaInP market grew 60%, from 250 million lamps to 400 million. The smaller InGaP market grew even faster, increasing by 140% to reach 120 million lamps in 2000.

"Taiwan is the center of gravity of the world's AlInGaP market," claimed Lee. Indeed, the huge manufacturing capacity installed in the country in recent years has had a significant impact on prices (see figure 6). The annual growth rate of the AlGaInP industry exceeds 50%, and Taiwan now produces more than 60% by volume of the world's AlGaInP chips. The country also dominates chip production for GaP, GaAsP and AlGaAs devices.

Lee estimates that the Taiwanese LED industry is composed of 27 lamp manufacturers, 10 chip-makers and 15 epiwafer suppliers. There are around 90 MOVPE reactors in Taiwan, and the number could exceed 120 by the end of 2001. There are probably around 10 growth systems in mainland China, with one or two operational now. Japan dominates the merchant epiwafer market for GaP, GaAsP and AlGaAs LEDs, while Taiwan has roughly 70% of the merchant market for AlInGaP and InGaP epiwafers. Of course, most InGaP epitaxy is carried out for internal use by giant producers such as Cree and Nichia. Although about one-third of epi systems in Taiwan are for InGaP growth, most are currently used for research rather than manufacturing. Markets are Asian

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countries other than Japan (to avoid patent issues). Lee said, somewhat ominously, that "Taiwan will soon be ready for InGaN epiwafer and chip production."

Another feature of the Taiwanese industry is that production is starting to move to mainland China, from local investment or through the movement of companies from Taiwan or Hong Kong.

Suppliers line up

A session entitled "Supplier Perspectives" brought together six leading makers of LEDs: Nichia, Toyoda Gosei, Cree, Osram Opto Semiconductors, LumiLeds Lighting and GELcore. Mike Holt, CEO of LumiLeds Lighting, explained that while general illumination applications for white LEDs are 10–15 years away, there are a number of areas where LEDs will become the dominant technology. Examples include LCD backlights, dental curing tools and automotive daytime running lights. However, the current 5 mm LED form factor is not sufficient to enable these applications; LumiLeds has focused on devices that offer a light density that is ten to thirty times higher than conventional devices, in roughly the same footprint. More details can be found on page 11 of this issue.

Noboru Tazaki described Nichia's recently completed manufacturing facility; the building has 35 000 m² of space and is about three-and-a-half times larger than the older fab. Koichi Ohta of Toyoda Gosei stated that his company's LED sales will exceed ¥20 billion (\$174 million) in the fiscal year ending March 2001, up from ¥14.8 billion (\$129 million) in the financial year ending 1999. The relative fortunes of Nichia and Toyoda Gosei were discussed by Chris Redl of UBS Warburg, as described on page 67 of this issue.

Capacity counts

Chuck Swoboda explained that his company Cree, like its competitors, has added a huge amount of capacity in the last 12 months, meaning this is no longer a constraint. "Additional capacity and competition will drive price reductions," he said. "Lower prices and higher performance will continue to drive volume growth from both new applications and the further penetration of existing applications." Furthermore price points are moving rapidly: while existing manufacturers can handle these changes, it will become

Technologies for directional lighting applications

Fixture	Flux (lm)	Power (W)	Efficiency (lm/W)	Lamp life (hours)	Initial cost (\$)
Incandescent 60 W A-lamp)	430	60	7.2	750	10
White LED system (700 × 5 mm LEDs)	420 (0.6 lm/LED)	42	10	10 000	700

Fig. 5. Comparison of technologies for use in directional lighting applications. LED lighting systems may be more energy efficient than incandescent lamps, but high initial cost may limit their use. Note that 700 individual 5 mm LEDs are required to provide the same total flux as the 60 W incandescent bulb – and more LEDs would be required for a non-directional lighting system.

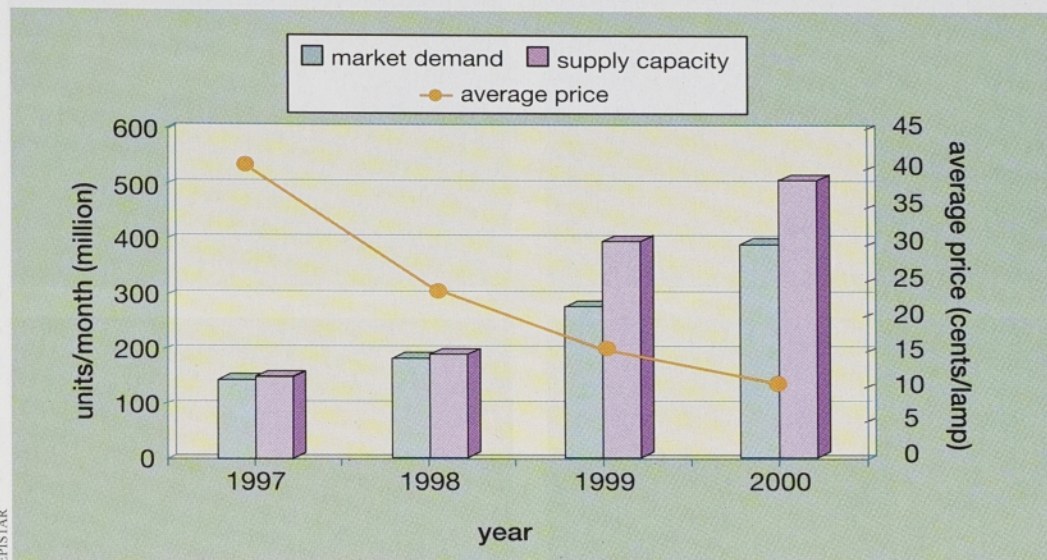


Fig. 6. Growth of the worldwide AlGaInP market. The supply capacity for packaged AlInGaP LEDs is now more than three times higher than in 1997 – most of this extra capacity is in Taiwan, the world's main producer. Since capacity is exceeding demand, the average selling price has dropped by a factor of four.

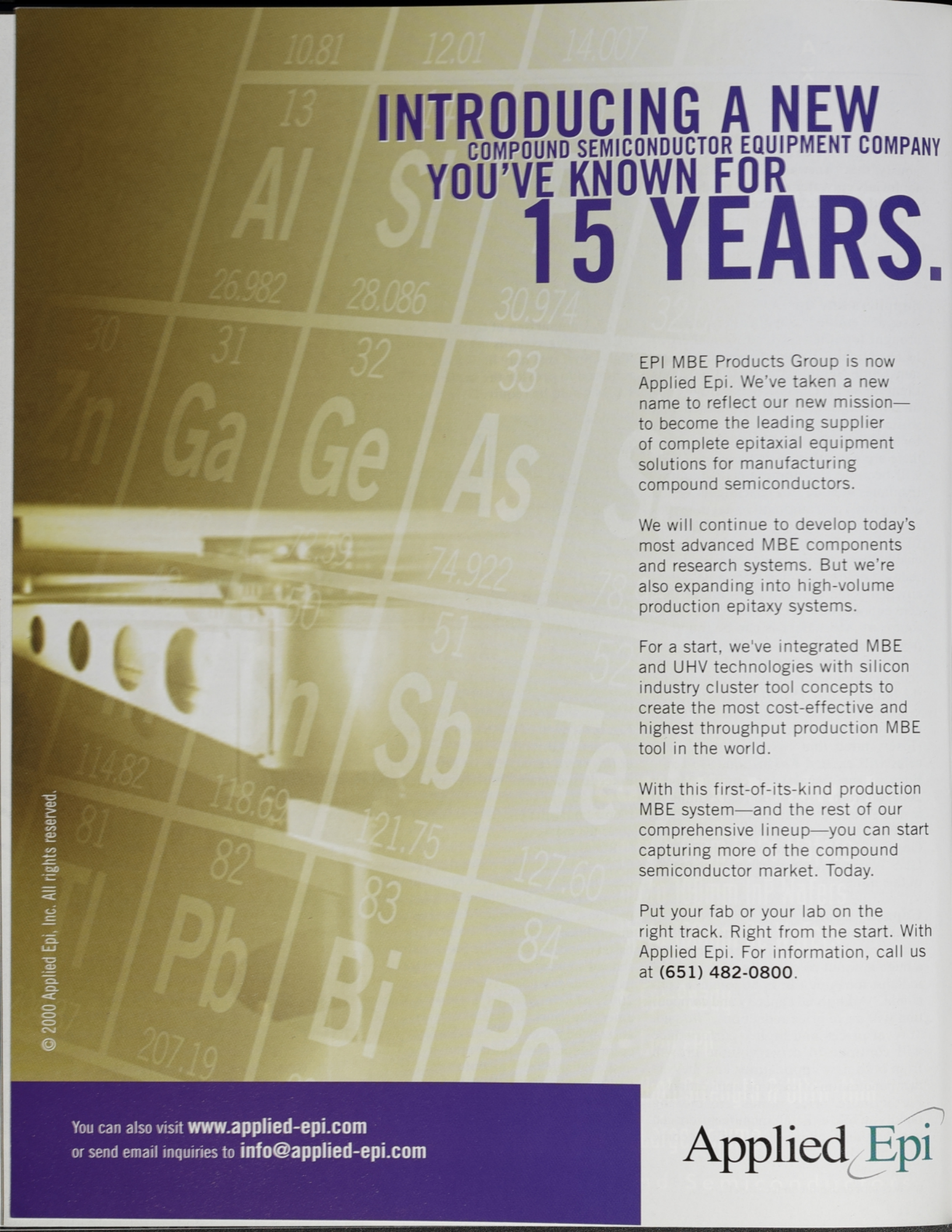
increasingly difficult for new players to enter the market.

Ruediger Mueller, the president and CEO of Osram Opto Semiconductors, described his company's philosophy as summarized by the phrase, "Don't waste photons." An example of the results of this attitude is the ATON chip, an InGaN-based device in which the SiC substrate is shaped so as to improve light extraction (see *Compound Semiconductor* February 2001, p7). In Mueller's view, a major emerging market for LEDs is visualization – the use of LEDs in displays. Full-color indoor and outdoor displays are now available from manufacturers, while LEDs and lasers are both potential light sources for digital projection displays.

AXT is a relative newcomer to the LED scene, but already has a potential

monthly capacity of 20–25 million chips. Morris Young, AXT's CEO, described a huge latent demand for LEDs that could be accessed with lower prices. "Customers have told us that a 30% reduction in price for InGaN-based LEDs could lead to a 50–60% increase in demand," he reported. And the overriding message from Strategies In Light was that the future market for high-brightness LEDs will prove to be very valuable, provided the device manufacturers can meet the challenges presented by each of the different market segments.

The Strategies in Light conference is organized by Strategies Unlimited, a market research company based in Mountain View, CA. Next year the event will be held on 7–8 February.



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AlGaInP LEDs break performance barriers

Mari Holcomb, Pat Grillot, Gloria Höfler, Mike Krames and Steve Stockman from LumiLeds Lighting explain how they overcame the challenges involved in developing amber, orange and red AlGaInP LEDs with impressive efficiency and power characteristics.

Incandescent lighting sources, first developed by Edison in the 1880s, still represent roughly a third of the energy consumed for residential and commercial building lighting in the United States. For monochromatic lighting applications such as automotive lighting or traffic signals, light from the incandescent bulb is typically filtered through a plastic lens of the desired color. This results in poor efficiency, since most of the visible light produced is thrown away.

Visible LEDs, as introduced commercially in the 1960s, offer the advantage of efficient direct monochromatic emission. However, until recently the commercial use of visible LEDs has been largely confined to indicator and display applications. The recent efficiency improvements of MOCVD-grown AlGaInP (red, orange and amber) and GaInN (blue and green) LEDs have enabled their use in a wide range of applications such as exterior automotive lighting, traffic signals and full-color outdoor signs. Further efficiency improvements and manufacturing cost reduction will enable LED-based systems to compete in the \$40 billion lighting market with conventional technologies such as incandescent bulbs, fluorescent lighting, sodium vapor lamps and neon.

The highest-efficiency LEDs demonstrated to date come from the quaternary AlGaInP material system, which encompasses the amber through red color regime. Four generations of AlGaInP chips are shown in figure 1, highlighting the major development stages of these high-efficiency and high-power devices. In this article, the key technologies responsible for the record performance of AlGaInP LEDs will be reviewed, including epitaxial growth, wafer bonding, chip shaping and LED packaging. Device design strategies for optimizing LED efficiency and the resulting state-of-the-art lamp performance characteristics will be

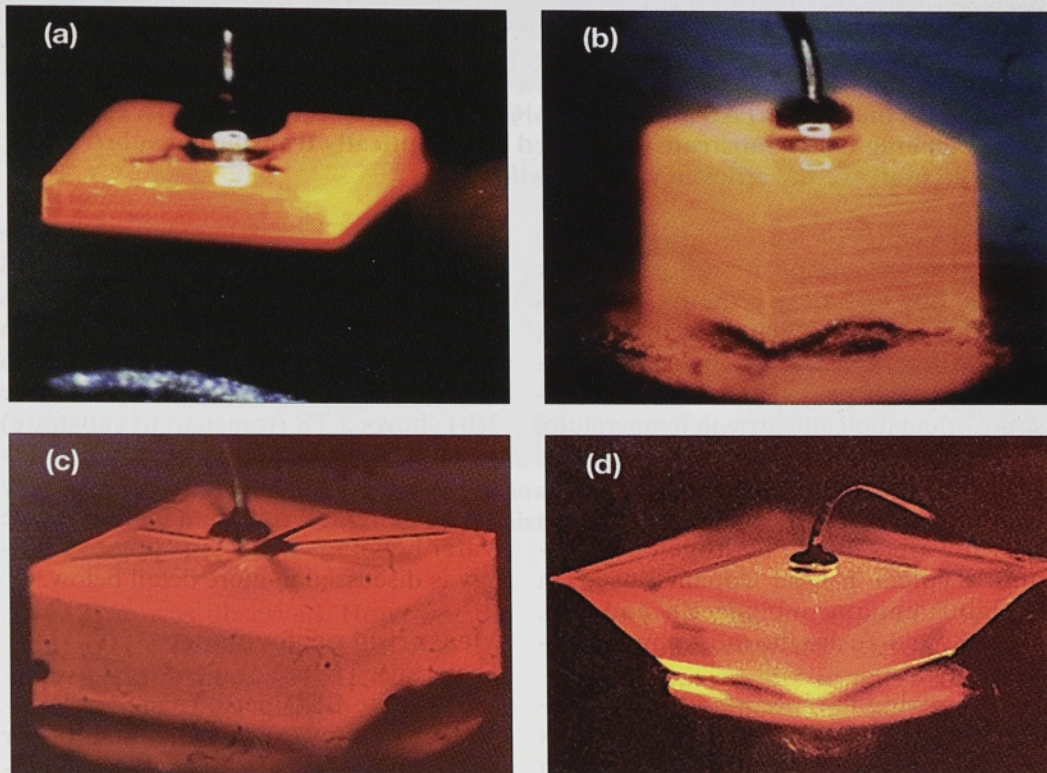


Fig. 1. Four generations of AlGaInP LEDs: (a) absorbing substrate (AS) LED; (b) transparent substrate (TS) LED with two to three times the AS flux; (c) high-power LED with five times the TS flux; (d) truncated inverted pyramid (TIP) LED with eight times the TS flux.

examined, along with the advantages AlGaInP LEDs provide compared with conventional lighting sources. Finally the limitations of AlGaInP technology are discussed, along with future challenges.

Growth and device structure

$(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$ is lattice matched to GaAs for Al compositions ranging from $x=0$ to $x=1$, and has a direct bandgap for $x=0$ to $x\sim 0.53$. In this direct bandgap compositional range, $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$ emits over the red (1.9 eV) to yellow-green (2.26 eV) spectral regime; however, the radiative efficiency drops significantly with higher Al composition as the alloy approaches the direct-indirect band-

gap crossover. As such, commercial AlGaInP LEDs are primarily limited to red, orange and amber emission.

Commercial AlGaInP LEDs are grown by low-pressure MOCVD. Alloy ordering, hydrogen passivation of acceptor atoms and unintentional oxygen incorporation are key issues in the MOCVD growth of high-quality AlGaInP material. Spontaneous AlGaInP ordering occurs when the AlGaInP material forms an unintentional superlattice of InP/AlGaP layers. This superlattice results in a lower bandgap (longer emission wavelength) than the random alloy. Since AlGaInP efficiency decreases as Al composition increases, it is generally desirable to min-

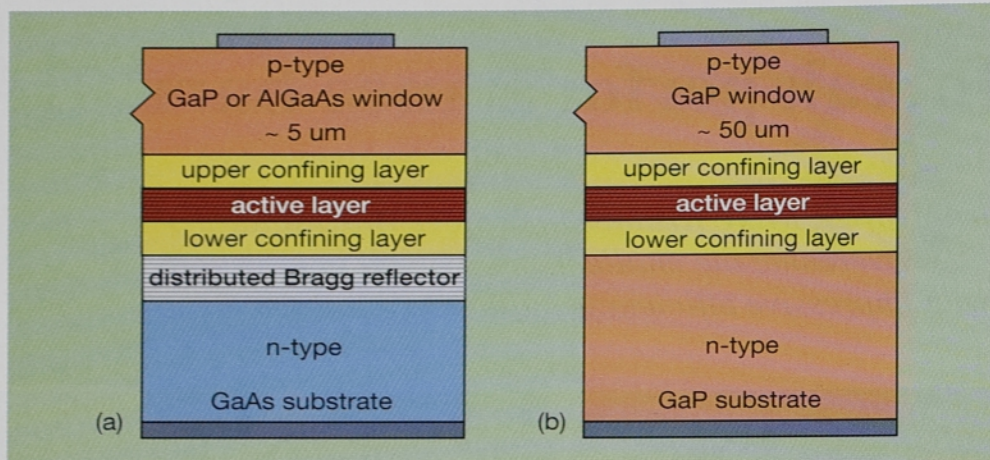


Fig. 2. Schematic of (a) AS and (b) TS AlGaInP LED structures. For TS LEDs the absorbing GaAs substrate is replaced by an optically transparent substrate in order to improve the efficiency of extraction.

imize the emission wavelength (bandgap) for a given Al composition. Reducing or eliminating this alloy ordering, which is also important for wavelength control, may be accomplished by choosing appropriate growth parameters such as substrate orientation and growth temperature, and by post-growth annealing. The latter is also used to fully activate acceptors, which are often initially inactive in as-grown wafers due to hydrogen passivation. Typical p-type dopants used in AlGaInP epitaxy include Zn and Mg, while Si and Te are the most common n-type dopants.

Minimizing the incorporation of oxygen is also important, especially in layers with a high Al content, since oxygen tends to introduce defect states in the semiconductor layers that decrease radiative efficiency. Oxygen incorporation depends strongly on Al content, as well as growth parameters such as substrate orientation, growth temperature and input V/III ratio. The careful optimization and control of growth parameters are thus used to help control material properties, resulting in AlGaInP with high radiative efficiency and enabling the commercialization and high-volume manufacturing of AlGaInP LEDs and laser diodes.

A schematic of two common AlGaInP LED structures is shown in figure 2. For both structures the active layer is sandwiched between two carrier-confining layers which are typically composed of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$, with $x > 0.7$. The top contact layer, usually GaP or AlGaAs, serves as both a current-spreading layer and a window layer to improve extraction

of light directed toward the side of the chip. The structure in figure 2(a) is an AS (absorbing substrate) LED. In AS devices a distributed Bragg reflector is often grown below the lower confining layer to increase on-axis light emission. Figure 2(b) shows a TS (transparent substrate) structure in which the absorbing GaAs substrate is replaced with an optically transparent GaP substrate by solid-state wafer bonding. Wafer-bonding technology is discussed in more detail below.

Measuring performance

The primary figure of merit used to evaluate visible LED performance is luminous efficiency, expressed in lumens per watt (lm/W). This is the wall-plug efficiency (optical power divided by the input power) weighted to match the human eye response. LED luminous efficiency is determined primarily by three factors: the internal quantum efficiency (QE), the extraction efficiency and the operating voltage. The internal QE characterizes how many photons are generated for each electron passing through the LED. The extraction efficiency is the percentage of the generated light that escapes out of the semiconductor chip. Due to the high refractive index mismatch between the semiconductor and the surrounding medium, most photons are internally reflected multiple times, during which they may be absorbed. The product of the internal QE and extraction efficiency is referred to as the external QE. The operating voltage is determined by the active region bandgap and the LED electrical series resistance.

The internal QE of LEDs is determined by the material quality and the active region design. The active region of the LEDs is typically composed of multiple thin AlGaInP layers, or quantum wells, separated by higher-bandgap barrier layers. For AlGaInP LEDs, the internal QE increases with the thickness of the active layer, due to reduced electron leakage current to the confining layers, especially for active regions with higher Al composition. However, the extraction efficiency decreases as the thickness of the active layer increases, due to increased absorption during multiple passes of the light through the active region. As a result of these opposing trends, there is an optimum total active layer thickness for a given wavelength so that the external QE is maximized. The total active layer thickness is therefore chosen through experimental optimization for a given target emission wavelength.

The extraction efficiency is limited by photon loss during multiple passes within the chip. The primary loss mechanisms are absorption in the GaAs substrate (in AS devices), the active layer and the ohmic metal contacts, and free carrier absorption in the window and substrate (in TS devices). The escape cone for a given point source in the active layer is defined by the critical angle according to Snell's law. Increasing the top window layer thickness significantly improves extraction efficiency, because the light directed towards the sides of the chip can escape before being internally reflected or absorbed at either the top or bottom LED surface. The thickness of the top window layer typically ranges from a few micrometers to 60 μm . Devices with a 60 μm GaP window have demonstrated efficiencies twice that of 10 μm windows (Huang *et al.*). In high-volume manufacturing, thick GaP window layers are typically achieved by regrowth using hydride vapor phase epitaxy.

For AS devices a large source of photon loss is the absorbing GaAs. The extraction efficiency can be significantly improved by replacing the absorbing substrate with an optically transparent substrate. TS AlGaInP LEDs were developed at the Hewlett-Packard Optoelectronics division in 1994 using compound semiconductor wafer bonding technology (Kish *et al.*).

After epitaxial growth, the GaAs substrate is removed by selective etching.

The remaining epitaxial wafer and the bonding GaP wafer are shown in figure 3. The wafer bowing evident in the epitaxial wafer results from the coefficient of thermal expansion mismatch between the AlGaInP layers and the GaP window layer. The epitaxial layers are placed in contact with the GaP so that the crystallographic orientation of the wafers is matched. Robust chemical bonds are created at the bonding interface upon application of uniaxial pressure to the wafers at elevated temperatures. Despite the 3.6% lattice mismatch between the two wafers, good optical transparency and electrical conduction are obtained across the interface. TS devices have at least twice the flux of AS devices made from the same epitaxial material. Interface states at the bonding interface do result in a small forward voltage penalty of 50–100 mV compared with AS devices. Nevertheless wafer-bonded TS LEDs are still the devices with the highest luminous efficiency available to date. Furthermore these good bonding characteristics can be achieved uniformly across wafers as large as 75 mm in diameter, enabling TS LEDs to be manufactured in high volumes.

Lamp performance

Epitaxial growth or wafer bonding are followed by deposition of top and bottom ohmic contacts. The wafers are subsequently diced into squares, typically 210–300 μm each side. The chips are then attached to a lead frame with silver-loaded conducting epoxy. After wire-bonding the top contact to the lead frame, both the die and lead frame are encapsulated in a hard transparent epoxy. A typical 5 mm lamp is shown in figure 4(a).

The highest luminous efficiency measured from conventional 5 mm lamps made with TS wafers is shown in figure 5 as a function of peak wavelength (Gardner *et al.*). The lamps have luminous efficiencies exceeding 50 lm/W at a current density of 40 A/cm² over the color range used for commercial AlGaInP LEDs. The highest luminous efficiency for the 5 mm lamps is 74 lm/W for lamps emitting at 615 nm. The external QE of AlGaInP LEDs improves with increasing wavelength (lower Al composition) due to better carrier confinement, higher relative electron population of the direct Γ minimum, reduced non-radiative impurity incorporation and reduced absorption. For these lamps an external QE of 32%

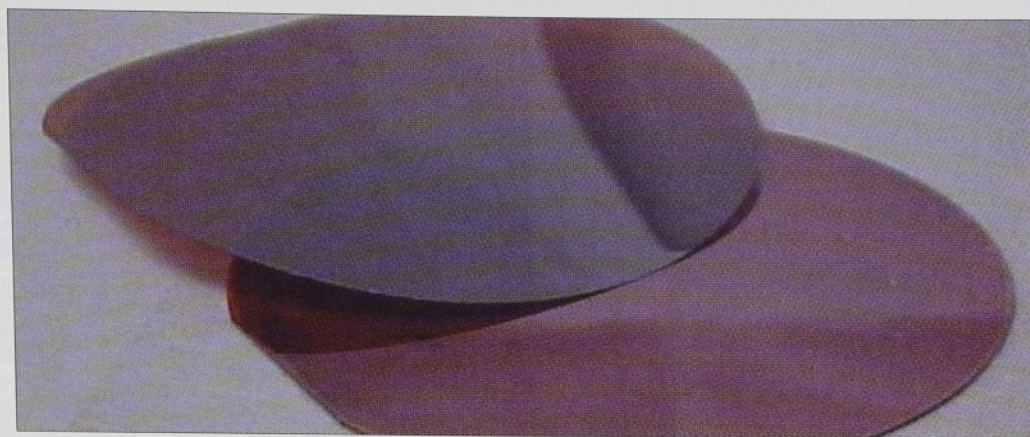


Fig. 3. A 75 mm epiwafer (after GaAs removal) and a GaP substrate before wafer bonding. Bowing of the epiwafer results from the coefficient of thermal expansion mismatch between AlGaInP and the GaP window.

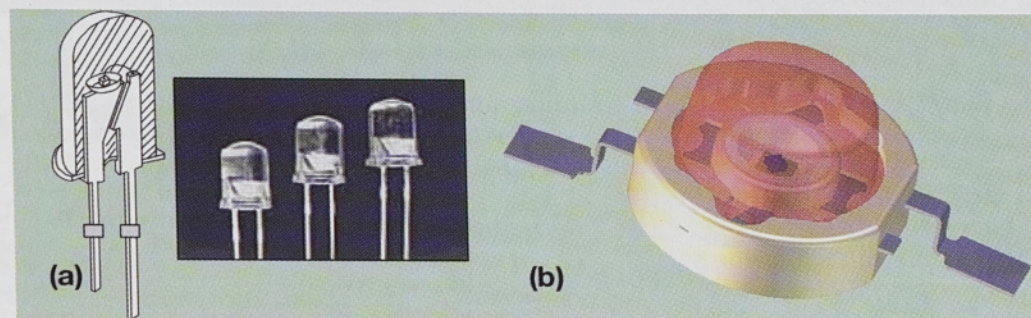


Fig. 4. Two examples of LED packaged lamps: (a) conventional T1-3/4 (5 mm) lamps which have 220 °C/W thermal resistance; (b) high-power LED lamp which has 15 °C/W thermal resistance.

at 632 nm was observed. However, the luminous efficiency drops due to the decreasing response of the human eye with increasing wavelength, as indicated by the CIE curve. The maximum DC output flux from 5 mm lamps driven at 50 mA is limited to 5–10 lm per LED.

High power and efficiency

Typical illumination systems require photometric output power of several hundred lumens. Simply increasing the number of conventional LEDs is often impractical for such systems. To solve this a new generation of high-power LEDs and packaging technology have been developed and commercialized by LumiLeds Lighting.

The simplest way of increasing the flux per LED is to make the chip bigger. One example of a chip with increased die area is shown in figure 1(c). The junction area of these devices is approximately five times that of the conventional die packaged in 5 mm lamps. Therefore driving the larger die with five times the current of the conventional die (equivalent current density) should in principle increase the flux fivefold.

However, simple scaling of the device area significantly reduces extraction efficiency. This results in part from a decrease in the fraction of the light within the critical-angle escape cone that reaches a chip side wall before being internally reflected at the die top or bottom surface. Photons must traverse a much longer path before encountering a surface, making internal absorption much more likely. For a fixed die height, modeling and experiments show a 25% decrease in external QE when the die area is increased from 210 × 210 μm^2 to 500 × 500 μm^2 (Höfler *et al.*).

In addition, conventional LED packaging used for 5 mm lamps is not sufficient to dissipate the heat associated with higher input powers to the larger chip. Thus a high-power package had to be designed in addition to a larger chip. One such high-power package is shown in figure 4(b). The die is solder-attached to a submount to compensate for the coefficient of thermal expansion mismatch between the copper heat sink and the LED. These features, combined with the reduced thermal resistance of the chip

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itself, result in a lamp with thermal resistances of between 12 and 15 °C/W, some fifteen times lower than that of conventional 5 mm lamps.

Another feature of the package is a soft encapsulating gel that minimizes stress on the die, which is injected through a hard outer protective lens. As a result of all these improvements, the maximum DC output flux from these high-power lamps is more than five times higher than that achieved by conventional 5 mm lamps made of the same epitaxial material.

The efficiency-scaling penalty can be overcome by shaping the die. The ideal geometry for maximum extraction efficiency is a sphere with an emitting volume in the center, but this is not practical to manufacture. The truncated inverted pyramid (TIP) shape shown in figure 1(d) was chosen as a manufacturable alternative. This geometry experimentally increases extraction efficiency up to 50% compared with square large junction devices with the same 500 × 500 nm² active area (Krames *et al.*). This is due to higher photon emission from both the side and top surfaces. Specifically, compared with conventional dice with orthogonal side walls, rays that are internally reflected from the top (beveled side) surface subsequently hit the beveled side (top) surface with a lower angle of incidence, hence increasing the number of rays within the critical-angle escape cone. The die is oriented junction side down for improved heat sinking and is packaged in lamps similar to those described for square high-power chips.

Peak performance

AlGaInP TS TIP-LEDs are the most efficient visible spectrum LEDs demonstrated to date in any material system. The DC luminous efficiency at 40 A/cm² of several TIP-LEDs with peak wavelengths from 594 to 652 nm is plotted in figure 5. The highest luminous efficiency of 102 lm/W was achieved for 611 nm lamps. The external QE for these devices ranges from 15% for amber lamps to 55% for deep-red 652 nm lamps. For the deep-red lamps, 60% external QE was observed under pulsed operation. As the internal efficiency is the highest for long wavelength devices, this 60% efficiency represents the lower bound of extraction efficiency for the TIP-LED structure.

More than 60 lm of output flux has been measured from single TIP-LED

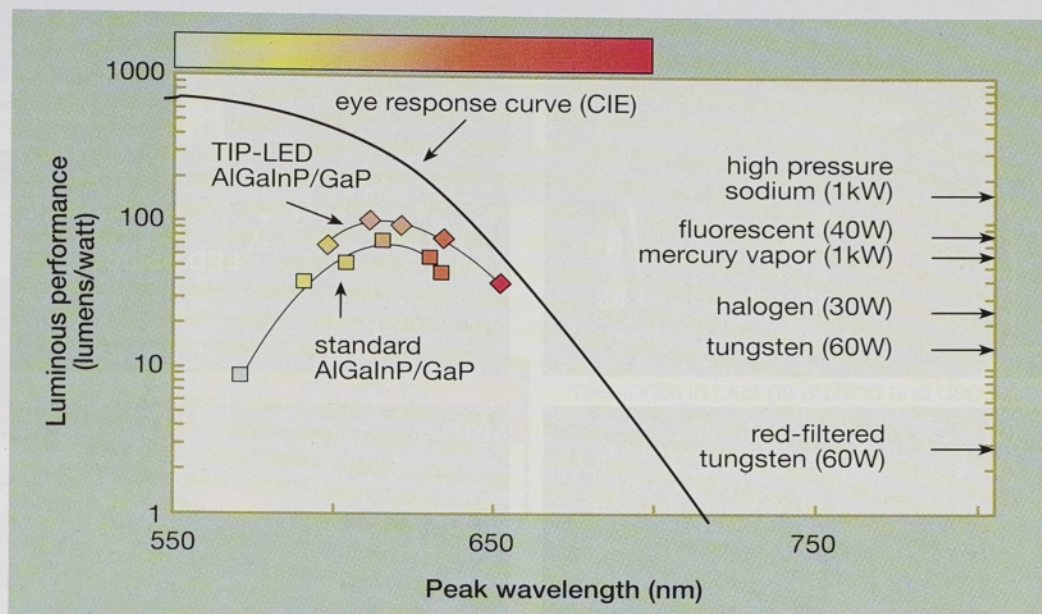


Fig. 5. Measured luminous efficiency for standard TS 5 mm lamps and high-power lamps using TS TIP-LED chips ($J = 40 \text{ A/cm}^2$). The 611 nm TIP-LED lamp has an efficiency of 102 lm/W. The 652 nm TIP-LED device has an external QE of 55%.

lamps over the wavelength range of 590–640 nm at DC drive currents less than 500 mA. This corresponds to roughly 100–350 mW of optical power. This is about 15 times higher than the output power that can be obtained from conventional 5 mm lamps. Mechanical and accelerated life testing indicate that the TIP-LED devices are just as robust and reliable as square chips.

Lighting applications

Commercial AlGaInP LEDs are expected to account for at least 30% of the high-brightness LED market, which is forecast to exceed \$3 billion per year by 2005 (see page 53). Several examples of AlGaInP lighting applications are shown in figure 6. In the automotive lighting market, AlGaInP LEDs are currently used as center high-mount stop lights on most new European automobiles. With increasing power per LED, LED utilization is expanding to include turn signals, tail lights and daytime running lights motivated by increased styling and design flexibility, faster turn-on times for improved safety and lifetimes exceeding that of the vehicle. High-power AlGaInP and InGaN LEDs are also enabling increased adoption in traffic signals, where the power savings, increased safety (LEDs are more reliable) and reduced maintenance/replacement cost are major advantages over conventional incandescent bulbs. For example, a 12 inch traffic ball using 12

high-power red LEDs requires less than 15 W of input power, an order of magnitude lower than the 150 W incandescent lamp-based traffic balls currently prevalent in the US. LED-based systems are also beginning to replace neon signs, which require hazardous high-voltage operation and are not as mechanically robust as LEDs. There is also growing interest in using LEDs for non-lighting applications such as dental curing and skin treatment.

Finally, high-power AlGaInP red and InGaN blue and green LEDs are expected in the future to be incorporated into projection displays and LCD backlighting applications. For these applications, the color purity and color range exceed those that can be obtained by conventional lighting sources. The largest potential market for high-efficiency LEDs is in the area of solid-state illumination. The demonstrated high efficiency of AlGaInP LEDs makes them well suited to these applications, either in the form of monochromatic amber illumination or as a part of a red-green-blue combination for the efficient generation of white light.

Future challenges

How quickly the market adopts LED lighting solutions will depend in part on the speed of reduction in system costs. This will result from further increases in flux per LED and from lowering the costs of manufacturing, so that the LED dol-

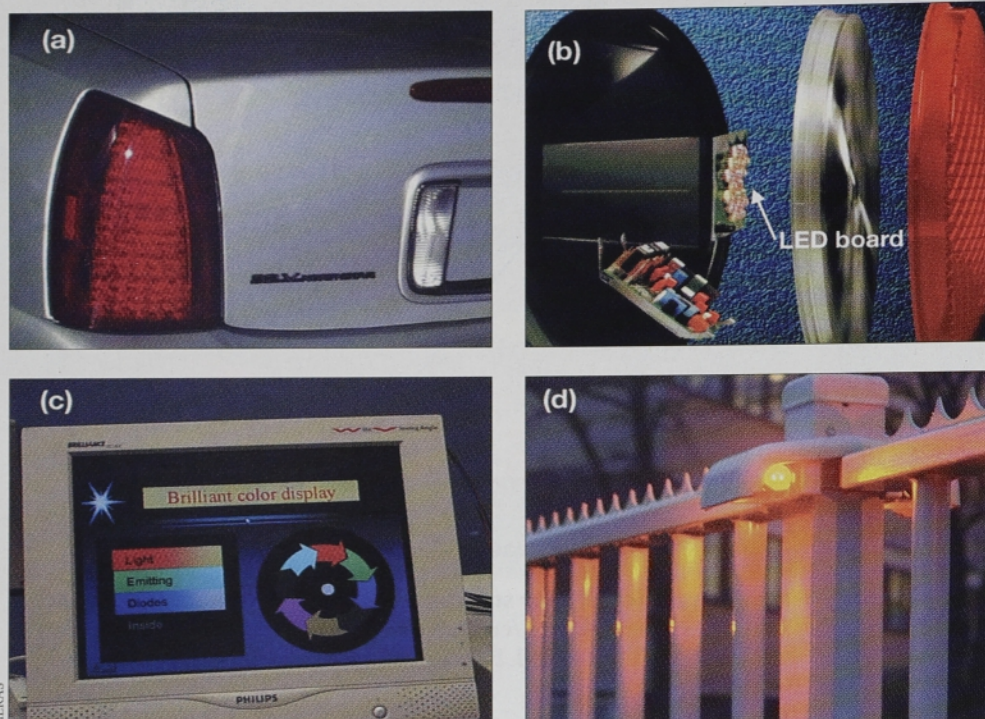


Fig. 6. AlGaInP LED applications: (a) rear combination and high-mount stop light with automotive lamps; (b) 15 W traffic signal with high-power LEDs; (c) LCD monitor backlit with AlInGaP and InGaN LEDs; (d) security light with TIP-LEDs.

lar/lumen cost is closer to those of conventional lighting sources.

Although the AlGaInP material system is relatively mature, there are fundamental physical properties that put a limit on high-power performance. The internal efficiency of AlGaInP LEDs is primarily limited by active-region electron loss to the surrounding confining layers, and the indirect conduction band minima. Carrier population of the indirect minima is especially severe for shorter wavelength devices such as amber and green.

This poor carrier confinement results in decreased efficiency at higher current densities and at high temperatures. For example, the shaped TIP-LED devices discussed earlier can have luminous efficiencies exceeding 100 lm/W for drive current densities equivalent to conventional 5 mm lamps (40 A/cm²). However, for most applications these TIP-LED devices are typically driven at current densities two to three times higher than conventional LEDs. At these operating current densities the luminous efficiency can drop by 20% or more, depending on the wavelength and how efficiently heat is removed from the active region.

Further increases in the drive current density are necessary to increase the out-

put flux per LED, despite the efficiency penalty. However, there is a maximum drive current for AlGaInP LEDs above which the flux decreases, as junction heating effects dominate due to the increased drive power dissipated in the LED.

In addition to the electron loss mechanisms described above, the decrease in luminous flux with increasing temperature also results from the decrease in the human eye response as the wavelength shifts away from the CIE peak with increasing temperature. Because of the high flux sensitivity to elevated temperatures, it is essential to ensure good heat sinking when designing a system based on AlGaInP LEDs.

Thus band-gap engineering and the modification of active region design to improve carrier confinement could potentially greatly enhance LED system performance, by improving internal QE and by increasing the current and ambient temperature range of LED operation.

For some applications the maximum drive current of AlGaInP LEDs is limited by the operating lifetime of the LED. The rate of flux degradation of AlGaInP LEDs over time increases with both increasing junction temperature and current density. Typical operating current densities of

AlGaInP LEDs are 50–200 A/cm².

Enhanced LED performance can also come from further improvements in packaging. For example, improved heat sinking would enable operation at both higher temperatures and higher current densities. The LED extraction efficiency could be significantly increased by developing alternative higher index encapsulants. For example, the typical refractive index of the current commercial LED encapsulant is ~1.5, less than half the value of the LED chip. Increasing the encapsulant refractive index by 30% could result in a 45–60% improvement in extraction efficiency, depending on chip geometry.

Ways forward

AlGaInP LED lamps have the highest efficiency demonstrated to date of all visible spectrum LEDs, and are commercially manufactured in large volume. The high efficiency results from technical developments in epitaxial growth, wafer bonding, packaging and device engineering. However, despite the recent breakthroughs in visible LED performance, the system dollar per lumen cost is still prohibitively high to meet requirements for general illumination. Reduction of the system cost will come through further fundamental breakthroughs or engineering development in device performance, as described above. In addition, manufacturing costs can be reduced by improvements in uniformity and reproducibility, and by identifying less costly manufacturing methods, while maintaining device performance. As these two objectives are met, the high efficiency and other inherent advantages of visible LEDs will enable large market opportunities, and have a significant impact on reducing worldwide energy consumption.

Further reading

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Mari Holcomb, Pat Grillot, Gloria Höfler, Mike Krames and Steve Stockman are with LumiLeds Lighting, a joint venture between Agilent Technologies and Philips.

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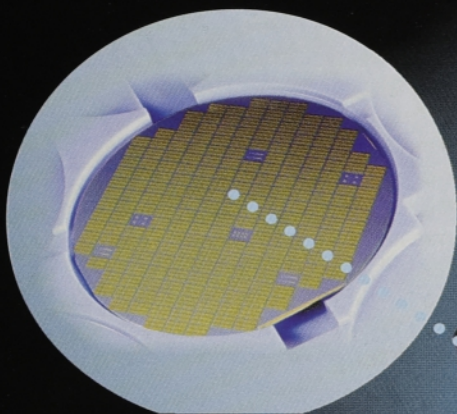
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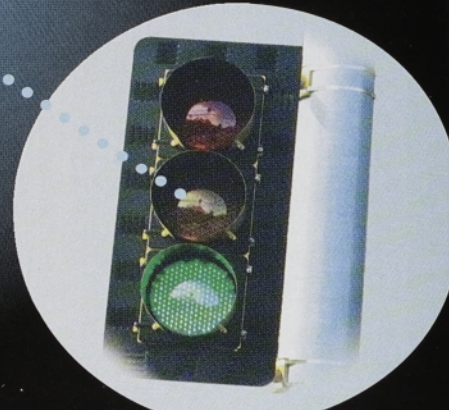
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Handset displays drive Japan's LED market

Japan is home to two dominant manufacturers of InGaN LEDs, Nichia and Toyoda Gosei, but other companies may be about to enter the fray. Chris Redl of UBS Warburg sheds some light on the Japanese market for blue, green and white emitters.

The demand for high-brightness InGaN LEDs continues to increase, driven by applications such as traffic signals, backlighting for displays in mobile phones and interior automotive lighting. In Japan this market is dominated by two companies, Nichia and Toyoda Gosei, who are estimated to have combined LED revenues of \$580 million in the 2001 fiscal year, compared to \$103 million just three years ago.

Following its agreement to license Cree's LED technology, Rohm looks set to enter the market in summer 2001 (see *Compound Semiconductor* February 2001, p8). Such is Rohm's reputation in Japan for aggressively driving down prices – through its expertise in high-volume manufacturing of high-tech components – that Toyoda Gosei stock fell 66% in the month following the Cree–Rohm announcement.

Other companies, including Toshiba and Sharp, have finished development of GaN-based LEDs but are still sitting on the sidelines, apparently awaiting the outcome of the Nichia–Toyoda Gosei lawsuits. As recently as February 7, Toshiba announced the joint development of white LEDs based on InGaN-based chips fabricated by Toyoda Gosei (see box, overleaf).

The big guns

As shown in figure 1, estimated revenues for fiscal year 2000 were \$407 million for Nichia (whose fiscal year ends in December) and \$174 million for Toyoda Gosei (fiscal year ends in March). In fact, Toyoda Gosei recently reduced its fiscal 2000 estimates from ¥22.5 billion (\$195 million) to ¥20 billion (\$174 million). The company cited lower sales volume, rather than lower pricing, as the reason; the lower volume was largely due to a lack of white LED products to compete with Nichia. However, Toyoda Gosei should have mass-production capabilities for its own white LED towards the end of this year.

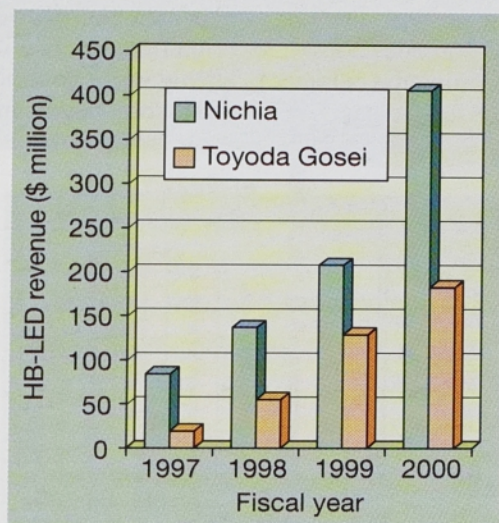


Fig. 1. High-brightness InGaN-based LED revenues from Nichia and Toyoda Gosei. In 1999, sales of HB-LEDs represented 50% of Nichia's total sales, but only 5.5% of Toyoda's. In 2000, Toyoda's revenues grew 43% year-on-year, while Nichia's shot up by 96%.

Both Nichia and Toyoda Gosei are investing heavily to continue increasing their production capabilities. Toyoda Gosei has roughly doubled its capacity over the last 12 months, and should have the capability to produce up to 75 million LEDs per month when its new factory is operational. Management expects to grow capacity by around 30% in fiscal 2001, mostly through higher yields. Meanwhile, Nichia has more than tripled its potential capacity via a brand-new factory which will allow the fabrication of around 100 million units per month.

The relative fortunes of the two companies have been closely linked to the market for HB-LEDs used as backlights for liquid-crystal displays (LCDs) in mobile phone handsets. In 1999, Toyoda Gosei's revenue showed year-on-year growth of 135%, increasing from \$55 million to \$129 million for the fiscal year end-

ing March 2000. This corresponded to a strong growth in demand for monochrome displays, which require single-color (blue, green etc) LEDs for the backlights. The cell phone manufacturers also largely required unpackaged chips, which Toyoda Gosei was well positioned to supply.

In 2000 the market shifted from monochrome displays towards full-color displays requiring white LEDs as backlights. Nichia enjoys almost total market dominance in this area as it is currently the sole supplier of white LEDs; consequently, the company's revenues increased some 96% over 1999 (compared to 43% for Toyoda Gosei).

Market demand

Display backlights for Japanese mobile phone handsets make up the majority of overall demand for InGaN-based LEDs in Japan, accounting for 55–60% of the output of both Nichia and Toyoda Gosei. Strong future growth is expected from western cell-phone makers, and also from the personal digital assistant market. The traffic signal market is not particularly promising in Japan – the country has only 180 000 signals compared to three million in the US. Moreover, existing manufacturers are protected by the government: specifically, retired officials from the National Police Agency, which controls the market, frequently get jobs with signal makers. Automotive manufacturers in Japan have lagged behind their European counterparts regarding the use of LEDs for dashboard backlighting and other interior lighting applications, although this is showing signs of change. By 2003, most of Japan's 11 auto makers should have a higher LED content per vehicle, especially in LED-based tail-lights.

The HB-LED market for handset displays has proved to be very aggressive and price-competitive. Emerging technologies such as W-CDMA place stringent demands on battery technology,

Toyoda Gosei and Toshiba join forces to develop a white-light LED

Two leading Japanese LED manufacturers, Toyoda Gosei and Toshiba, have jointly developed a white LED, which will be marketed separately by both companies under their own brand names. The white lamp combines a 380 nm InGaN-based chip, fabricated by Toyoda Gosei, with a red, green and blue phosphor in a transparent package developed and produced by Toshiba.

The new device is the first

example of a white LED that combines a near-UV LED with a tri-color phosphor. Other products, such as those made by Nichia, use a blue LED in combination with a phosphor that emits in the yellow region, and have poor color stability because the wavelength of the blue LED varies with temperature.

In the new product, the 380 nm emission does not directly determine the color output, so the device has

improved controllability and wavelength stability.

The partners plan to begin shipping samples in April, with a sample price of ¥200–300 (\$1.70–2.60). This is roughly double the price of Nichia's white LEDs, which are more than twice as bright as the Toyoda/Toshiba product. However, Toyoda's management believes that brightness levels will match Nichia when commercial production begins in

November at 500 000 units per month. The chips will be manufactured by Toyoda and packaged by Toshiba: the surface mount devices will be housed in a 3.2×2.8 mm package. Planned production will reach four million units by March 2002, by which time prices should fall to the level of Nichia's white LEDs. Target applications include the instrument panels of motor vehicles and LCD backlighting.

requiring the use of the highest-efficiency light source for the display. Currently, the HB-LED market for handset displays is estimated at around \$350 million, up 200% year-on-year. Roughly 30% of handsets sold in Japan now have full-color displays, and this should increase to nearly 70% within three years. The market is expected to peak at \$542 million in 2003, as shown in figure 2. After that, displays made from organic LEDs are expected to steal market share from LCDs with LED backlights.

Nichia is currently estimated to have a 60% share of the handset market, as it is the sole supplier of white LEDs. Toyoda Gosei has 30%, with Cree taking the other 10%, although this split is likely to change once Rohm enters the market.

Law and disorder

The current patent dispute between Nichia and Toyoda Gosei, which has taken the form of more than 10 lawsuits between the two companies, is creating a barrier to market expansion and keeping prices high. If the lawsuits are resolved soon, the cost per lumen for InGaN-based LEDs should drop rapidly as other manufacturers enter the market, allowing these products to penetrate new market segments.

Although the courts have favored Nichia in the two rulings made to date, six of the seven lawsuits filed by Nichia refer to products that are no longer in production by Toyoda Gosei. The seventh refers to the aluminum content of the electrode materials in Toyoda Gosei's devices, and at the moment Nichia appears to have a weaker case against Toyoda Gosei in this area due to reported requests by Nichia

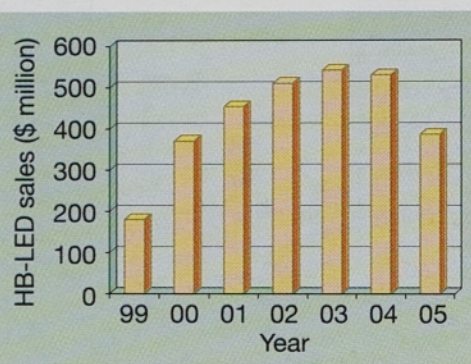


Fig. 2. Estimated sales growth for HB-LEDs in Japan's mobile phone display market. Roughly 30% of phones have full-color displays, which require white LEDs as backlights. Around 50% growth is expected over the next three years, after which the market is expected to fall due to the introduction of displays based on organic LEDs.

to withdraw some of the sections of the lawsuit. However, Nichia has a range of other patents that could be used as the basis for further lawsuits, particularly in annealing.

Several key issues are waiting to be resolved in the patent dispute. For example, will Nichia continue to push for a monopoly, or will it cross-license with other companies? Or will Nichia succeed in its stated aim of putting Toyoda Gosei out of business? Furthermore with such a large market at stake, will Japan's Fair Trade Commission allow Nichia to hold a monopoly, if Nichia pushes Toyoda Gosei out of the market and decides not to cross-license?

The lawsuits are time-consuming, and are keeping new entrants out of the

market. In the meantime, prices for InGaN-based devices are staying at an artificially high level, and the leading suppliers are generating huge profits. This has funded further expansion, which in turn will make it much more difficult for potential competitors to enter the market in the future.

Looking to the future

While Nichia currently dominates the white LED market, the recent Toshiba-Toyoda Gosei announcement suggests these two companies will provide strong competition within a year. Perhaps more importantly, following its alliance with Cree, Rohm is likely to make inroads into the blue and green LED market, initially at the lower brightness end and subsequently for higher brightness applications.

We can also speculate that Nichia may become involved in some interesting developments in the near future. One possibility is that Nichia could make a supply agreement with a major manufacturer, the likely candidate being Sony which, like other consumer electronics makers, requires Nichia's blue lasers to produce next-generation DVD systems with both read and write capabilities. Another possibility is that Nichia could file for an initial public offering; given Nichia's strong market position, the flotation could create a public company worth as much as \$5 billion.

Chris Redl is a director in the equity research department of UBS Warburg's Tokyo office. He covers Japan's automotive stocks, as well as Toyoda Gosei and the Japanese high-brightness LED industry as a whole.

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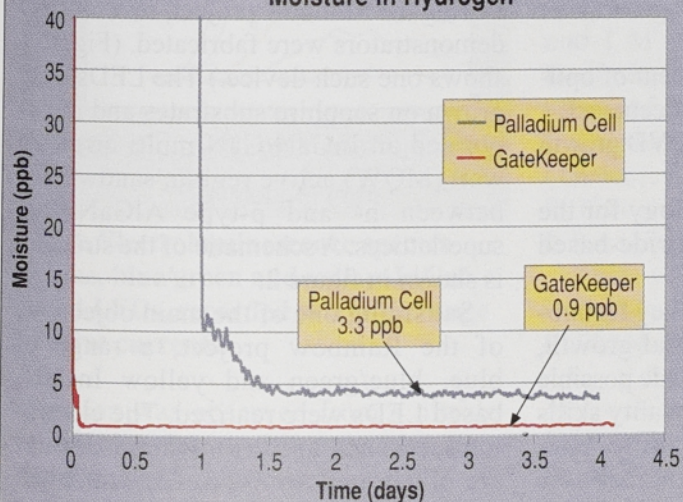
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Rainbow project brings color to LEDs

A European project to develop a manufacturing base for nitride-based devices has ended with the demonstration of multicolored LEDs, writes project coordinator Marie-Antoinette di Forte-Poisson of Thomson-CSF.

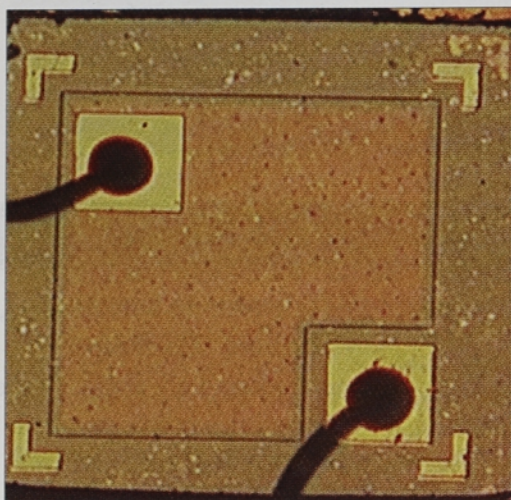


Fig. 1. A cleaved InGaN-based LED chip with gold wire bonds, fabricated as part of the Rainbow project.

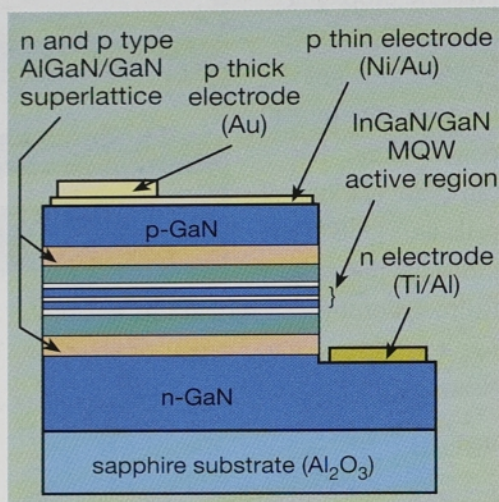


Fig. 2. Schematic of the InGaN/GaN multi quantum well LED structure, grown on a sapphire substrate.

LED performance

Property	Blue LED	Blue/green LED
Emission wavelength (nm)	460	500
Optical power (mW)*	1.8	0.25
Luminous intensity (mcd)*	850	130
Viewing angle	3° cone	3° cone

*These properties were measured at a drive current of 90 mA.

Funded by the European Union, the Rainbow project, which ended in July of last year, brought together a multidisciplinary consortium from industry and academia to develop nitride-based devices and related manufacturing infrastructure. The Gallium Indium Aluminum Nitride For Multicolor Sources project ran for 42 months and was designed to address two important growing markets: first, high-brightness outdoor lighting, as used in traffic signals, large outdoor displays, automobile lighting, etc; and second, the market for high-density optical disk storage, as used in multimedia environments.

With the final target being the production of LEDs and laser diodes, the major technical objective that had to be achieved in the framework of the Rainbow project was the realization of optoelectronic device demonstrators. These included LED prototypes emitting in the 400–590 nm range and laser diodes operating at a wavelength of around 400 nm.

This ambitious challenge required the development of a complete GaN-based technological background, from material studies to device realization and characterization. This process included four major technological milestones, which were all successfully reached:

- development of a multiwafer metal-organic chemical vapor deposition (MOCVD) reactor for the growth of group III nitride materials;
- identification and development of optimum group III and nitrogen precursors;
- optimization of the LP-MOCVD growth process for group III nitrides;
- definition of basic technology for the fabrication of group III nitride-based devices.

The optimization of these key technological process steps (material growth, device processing, etc) was made possible because of the varied, high-quality skills contained within the Rainbow consortium. These included manufacturers of electronic components (Thomson-CSF/Thales LCR), MOCVD growth reactors (Aixtron) and starting chemicals

(Epichem), together with experts in device design and characterization (University of Surrey, UK), reactor design (University of Erlangen, Germany), material characterization (University of Aveiro, Portugal) and material growth (CRHEA, France).

Project results

During the Rainbow project, several LED demonstrators were fabricated. (Figure 1 shows one such device.) The LEDs were grown on sapphire substrates and incorporated an InGaIn/GaN multi quantum well (MQW) active region, sandwiched between n- and p-type AlGaIn/GaN superlattices. A schematic of the structure is shown in figure 2.

Satisfying one of the main objectives of the Rainbow project, a range of blue, blue/green and yellow InGaIn-based LEDs were realized. The electroluminescence spectra of these devices are illustrated in figure 3, while the performance characteristics (see table) are close to being state of the art. As part of the Rainbow project, spontaneous

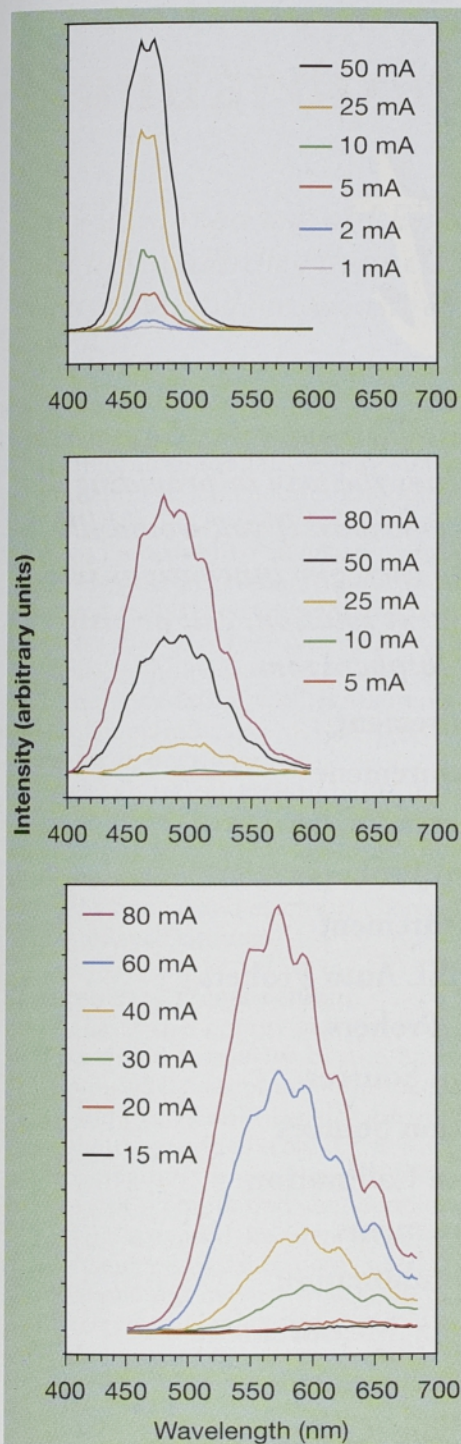


Fig. 3. Electroluminescence spectra of blue, blue/green and yellow InGaN-based LEDs, recorded at a wide range of drive currents.

emission was observed from a nitride-based blue laser, although stimulated emission was not recorded.

In addition to the device demonstrators, significant progress was made to establish the necessary infrastructure for the epi-

taxial growth of nitride materials. High-purity group III and dopant precursors are now routinely produced by Epichem, while Aixtron is supplying LP-MOCVD multiwafer reactors for the growth of group III nitride materials.

Future directions

Thomson-CSF intends to use the results of the Rainbow project in numerous applications, and the company's central research laboratory (LCR) is already developing components and systems using nitride-based devices.

Components based on blue and green resonant cavity LEDs are currently under development. Transceivers for use with plastic optical fiber will enable multimedia optical data buses for various automotive and avionics applications.

Concerning the use of blue lasers, Thomson-CSF is targeting the liquid-crystal display (LCD) projection market, with applications in areas such as air-traffic control and entertainment simulation devices. Research studies are being carried out on a compact LCD projector using blue, green and red solid-state laser illumination.

Electronic applications are also being considered: GaAlN/GaInN/GaN technology is being optimized for power amplifier studies in the 12–18 GHz frequency range. Applications include satellites and broadband communications.

Acknowledgements

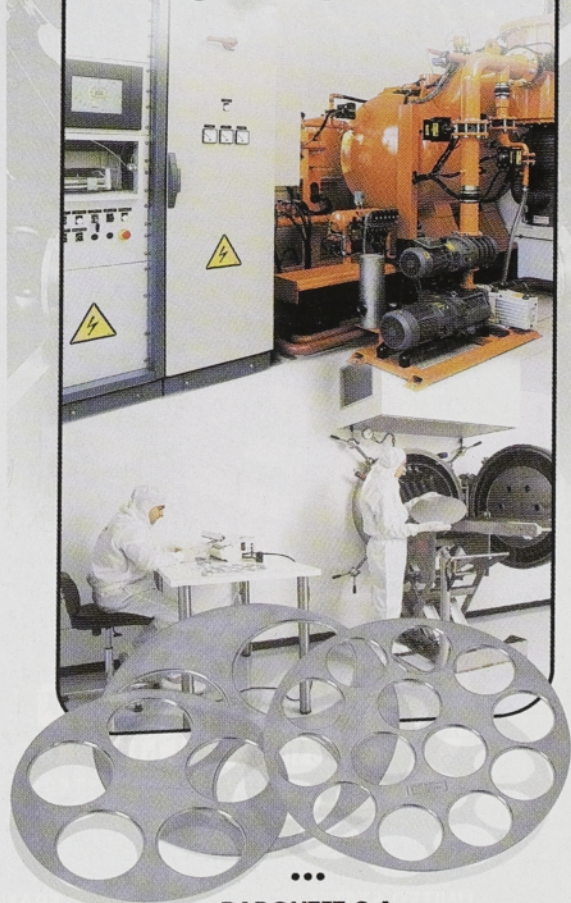
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Standardization helps LEDs measure up

The widespread use of LEDs in an increasing range of applications presents a growing need to standardize their characterization. Scott Jennato and Greg McKee of Labsphere discuss methods to measure the radiometric intensity and other properties of LEDs.

Experts in the field of light measurement sit on committees such as the International Commission on Illumination (CIE) and the Illumination Engineering Society of North America (IESNA) to establish standard methods or guides which encourage uniformity in the practice and reporting of lamp measurements. For general lighting the methods and equipment are well established, and the standards and measurement guides are periodically revised to remain current with the technology.

However, recent growth in the use of LEDs, which is largely due to their efficiency, long life and the multiple colors available, has expanded the focus to include the optical and electrical characterization of such emitters.

Radiometric measurement

In an LED the energy of the photon is determined primarily by the energy bandgap, where recombination occurs. Since the eye is only sensitive to light with photon energies from 3.1 to 1.6 eV – corresponding to wavelengths of 0.40 to 0.78 μm – compound semiconductor materials are used because they have direct bandgaps and the energy needed to produce photons in the visible spectrum.

To convert the wavelength (λ) measured in micrometers to photon energy (E) measured in electron-volts, the relationship $\lambda = 1.24/E$ is used. Figure 1 shows some examples of semiconductors and their corresponding photon energies, wavelengths and relative response to the human eye.

The characteristics of LEDs, including physical size, flux levels, spectrum, temperature sensitivity and spatial distribution, set them apart from typical light sources which are generally used and measured for their photometric and radiometric quantities. With an LED it is often difficult to achieve a high level of photo-

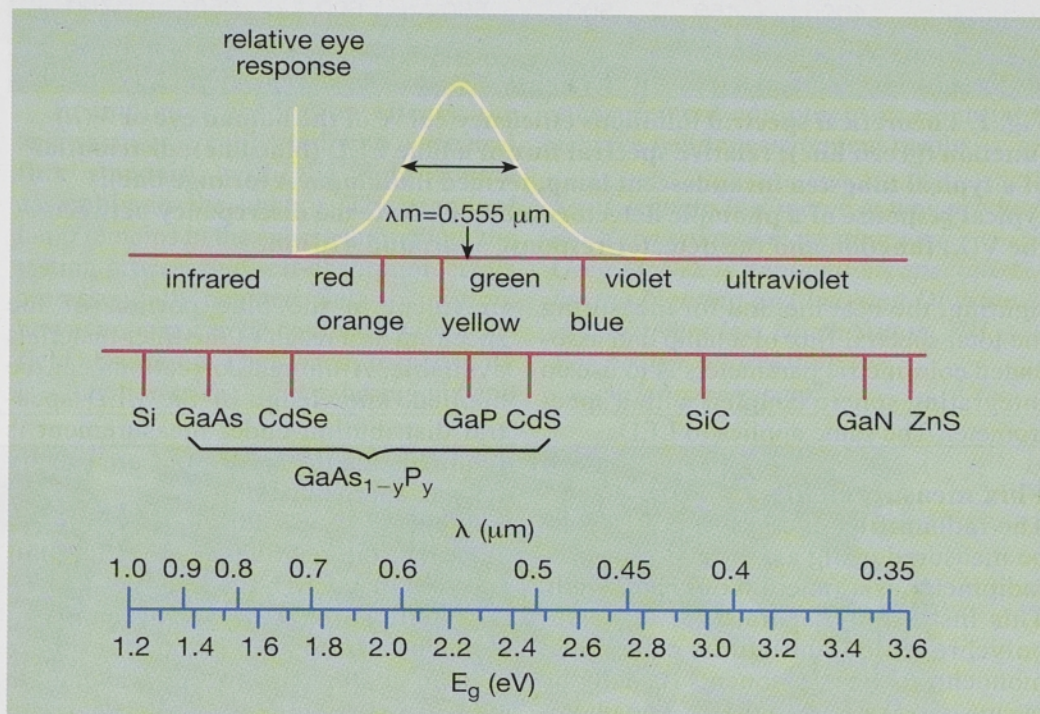


Fig. 1. Examples of compound semiconductors and their corresponding photon energies, wavelengths and relative response to the human eye.

metric or radiometric measurement accuracy due to uncertainties within measurement equipment and improper test set-up.

Averaged LED intensity

In an attempt to agree upon a procedure for comparing the intensity of LEDs, the CIE Committee TC 2-34 has published CIE Report 127, which presents the concept of an “averaged” LED intensity. This does not correspond to the physically precise definition of luminous intensity, but relates more to the measurement of illuminance for a fixed geometry.

CIE’s report recommends two measurement geometries: CIE Standard Condition A and CIE Standard Condition B, which are used to measure average intensities under “near-field” conditions. For averaged LED intensities determined under these conditions, the symbols I_{LEDA}

and I_{LEDB} are recommended.

Both conditions use a detector with a circular entrance aperture and an area of 100 mm^2 (corresponding to a diameter of 11.3 mm). The LED is positioned facing the detector aperture, and it is the distance between the front tip of the LED and the detector that constitutes the difference between condition A and B. The distances, solid angle subtended, and the plane angles are given in table 1.

The output of one LED is compared with another following the recommendation in CIE Report 127. It should be noted that a number of manufacturers use conditions A and B to specify intensity rather than average intensity. In some cases these values may be the same, but as this is not always the case, caution is advised.

Reports for LED flux measurements are still in development. As with general

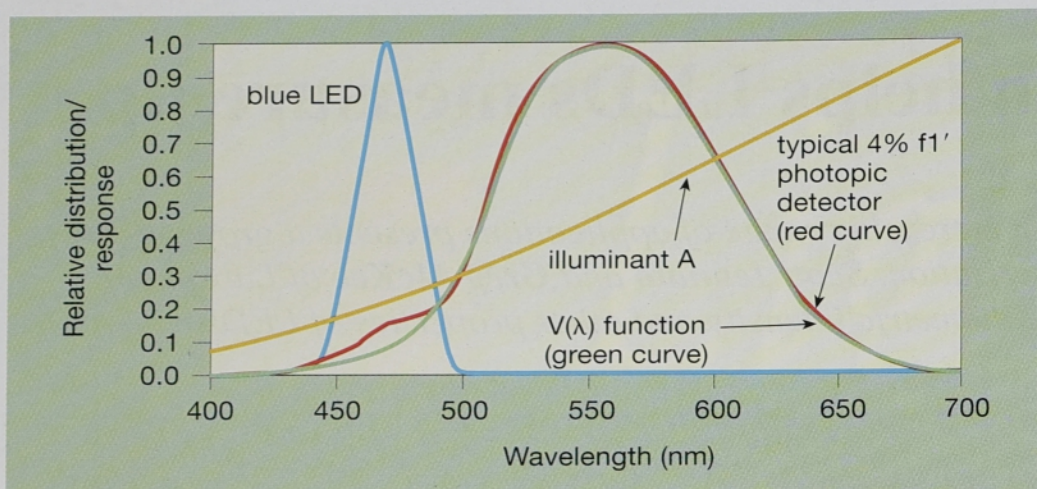


Fig. 2. Theoretical spectral luminous efficiency curve of the human eye or $V(\lambda)$ function (green line); relative spectral flux of a blue LED (blue line); distribution of a typical tungsten incandescent lamp, termed illuminant A (orange line); typical response of a photopic detector (red line). Note the discrepancy between the $V(\lambda)$ function and the detector response at around 470 nm.

lighting, the best method for measuring the total spectral flux of a lamp and associated colorimetric parameters is to use an integrating sphere coupled with a spectrometer. The same applies to LEDs.

Flux measurement

The radiant flux energy of an LED can be measured using a calibrated spectroradiometer as a function of wavelength. This instrument separates or disperses polychromatic light into its constituent monochromatic components (usually by means of prisms or gratings). The photometric value may then be computed (often using special software) from this measured spectrum.

Photometers, on the other hand, use a broadband detector in conjunction with an optical filter in an effort to simulate the spectral luminous efficiency curve of the human eye, commonly referred to as $V(\lambda)$, which is referenced using CIE 15.2 Colorimetry Table 2.1. The process involves a change in the detector characteristics which is caused by the absorption of visible photons.

The electrical signal generated by the detector is a response to the visible radiation incident on the active area of the detector. This basic difference between spectroradiometers and photometers is extremely important in LED metrology.

A disadvantage of photometers is the difficulty in designing a filter that, when combined with a detector, fits the spectral luminous efficiency of the eye accurately. A mismatch is particularly

prevalent in the blue portion of the spectrum as a result of the filter materials available. Although corrections can be applied, knowledge of the LED spectral distribution under measurement is required, and the corrections are usually only an approximation.

Figure 2 shows the theoretical $V(\lambda)$ function, the relative spectral flux output of a blue LED, the relative spectral distribution of a typical tungsten incandescent lamp, and the typical response of a photopic detector. At a wavelength of 470 nm, a typical photopic detector with an $f1'$ response of 4% can exhibit spectral mismatches as large as a factor of 2 between the $V(\lambda)$ function and the detector response.

If an incandescent source or a source of similar spectral content is measured, the correction for the slope of the photopic detector to the $V(\lambda)$ curve is minimal, since the light is continuous and there is relatively little light in the blue portion of the spectrum in relation to the higher wavelengths. A mismatch in the response curves results in only a slight error of the measured photometric value.

LEDs, however, have a completely different spectral power distribution, which tends to be a narrowband Gaussian distribution with a specific peak and FWHM of a couple of tens of nanometers. The relatively poor match of the photopic detector to the $V(\lambda)$ function can result in large deviations in the measured photometric quantities. This is particularly true for blue and red LEDs. Errors

exceeding 100% are not unusual for blue LEDs (figure 2).

Within the production environment, 20 000 or more LED die on a 2 inch wafer are commonplace. After the fabrication process, some or all of the LED die on the wafer are characterized for optical and electrical output (based on manufacturer specifications). During the measurement process, bad die are usually “inked out” and good die are “binned” and sold as die, or made into lamps. When it is time to sell the LED die, a brighter product translates into more money.

Another variable observed closely during the characterization process is color. The eye is very sensitive to color and it is not unheard of for it to determine the differences in two LEDs based on a 2–3 nm spread in dominant wavelength, especially from blue to yellow. Since few end-users want their product to have a multitude of colors, accuracy in dominant wavelength is critical.

Once its quality has been verified, the die is made into a lamp by attaching a lead-frame assembly, and is then fixed with an epoxy lens. After the LED lamp is constructed, most manufacturers characterize 100% of the LED lamps optically and electrically. Based on the sheer volume of LEDs manufactured on a daily basis, there is a great need for accurate high-speed radiometric measurements. A useful tool for this is an integrating sphere coupled to a CCD-based spectroradiometer attached to an autoprober or an in-line lamp tester.

The integrating sphere

The function of an integrating sphere in this application is to gather the light output from the die or lamp. Since the light is being spatially integrated, the sphere removes any concerns about accurate alignment of the light source to the aperture of the integrating sphere.

The theory of the integrating sphere assumes that the interior surface is perfectly diffusing and has spatially uniform reflectance. The radiant exchange from diffuse surface to diffuse surface integrates the light, resulting in equal radiance at any point on the sphere wall.

Theoretically, light received on any area of the sphere-wall surface is directly proportional to light introduced to the sphere. When a spectroradiometer is used to detect the indirect illuminance of the source, the user must consider the possible errors that may contribute to the mea-

surement results, including – but not limited to – non-linearity, directional and positional effects, detector instability, reference and sample instability and noise.

The size of the sphere and the sphere-wall coating reflectance affect the throughput. Higher reflectance provides better sphere responsivity, and the sphere is less subject to errors caused by the differences in the angular intensity distributions of the LEDs. The smaller the integrating sphere the greater the throughput, but the smaller sphere is more sensitive to angular intensity distributions of the LEDs.

As the diameter of the sphere increases, the throughput decreases and the sphere becomes more difficult to mount on an autoprober or other piece of manufacturing equipment. However, the sphere becomes increasingly less sensitive to angular intensity distributions.

Three main factors help decide the optimum size of the sphere. These include the size of the LEDs, self-absorption of the LED sockets and LEDs (if applicable), and finally the sphere responsivity.

Averaged LED intensity

CIE recommendation	Distance between LED tip and detector (mm)	Solid angle (sr)	Plane angle (°)
Condition A	316	0.001	2
Condition B	100	0.01	6.5

Table 1. CIE recommendations for the concept of averaged intensity, which shows the distances between LED tip and detector for two standard test conditions. The area of the detector is always 100 mm².

The first two factors tend towards making the sphere as large as possible, while the responsivity limits the sphere size.

To minimize absorption effects, the sphere may be calibrated with a spectral flux standard, with the light source assembly in the sphere. The standard lamp remains in the sphere throughout the testing process and self-absorption errors are essentially negated. Self-absorption, however, is not to be confused with near-field absorption. The system responsivity is a function of the sphere throughput and

spectrograph and optical coupling of the two. Careful consideration in the design of and the use of high-speed LED test and measurement equipment is essential to achieve valid measurement results.

Scott Jennato is director of new product development and marketing and Greg McKee is applications specialist for the Lighting and Imaging Division of Labsphere Inc, North Sutton, NH. For further information see "www.labsphere.com".

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LEDs light up medical diagnostics

*Medical diagnostic systems that measure the oxygen content of the blood or allow non-invasive imaging of the eye are benefiting from optoelectronic devices such as LEDs and superluminescent diodes, says **Daniel McGraw** of Light Diagnostics.*

Medical diagnostic systems produce quantitative measurements that help doctors to diagnose and treat a range of illnesses accurately. For example, with the help of new LED-based diagnostic instruments that measure oxygen in the blood, a doctor is able to pronounce not only that you have a heart rate of 64 beats per minute, but that 93% of the hemoglobin molecules in your arteries are carrying this gas; or to conclude that the nerve fiber layer of your retina is suffering from an early stage of degeneration.

This article examines how LEDs are being used to diagnose a patient's state of respiratory and retinal health, and how these relatively simple optoelectronic devices could provide a bright future for photonic diagnostics in medicine.

Pulse oximetry

Pulse oximetry is currently the most successful optoelectronic-based diagnostic application in medicine. The worldwide market for these systems – more than half of which are sold in the US – is currently around \$450 million per year and is projected to grow to \$600 million by 2003 (see *Pulse Oximeters – A Global Strategic Business Report*, Global Industry Analyst Inc, Fremont, CA, for further information).

Most pulse oximeters consist of a probe that contains two LEDs – one infrared and one visible – which is pressed against the finger (figure 1). The probe monitors the pulse rate and the amount of oxygen saturation in the arteries (i.e. the fraction of arterial hemoglobin that is carrying oxygen), and it can be used in applications ranging from endoscopic surgery to neonatal intensive care and dentistry.

Initial observations of the near-infrared light transmission in tissue led to the development of a probe based on a filtered incandescent lamp and fiber optics.

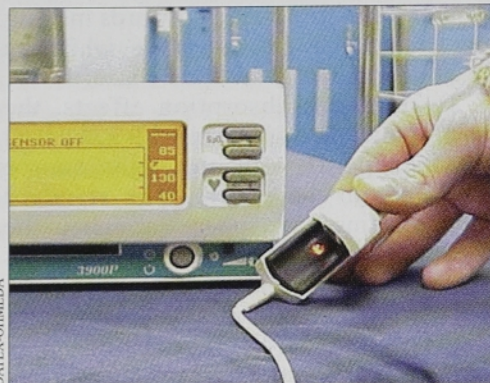


Fig. 1. The pulse oximeter finger probe determines oxygen saturation by maintaining a running average of the light transmission modulation ratio from red and infrared LEDs.

However, the subsequent direct coupling of LEDs to tissue has largely enabled the application. This is because of the stable center wavelength and high intensity provided by LEDs at low cost, in addition to a modulation bandwidth capability at megahertz frequencies.

For this application the ideal sources are red (660–760 nm) and infrared (880–940 nm) LEDs based on highly efficient GaAs. Typically, LEDs for these applications are almost exclusively supplied by Japanese companies, including Shin-Etsu and Showa Denko.

Anesthesiology One of the most important applications has been in the field of anesthesiology. Prior to 1982, determining whether a patient had sufficient oxygen under a general anesthetic was a very tricky business. One study found that 20% of patients underwent potentially dangerous hypoxic episodes, defined as an oxygen saturation of less than 81% – a point below which brain damage can begin after 10 to 20 minutes. In addition, 7 out of 10 of these episodes went undetected by the anesthetist.

As accurate LED-based pulse oximeters came onto the market in the 1980s, mortality among healthy patients undergoing anesthesia dropped considerably – in one study it was estimated that cases decreased from 1 in 10 000 to 1 in 100 000.

How it works It is well known that a person deprived of oxygen appears to turn blue. This is due to the stronger absorption of red light by non-oxygenated hemoglobin compared with oxygenated hemoglobin. What is not so well known is that we blush with every heart beat or pulse. While this effect is too small to be detected with the naked eye, it can be continuously monitored using an LED-based oximeter that probes the tissue of the finger.

In essence the LED is used as an intense light source to observe the modulation or change in light transmission (or reflection) resulting from the pulsing blood, which is itself due to an expansion under pressure of the arterial volume fraction. The amplitude of this modulation is about 3% of the transmitted intensity, which is well within the sensitivity range of an LED-based instrument.

The finger probe consists of two LEDs pressed against one side of the patient's finger and a silicon photodiode on the other side. The LEDs are modulated at kilohertz frequencies and the light transmitted through the finger is detected by the photodiode and a trans-impedance amplifier.

Typically, one of the LEDs is a red emitter that contains an active region based on AlGaAs and it has a wavelength centered on 660 nm. The other is a GaAs-based diode operating in the near-infrared at 940 nm. The instrument maintains a running average of the red to infrared transmission modulation ratio using the two different wavelengths. These measurements are then combined with a cali-

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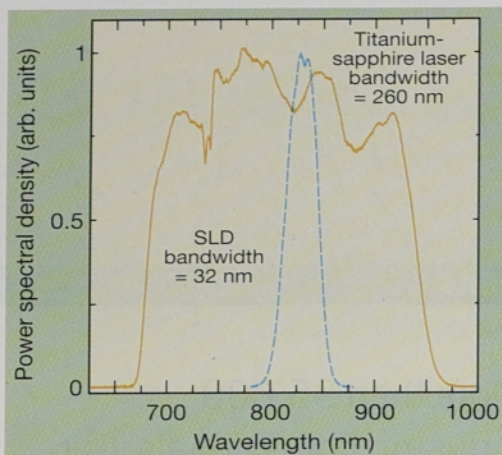


Fig. 2. Optical output spectrum for a titanium-sapphire laser vs a GaAs-based SLD operating at 830 nm. The optical bandwidth of 260 nm for the laser is about 20% of the center wavelength, which allows OCT images with higher resolution ($\sim 1\text{--}2\text{ }\mu\text{m}$) than conventional SLD-based illumination systems (typically $11\text{ }\mu\text{m}$ resolution). Reproduced from W Drexler *et al.* 1999 *Optics Letters* 24, 1221.

bration table to assign a unique oxygen saturation to each measured ratio.

A labor market Future sales of oximeters could be substantially increased when the technique is extended to fetal oximetry, where the probe can be used to monitor whether a fetus is receiving enough oxygen during labor and delivery. Last year an instrument company called Tyco/Nellcor received permission from the Federal Drug Administration to sell an LED-based fetal pulse oximeter in the US.

This application requires the resolution of smaller (0.1–1.0%) transmission modulations and the use of LEDs operating at wavelengths above 700 nm. The longer wavelength optimizes the accuracy at low oxygen saturation, which is commonly found in babies. In addition, innovative packaging is needed to allow the optoelectronic probe to be attached to the baby's scalp during labor and delivery.

Interestingly, the main value of such a device may not be in lowering the already low birth mortality rate in the US, but rather to prevent unnecessary cesarean section deliveries. Cesarean section is the most common form of major surgery in the US and currently accounts for about 25% of all deliveries. This high rate is caused in part by the lack of good diagnostics for fetal distress. Improved fetal

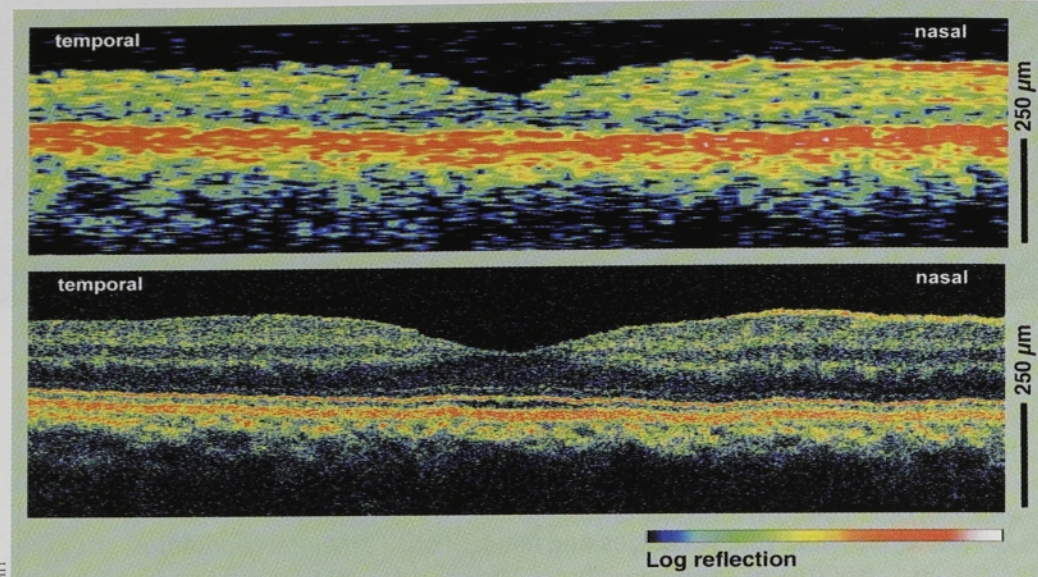


Fig. 3. Conventional image (top) and high-resolution (bottom) OCT images of the human retina. The bottom image is obtained with a titanium-sapphire laser as the illumination source. The axial resolution is $10\text{ }\mu\text{m}$ in the top image and $3\text{ }\mu\text{m}$ in the bottom image. Potential exists for SLD sources with a much wider spectral bandwidth of 150 nm, increasing the depth resolution in the conventional system. Figure courtesy of Massachusetts Institute of Technology, from W Drexler *et al.* 2001 *Nature Medicine* (in press).

monitoring could therefore reduce the number of cesarean sections to 5%.

Optical coherence tomography

Another important use of optoelectronic devices is as an illumination source for optical coherence tomography (OCT), a technique that non-invasively creates depth profile images of the human retina. Previously this has been achieved post mortem by taking sections for examination using microscopy. Commercially available instruments for retinal optical cross-sectioning are now used to diagnose and treat retinal diseases such as macular degeneration and glaucoma.

The superluminescent diode Commercial OCT scanning systems use a superluminescent diode (SLD) to provide the illumination used to image the retina. The SLD is a lesser-known hybrid of the LED and laser diode that can be described as a laser without an oscillator, or alternatively as an LED with a waveguide. In this case, mirror facets are not incorporated into the SLD, in order to repress stimulated emission that would lead to a narrow band source.

The emitter is a promising source of high brightness and short coherence length. The latter property is due to the broader bandwidth and determines the

depth resolution (a broader spectrum creates a higher depth resolution). In fact the SLD has a bandwidth-brightness product several orders of magnitude greater than laser diodes, LEDs or similar light sources. This makes it a potential source for a host of other physical metrology applications that require a low coherence source. The SLD is used in a Michelson interferometer configuration to provide depth scanning. This uses a scanning reference mirror to depth-resolve the back-scattered light, and transverse scanning is used to build a two-dimensional image.

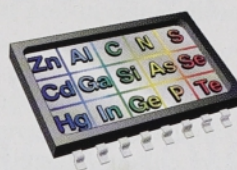
SLDs used in the commercial OCT system made by Humphrey Instruments/Zeiss have a bandwidth that is 3–4% of the mean emission wavelength. A typical SLD has a ridge-type waveguide structure designed to provide a very low reflectivity from the end facets, so the emission arises almost entirely from a single pass through the device. The feedback is kept below the threshold for the onset of laser oscillation. This is important because it maintains a broad and smooth spectral output similar to that of an LED.

In addition, the high brightness of the ridge waveguide structure allows efficient coupling into single-mode fiber, which allows the system to also be used in endoscopes to peer into the walls of intestines and arteries. The GaAs/AlGaAs-based

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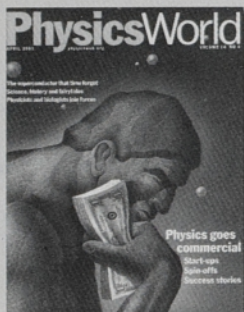
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device operates at around 830 nm, although longer wavelengths can also be used to increase the penetration depth.

Increasing resolution Improvements to the resolution of OCT can be achieved through the use of a broader spectral emission source. Figures 2 and 3 show how an ultra-broadband source (a mode-locked titanium-sapphire laser) can be used to produce dramatically improved ($\sim 1 \mu\text{m}$) images of the retina from live patients. At 260 nm, the laser bandwidth is about 30% of the center wavelength. This compares with an SLD source with a 3% bandwidth, which typically achieves around 11 μm resolution when employed in the commercial instrument.

However, the titanium-sapphire laser comes with a price tag of around \$200 000. This bodes well for optoelectronic light sources such as the SLD: the current SLD-based OCT system costs around \$30 000, and, while 70 nm bandwidth sources are becoming available, it is feasible that a higher-resolution system

using an SLD with a spectral bandwidth up to 150 nm will be achieved. A relatively inexpensive optoelectronics-based solution to this problem will enable a new generation of non-invasive disease diagnosis in future.

Potential new applications

Another potential area of application is in the treatment of neonatal jaundice, which is currently treated with phototherapy. This assists the liver in breaking down bilirubin – a product of hemoglobin decay generated in large quantities following birth – into a form that is easily removed.

The jaundice manifests itself as a yellowing, which is caused by the bilirubin absorbing blue light in the skin. Phototherapy systems for this application use blue fluorescent lights operating at 447 nm, but recently introduced high-brightness 470 nm blue LEDs could also feasibly be used to increase the rate of bilirubin breakdown.

A high concentration of bilirubin is toxic to infants, so it is important to have an effi-

cient phototherapy system. An LED-based illumination system may be more effective here for two reasons: the longer wavelength of the commercially available blue LEDs compared with existing fluorescent lamps allows more efficient photo-decomposition of bilirubin in the presence of the strong hemoglobin absorption. In addition, LEDs generate considerably less heat and would allow a closer, and therefore more efficient, illumination of the baby.

A system could be envisaged where LEDs placed on a flex circuit are fashioned into a blanket, which would replace the banks of high-power fluorescent lights currently being used in neonatal intensive care.

Whether for sensors, phototherapy or non-invasive imaging, recent advances in LEDs seem destined to shed a new light on medicine.

Dan McGraw is CEO of Light Diagnostics, a medical photonics consultancy based in Utah. Contact "lightd@att.net" for further information.

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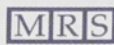
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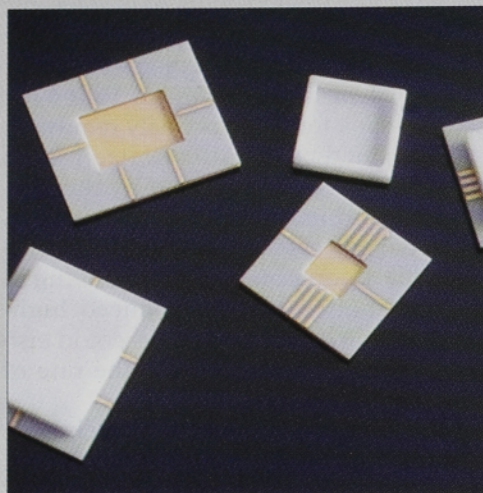


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StratEdge's SE50 packages operate from DC to over 50 GHz, and can withstand the heavy electrical and thermal demands required to protect the



broadband and power MMIC amplifiers used in LMDS, point-to-point, and point-to-multipoint technologies. The packages have a standard copper laminate base and a patented microstrip-imbedded microstrip-microstrip transition design.

Two sizes are available, and custom configurations can also be produced upon request. The 0.390×0.330 inch package has a cavity length of 0.200 inches and a width of 0.140 inches, and includes six RF I/Os. The 0.3×0.3 inch package has a cavity length of 0.1×0.1 inches, with two RF I/Os and eight DC I/Os.

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Refined procedures boost GaAs capability

ST Assembly Test Services (STATS) has refined the wafer handling procedures and processes of its existing silicon manufacturing equipment to address

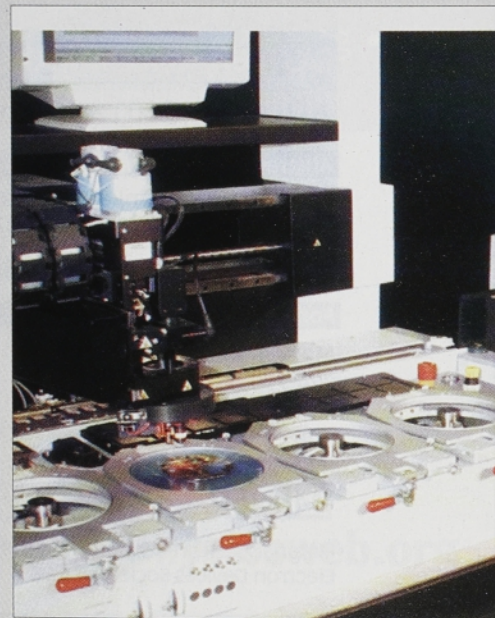
GaAs processing and package assembly.

The company's new package and test services now include mixed signal ICs manufactured on pre-sawn GaAs wafers with thicknesses down to 4 mm. In addition, STATS has built a comprehensive management program for its GaAs assembly area that includes a separate sludge and waste water management system for back-grind and saw equipment.

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Precision positioning with amplifier cell

Palomar Technologies' model 3500-II RF component amplifier assembly cell allows steady-state heat eutectic processing and precise positioning of adjacent die required for wire bonding and consistent wire loop profiles in RF and microwave devices. The 3500-II employs a temperature control system that allows eutectic bonding of adjacent die in RF packages. For faster part presentation, pre-heat mesas (hot rails) are available, and the assembly cell can be integrated into an in-line automation system with cassette-to-cassette handling.



The assembly cell's eight-position turret head allows fast, precision alignment and calibration for up to eight vacuum tools. In addition, an automatic tool changeover allows a wide range of parts and die during production, and provides flexibility and increased production speed and yield.

The RF component assembly cell accommodates very large components, in addition to die as small as 7.0 mm (0.27 inches). Components greater than 2 inches² can be transferred from the input tray to the eutectic heater stage for assembly.

The system's small component tool can pick small and delicate components from wafer or gel packs, tape and reel feeders, up to 8 inches expanded wafer, and other forms of presentation. The Cognex pattern recognition system allows a high degree of die divergence and rotation from the basic presentation pattern.

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Fax +1 760 931 3444
Web www.palomartechnologies.com

Wafer bonding system offers rigid support

In order to support thin wafers for bonding, the substrate needs to be temporarily mounted to a rigid support



disc using wax. The Logitech WSB2 wafer substrate bonding unit is specifically designed for temporarily mounting delicate wafers such as GaAs and InP on wax.

The bonder incorporates a new heat exchanger that leads to a reduction in the time required for cooling of up to 70% – increasing the wafer throughput. In

addition, the heat exchanger is a sealed unit that produces no oil exhaust, which allows the unit to be run in the same room as lappers and polishers.

Logitech's WSB2 also features a flexible diaphragm within the bonding jig, which ensures that the wafer is pressed into the wax layer to provide a uniform bond and protect the wafer and its devices.

Available as a single- or three-station unit and for whole or part wafers up to 6 inches in diameter, the WSB2 incorporates both pressure and vacuum wax mounting capabilities.

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Fax +1 440 871 8188
Web www.logitech-us.com

Single wafer tool set for metal lift-off

Karl Suss has unveiled the M6000L metal lift-off cluster system, a single wafer processing tool designed to remove deposited metal films. The system addresses drawbacks in batch processing during device manufacture by preventing metal re-deposition onto the wafer. Furthermore, the single wafer dry in/dry out processes improve process control and tuning to accommodate various metal and resist film stacks.

The M6000L can be used to create air bridges such as those employed in high-frequency devices. In addition, the system can be used to deposit or pattern materials such as gold, tantalum and titanium, which are not easily etched using traditional plasma or wet chemical processes without causing substrate damage.

Specifically addressing the processing needs of GaAs-based laser diodes, SAW filters and other high frequency chips, the M6000L lift-off system features a compact 1.2 m² footprint and low chemical consumption.

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Compact gas purifier filters out problems

Aeronex has introduced the GateKeeper 30K gas purification system, a highly compact purifier that removes the molecular contaminants that filters are often not able to catch. The GateKeeper design features a panel clearance of just 0.5 inches and provides five times the life of existing purifiers. Its small size



also provides significantly lower pressure drop for greater safety.

Previously, purifiers could not be used for gas panel applications, as they had to conform to very small space requirements. This meant that the capacity (volume) was sacrificed. In addition, the small body diameter led to very high pressure drops forcing users to keep toxic and hazardous gases at higher pressures, and therefore to operate under more dangerous conditions. With the new system, companies can now replace filters with purifiers, without replacing or modifying the entire gas panel.

The GateKeeper 30K has a center line to base dimension of 10 mm or 0.375 inches. The system can be used with all gases and can be cleaned and re-used, lengthening the life of the system and reducing the costs and problems associated with hazardous waste disposal.

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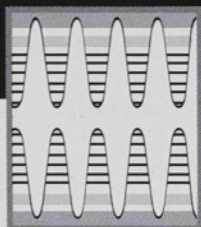
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The 2001 Conference will host a wide range of sessions, invited papers, exhibits, and special activities. Keynote addresses in areas of cell phone technology as well as the history and future of GaAs manufacturing from renowned manufacturers are actively being explored.



For more information visit the conference web site at <http://www.gaasmantech.org/> or use the link in the "Calendar" section of www.compoundsemiconductor.net

Stocks sink as outlook worsens

MARIE MEYER

With the NASDAQ composite having fallen all the way from 5000 to less than 2000, it is not surprising to see that virtually all of the Portfolio companies are now trading within striking distance of their 52 week lows. There are times when share prices go up and down for no reason other than that is the direction that market momentum is heading. Sadly, this is not the case here.

The outlook for the next several quarters is deteriorating rapidly. Almost all of the GaAs IC companies have already issued warnings. Alpha Industries announced that its revenues were slowing by around 20% and that its profit targets for the March quarter would be slashed from around 20 cents per share to 5 cents. The company cited slowing demand from both handset and infrastructure customers. RF Micro Devices lowered their outlook for the quarter to a loss of 3 to 4 cents per share, down from the January projection of 2 cents per share profit. Revenue is expected to be \$55 million, down from \$85 million in the year-ago period. RFMD cited slowing demand from handset, infrastructure, and broadband customers, and said that is seeing some orders pushed out as well as some cancellations. Stanford Microdevices anticipates first-quarter net revenues of around \$8.0 million, 25% lower than previous projections, and earnings expectations have been cut from 5 cents per share to break-even. The company blamed "the actions and plans of the worldwide telecommunications industry to reduce component inventory levels and planned equipment production volumes, and to delay the build-out of new wireless network infrastructure."

Wireless in decline

These gloomy tidings are driven primarily by slowdowns in the wireless industry. As noted previously in this issue (see page 7), leading analysts are now predicting almost no growth in handset production in 2001, whereas just a few months

Company	Symbol	Closing price March 15	52 week low-high	Market cap*	P/E ratio**
GaAs IC companies					
Alpha	AHAA	15 ¹ / ₁₆	13 ³ / ₁₆ -72	654.1M	15.53
Anadigics	ANAD	12 ¹ / ₂	10 ¹ / ₂ -109 ¹ / ₄	375.4M	20.83
Celeritek	CLTK	12 ⁷ / ₈	11 ¹ / ₂ -85 ¹ / ₄	153.5M	25.25
Conexant	CNXT	11 ¹ / ₁₆	10 ¹⁵ / ₁₆ -93 ¹ / ₂	2.689B	N/A
Endwave	ENWV	2 ¹³ / ₁₆	2 ¹ / ₂ -20 ⁵ / ₈	96.0M	N/A
RF Microdevices	RFMD	11 ⁵ / ₈	10 ³ / ₄ -84 ³ / ₄	1.896B	36.33
Stanford Microdevices	SMDI	5 ⁹ / ₃₂	4 ⁷ / ₈ -60 ¹ / ₄	139.2M	N/A
TriQuint	TQNT	16	14 ¹¹ / ₁₆ -66 ⁵ / ₈	1.256B	19.28
Vitesse	VTSS	38 ⁷ / ₈	34 ³ / ₄ -110 ¹ / ₂	7.386B	204.61
Opto companies					
Agilent	A	34.85	34.4-138.9375	15.904B	20.03
Alcatel Optronics	ALAO	34	31-71 ³ / ₄	561.0M	29.82
Coherent	COHR	32 ⁹ / ₁₆	25-93 ¹ / ₂	890.3M	12.77
Cree	CREE	15.91	14.95-96.625	1.181B	25.25
JDS Uniphase	JDSU	24 ³ / ₁₆	22 ³ / ₁₆ -140 ¹ / ₂	31.549B	N/A
SDL	SDLI	146 ³ / ₄	117 ⁵ / ₈ -460 ¹ / ₂	N/A	N/A
Uniroyal Technology	UTCI	7 ¹ / ₁₆	5 ¹ / ₄ -35 ¹ / ₈	182.1M	N/A
Semiconductor materials & equipment companies					
ATMI	ATMI	18	14 ³ / ₈ -60 ³ / ₄	543.7M	12.50
AXT	AXTI	17 ⁷ / ₈	17 ³ / ₄ -47 ³ / ₁₆	393.7M	15.41
Emcore	EMKR	23 ¹¹ / ₁₆	20-81 ¹ / ₄	813.9M	N/A
Kopin	KOPN	6 ⁷ / ₃₂	6-47 ⁷ / ₁₆	394.4M	69.10
Tegal	TGAL	2 ¹³ / ₃₂	1 ³ / ₁₆ -8 ³ / ₈	30.3M	10.46
Trikon	TRKN	10 ⁴⁷ / ₆₄	8 ¹ / ₂ -28 ⁹ / ₁₆	125.3M	6.79
European shares (currency data in Euros)					
Aixtron	AIX	78.9	68.8-175.5	2.54B	87
Filtronic	FTC	3.08	3.08-4.83	226M	N/A
IQE	IQE	2.76	2.76-4.35	448.9M	185
Picogiga	PICO NM	20.99	20-35.60	136M	46
Riber	RIBER	12.8	9-38.5	247M	N/A

*Market capitalization = # shares × current share price.

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

ago the forecast was in the double digits, with a significant recovery in the second half of the year. It now appears that this scenario was too optimistic. Since wireless accounts for 60-70% of all GaAs IC sales, the impact on the GaAs industry is going to be significant.

Kopin has been particularly hard hit. The company has two divisions, one that

sells HBT epiwafers and one that is developing display products. The poor visibility in both areas has lead analysts to speculate that revenues could decline precipitously in the March quarter, in comparison to the December quarter. According to Dale Pfau of CIBC World Markets: "Continued weakness at Conexant, coupled with weakness from Mitsui-

bishi on GSM will cause a significant sequential decline, perhaps 50%, in III-V product revenues in the first quarter." CIBC has cut their estimate for the year from earnings of 29 cents a share on \$128 million in revenue to a loss of 2 cents per share on revenue of \$80.5 million. At the time of writing, Kopin was trading at a new 52 week low.

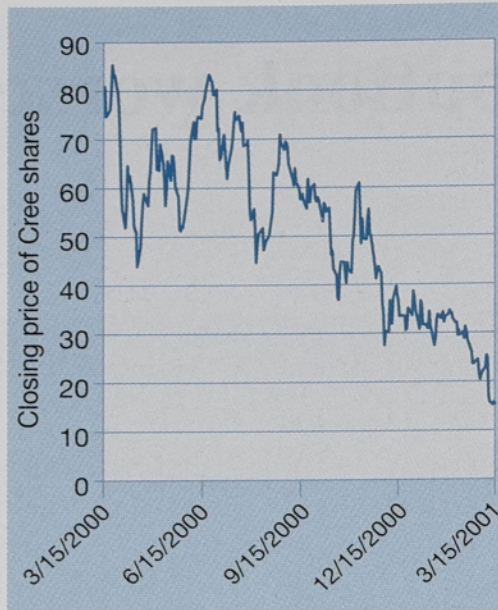
Unfortunately, wireless is not the only area that is suffering. Capital spending has also dried up in the fiber-optic and CATV communications sectors, leading to more bad news for GaAs companies. TriQuint Semiconductor now says that it expects to show little or no growth in revenue in the first three quarters of this year. The company reported slowness in most areas, but fiber optics, which accounted for 29% of TriQuint's revenue in the December quarter, was noted as particularly weak. Slowing demand for CATV components is likely to lead to a 25% drop in revenue for Anadigics in the June quarter. CATV accounts for around 60% of Anadigics' sales.

Most shocking of all is the fact that even Vitesse, the steadiest performer of all the GaAs fabs, has been forced to issue a warning for the March quarter. The revenue forecast was lowered from \$180–190 million to \$150–160 million, and projected net income was said to be 21–22 cents per share, 5 cents lower than previously expected. Communications account for over 90% of Vitesse's sales. One bright spot in the announcement was the fact that OC-192 modules continue to show robust growth.

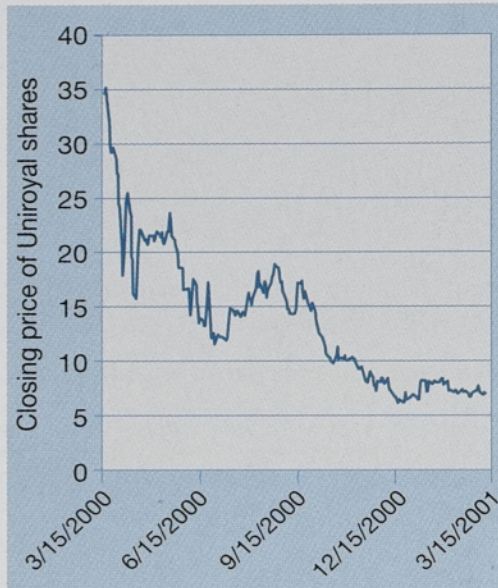
LEDs – on or off?

There have been several recent reports of "softness" in the LED market. While some macro-economic trends, such as the energy shortage in California, would seem to favor LED manufacturers, a general economic slowdown will reduce demand for consumer-oriented products that use LEDs for functions such as indicator lights. Some manufacturers have significant exposure to the wireless handset market which, as discussed previously, is suffering.

It wasn't surprising then, when Cree announced on March 7 that despite the fact that it is on track for the March quarter, it was lowering its guidance for the June quarter. In January the company had indicated that it was 90% booked for the March quarter and 75% booked



Cree share prices for the past 12 months.



Uniroyal Technology share prices for the past 12 months.

for the June quarter. Since then order trends have softened dramatically.

The company expects its revenue and earnings for the June quarter will be 10–15% below the March quarter. This would result in revenue of approximately \$45–48 million, with earnings per share of \$0.14–0.16.

Cree's CEO Neal Hunter explained, "Obviously, we are dealing with a slowing economy that puts pressure on our customers which, in turn, inhibits our revenue growth. In the face of these obstacles, Cree has a solid arsenal of resources to create new products, lower existing costs and penetrate applications. We also

have much of the equipment and facilities in place to serve a growing market over the next 12 to 18 months as economic conditions improve. This should limit capital spending requirements and position us to build cash, assuming our revenue and earnings targets are attained. With the strength in our balance sheet, we can continue to focus on those elements that provide the greatest leverage over the long term."

In light of the Cree announcement, which was made on March 7, it was interesting to see Uniroyal Technology Corporation (UTC) issue a press release the very next day saying that the high-brightness LED (HB-LED) market is not slowing. UTC and Emcore are partners in an LED-manufacturing joint venture called Uniroyal Optoelectronics (UOE). It should be noted, however, that UOE's total LED-related sales are currently less than \$1 million per quarter, giving them much less exposure to the market downturn than Cree, which has quarterly LED revenues in excess of \$40 million.

"Although recent announcements indicate a slowdown in some segments of the market, this does not appear to be the case in markets requiring the increasingly higher brightness levels that Uniroyal Optoelectronics has developed," said Robert L Soran, president and CEO of UTC. "The very high-brightness products have traditionally been produced on sapphire substrates and the leading suppliers have been Toyoda Gosei and Nichia. Comparative lamp testing indicates that UOE's gallium nitride blue and AlInGaP 626 nm red products are at the high end of the brightness levels." He went on to say that while markets such as LCD backlighting for mobile phones may experience a slowdown, demand for very high brightness products for applications such as outdoor video displays, signage and traffic signals remains strong. The achievement of higher-brightness levels has decreased the number of LEDs required in high-brightness applications. This, in turn, has resulted in more cost efficient conversions to LED lighting from traditional incandescent methods, creating a wide variety of new applications for high-brightness LEDs.

Investors will no doubt review UTC's financial results with great interest to see what kind of impact these trends have on the company's bottom line.



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