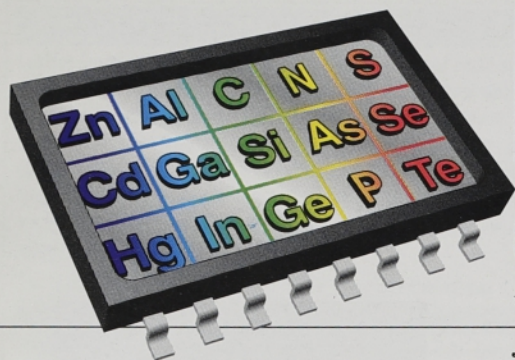




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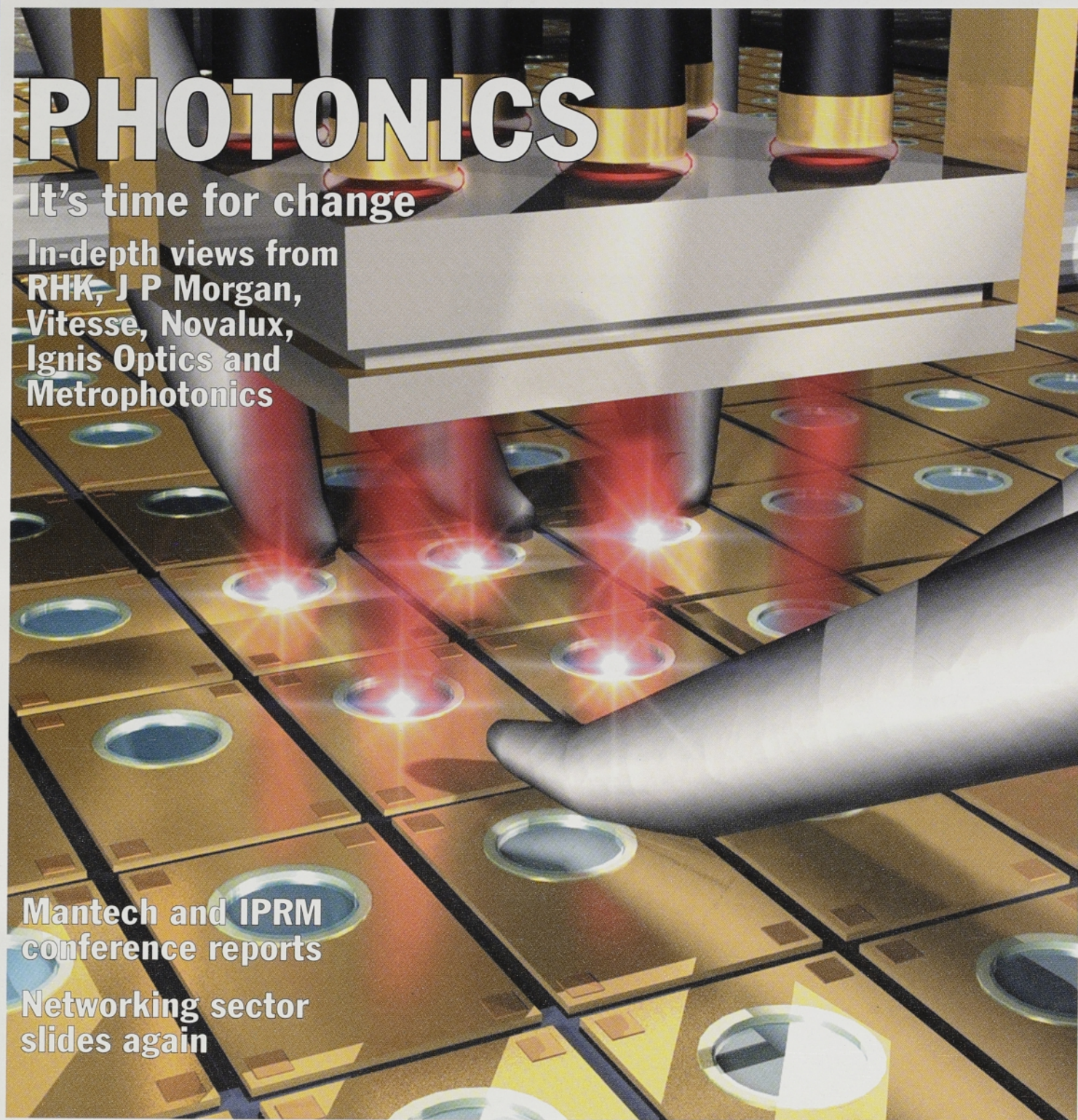
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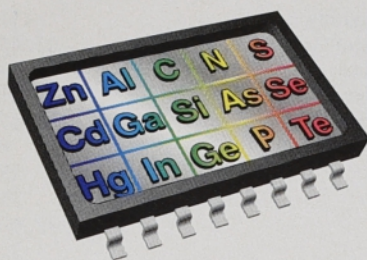
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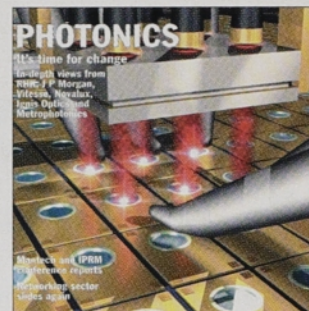
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On the cover: Vertical emitting lasers such as these NECSEL devices from Novalux can be processed and tested automatically, greatly enhancing their manufacturability. Probe test simulation courtesy of Alex Joseph.

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Networking sector takes turn for the worse

A week in June filled with bad news from four of North America's largest fiber-optic equipment companies has dashed hopes for an early recovery in the networking sector.

On June 15 **Nortel Networks** said it will report a staggering second-quarter loss of \$19.2 billion for the June quarter, on revenue of \$4.5 billion. The loss from operations will be around \$1.5 billion; the remainder of the damage comes from restructuring costs. Nortel will also lay off an additional 10 000 workers, on top of the 20 000 layoffs previously announced.

Inventory problems at JDSU

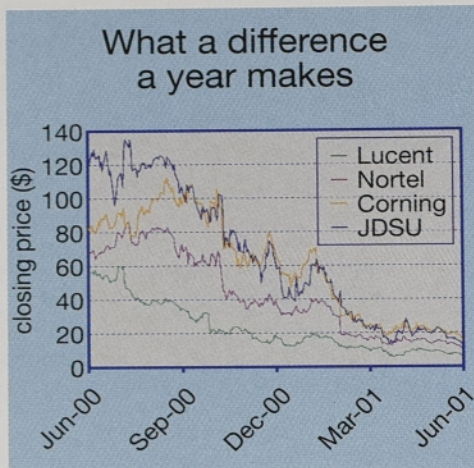
The Nortel announcement followed hard on the heels of a similar warning from **JDS Uniphase**, which cut its sales forecast from \$700 million to \$600 million for the June quarter. Executives said that sales for the September quarter would likely plummet to \$450 million. The company also said it expects to post a loss of \$80–100 million for the June quarter, excluding one-time charges, amid record inventory write-downs. Wall Street had been expecting a profit of \$65 million, and revenues of \$690 million.

The inventory write-downs are expected to total \$225–250 million. JDSU typically reserves a six-month supply of components and modules for manufacturing. Excluding those write-downs, JDSU said it would likely have recorded a fourth-quarter profit.

Lucent and Corning also struggle

Earlier in the week, the ratings agency Standard & Poor's cut **Lucent Technologies** debt rating to "junk" status after finding "significant uncertainties" about Lucent's ability to turn around its business. The move is another humiliating blow for Lucent, coming so quickly after a proposed merger with Alcatel was undone in the eleventh hour. However, the downgrade was not a huge surprise to the bond market, which has been trading Lucent debt at junk levels for at least six months.

And, finally, **Corning** was also on the receiving end of some bad news in this memorably bad week. Analyst Steven Fox of Merrill Lynch grabbed headlines when he downgraded his recommen-



dation for the company using the vivid phrase "nuclear winter" to express his belief that the next few quarters will be "below even our worst-case scenario".

Is this the bottom?

When the telecom equipment slump set in several months ago, there were many predictions that it would reach its nadir in mid-2001. Recovery was expected to begin once built-up inventories were exhausted. But, in the absence of any evidence suggesting that the telecom carriers are ready to begin spending again on new networks, a new consensus is building that this sector will remain weak for sev-

One analyst used the phrase "nuclear winter" to express his belief that the next few quarters will be "below even our worst-case scenario".

eral more quarters, with recovery beginning in early 2002 at the earliest.

There was a noticeable change in tone among Nortel executives in their June 15 conference call with investors and analysts. For example: while they were willing to say that the slimmed-down company could turn a profit, with \$5 billion in sales per quarter, they absolutely refused to predict when they might achieve that revenue figure – disturbing when you recall that their worst quarter in 2000 saw \$6.33 billion in revenues.

CEO John Roth said the telecom sector

is being hit by more than just an anomaly in demand and inventory patterns, and that it has to adjust to lower sales figures. "We're experiencing a very significant reduction in sales in the industry and, in our case, optical long-haul networks," Roth said. "We are focusing on getting our cost structure in place and going forward."

"Carriers have shifted away from last year's renovations of their networks to a 'make do with what you have' approach," said Steve Kamman, a telecommunications analyst with CIBC World Markets. "We believe this shift supports our expectation that carrier capital spending will drop by at least 5%, and more likely 10% this year, with the likelihood of further cuts in 2002."

Nortel executives supported that view in their conference call. CFO Frank Dunn cited the example of one customer who initially planned to order around \$350 million worth of equipment. But as engineers worked on the network, they were able to expand its capacity with less-extensive renovations, and ended up ordering only about a quarter of that amount.

Some analysts do see bright spots, such as the consumer broadband area. Kamman said that the current outlook "does not condemn this industry to eternal damnation." He predicts: "A massive return to spending once we reach critical mass in US residential broadband, which we expect to occur in the latter part of 2002."

Nasdaq bears the brunt

The cumulative effect of all this bad news contributed to the worst week the Nasdaq stock market has seen so far this year. Reuters calculates that so far this quarter, 498 companies have said their earnings would fall short of expectations – a five-fold increase from a year ago.

Nortel dropped 74 cents to \$9.86, and JDSU sank \$1.37 to \$12.44 after their warning. JDSU shares, among the most active on Nasdaq, had earlier sunk to a fresh 52-week low at \$10.81. Shares of Corning dropped by 8% to \$16, a new 52-week low, and shares of Lucent fell from \$8 to below \$6.50. In the past 12 months the market capitalization for Lucent has dropped from \$295 billion to just under \$22 billion.

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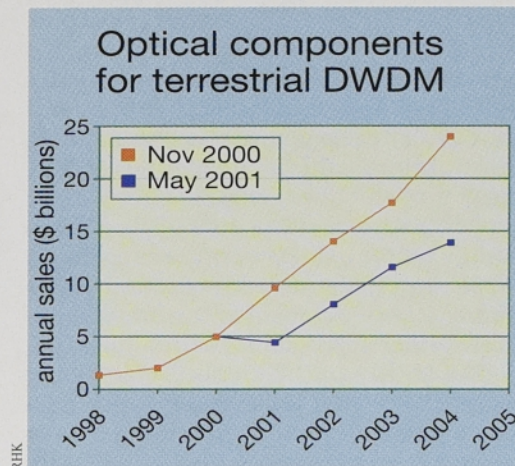
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Optical components market to decline 11%

New forecast data from telecom market research firm RHK shows that worldwide spending on optical components used in terrestrial DWDM and optical networking applications will decline 11% in 2001. RHK has been forced to revise its data in light of the recent market turmoil in this sector. Six months ago, RHK predicted that sales of optical components would increase from \$5 billion in 2000 to just under \$10 billion in 2001, and would continue rising rapidly, reaching \$24 billion in 2004 (see figure). Now, the company estimates that sales will fall to \$4.45 billion in 2001. Looking further ahead, a return to growth is expected in 2002, but at a slower rate than experienced in recent years. The revised 2004 figure is now close to \$14 billion. Despite the "hiccup" in 2001, RHK's figures still represent a compound annual growth rate from 2000 to 2004 of 29%.



The slowdown this year has been blamed on excess inventory levels, which were brought about by over-purchasing last year as systems OEMs desperately tried to secure supply. A slowdown in

network construction and reduced spending by telecommunication carriers worldwide has contributed to the decline. As the excess inventory works through the system this year, demand will pick up to double-digit growth rates in 2003 and 2004.

Growth will be driven by an increase in the number of functions performed optically rather than electrically, deployment of new systems, and higher-performance, higher-priced, next generation components. Different product groups are predicted to grow at different rates as some carriers shift emphasis from building new networks to lighting additional channels on existing networks. One product category expected to do well from this shift is lasers and photodetectors. RHK forecasts this product group to grow from \$2.7 billion in 2001 to \$6.6 billion by 2004.

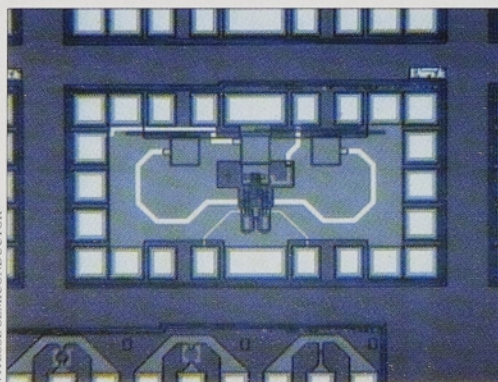
Vitesse unveils in-house 40 Gbit/s indium phosphide process

Vitesse has unveiled a 1.0 μm InP HBT process designed for analog and digital chips used in next-generation 40 Gbit/s optical networks. The process will be used to manufacture physical layer ICs for SONET OC-768 applications and circuitry for 10 Gbit/s systems employing return-to-zero encoded data. Vitesse expects succeeding generations of the process to be scalable to ICs with operating speeds up to 100 Gbit/s.

The new process employs a vertical, mesa-isolated NPN bipolar transistor with a demonstrated peak cut-off frequency f_t of 150 GHz, and maximum oscillation frequency f_{max} of 160 GHz. This performance is consistent with the bandwidth requirements of circuits operating at 40–50 Gbit/s, and also allows forward error correction. Vitesse believes the extra margin afforded by InP HBTs offers an advantage over competing technologies.

Vitesse's InP roadmap

According to Alan Huelsman, Vitesse's InP program director, the first products are expected to be available for sampling early in 2002. These will be 43 Gbit/s front-end receive chipsets. First iterations will integrate the clock data recovery and demux circuits in one IC, with PIN detec-



A 43 Gbit/s VCO, one of the first ICs from Vitesse's 1.0 μm InP HBT process.

tor, TIA and limiting amplifier making up the three other requisite ICs. The first working circuits, which include an integrated 43 Gbit/s VCO (see figure) and 2:1 demux chip, are now being characterized, says the company.

Later generation devices are expected to consist of a two-chip solution – one IC will integrate a PIN detector with a TIA, while the other will combine limiting amplifier and demux functions. This will be followed by receivers with all functions integrated onto a single InP chip. By 2003, the aim is to produce a receiver with a 3.3 V operating voltage and power

consumption of around 2 W.

"InP is the only IC technology that combines the high-frequency performance and high-breakdown voltage required to implement all transmit, receive and clock recovery functions for 40 Gbit/s systems," says Alan Huelsman.

"All other IC technologies result in compromises in system performance or complications in architecture for thermal or functional partitioning reasons. In addition, InP is the only IC technology that provides a path to monolithic integration of long wavelength optical sources and detectors."

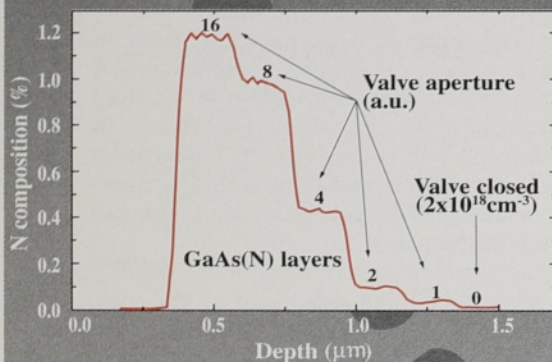
Vitesse began development of InP HBT processes at the beginning of the year using its 4 inch GaAs production line in Camarillo, California. About 50% of the current line has been converted to InP wafer processing. The company says it is also considering offering foundry access to strategic partners.

Further reading

"Vitesse has a Versatile approach to modules" – see Fiber News, page 16.
 "Optical networking components gear up for 40 Gbit/s and beyond" – see page 77.
 "Vitesse execs feel your pain" – see Portfolio, page 101.

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HEADLINE NEWS

Microsemi and Cree work on SiC devices

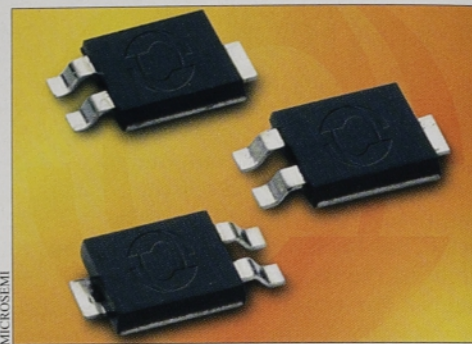
Microsemi (Irvine, CA) and Cree Inc have signed an agreement to jointly develop and commercialize SiC Schottky diodes. The agreement is intended to allow Microsemi to accelerate its SiC program, which will employ Cree's high-power SiC Schottky diodes in Microsemi's patented Powermite packages. While the collaboration focuses on development, both companies expect to negotiate further agreements for volume sales.

The ability of SiC Schottky diodes to handle both high voltages and very high power densities offers advantages over other materials such as GaAs and Si for applications including switching power supplies and telecom rectifier diodes.

"Microsemi has demonstrated a leading position in high-density, high-power packaging," said Chuck Swoboda, Cree's president and COO. "Combined with Cree's SiC chip technology, we believe this relationship will prove beneficial in developing SiC Schottky devices for high-volume applications, and enable initial penetration into the power device market."

Microsemi upgrades Schottky diodes

Microsemi has unveiled two SiC power Schottky rectifier diodes for operation at 100 and 200 V. The company says the new



Powermite packages from Microsemi.

devices address mechanical reliability and electrical variances uncovered in its initial products, announced early in 2000.

Until the alliance with Cree, Microsemi worked with university R&D groups to develop commercial SiC diodes. The company's first devices were developed with Cree and SemiSouth, a spin-off company of Mississippi State University. Cree provided 1 and 2 inch SiC wafers, and SemiSouth performed the processing.

"I believe we've overcome some of the final hurdles required to commercialize a line of SiC Schottky devices in our Powermite packages," said Manuel Lynch, vice-president of marketing and business development. "We started this project two years ago, but recently have seen accelerated progress due to the higher quality of available SiC substrates and the improvements in the device fabrication process."

Job cuts and mounting losses at Anadigics

On June 11 Anadigics announced that it was laying off 10% of its workforce – about 65 employees – in response to the worsening conditions in the communications semiconductor market. The company also said that it would post a larger-than-expected loss in the June quarter. A previous warning had been issued in March.

"Current market conditions that are impacting the visibility for the company and the industry at large, as well as our efforts to return to profitability, necessitate these actions," president and CEO Bami Bastani said.

In addition to the layoffs, Anadigics is also restricting travel, eliminating temporary personnel, and consolidating manufacturing shifts. These moves are expected to produce annual pre-tax savings of \$5–7 million.

The company will take one-time char-

ges in the range of \$35–37 million, and will also post an operational loss of around \$13.2 million. Wall Street had been expecting a loss of \$7.25 million.

Anadigics said broadband cable is currently its strongest segment, with sales of chips for set-top boxes outpacing cable modems. Company executives held out hope that the wireless segment might begin to recover in the third quarter; however, their conference call was held the day before Nokia revealed a more pessimistic forecast for handset sales (see next page). Anadigics' third product area, fiber-optic products, is not expected to rebound until the end of the year.

The company indicated that in the September quarter they expect some increase in sales of broadband products, with fiber-optic products flat to slightly down; wireless sales will be flat to slightly higher.

RFMD hit hard by bad news from Nokia

On June 12 Nokia sprung a surprise on the world's markets by issuing a major profit warning. The world's largest maker of mobile phones (see page 27 for updated market share information) said lower than expected cell-phone growth would cause an earnings shortfall. Sales for the June quarter are now expected to grow less than 10% compared with earlier estimates of 20%, due to deterioration in the general market and economic uncertainty. Nokia, which controls more than 35% of the handset market, said it would revisit its outlook for the second half of the year too because the market slowdown was expected to continue having an adverse effect. Updated estimates will be given in mid July.

Nokia shares tumbled nearly 19% on the news, and they took all of their competitors and most of their suppliers down with them. Among the hardest hit was RF Micro Devices, whose shares slid 25%. Nokia accounts for between 50–60% of RFMD's revenues.

RFMD's chief financial officer Dean Priddy told Reuters Nokia's revised forecast will not affect his company in the short term as it is experiencing a strong June quarter. Priddy stood by RFMD's previous earnings and sales guidance, including an expected net loss of about 5 cents to 6 cents a share, with around 20% in growth over the March quarter. RFMD reported revenues of about \$55 million in the March quarter.

Hitachi and TRW to develop InP modules for 3G wireless and fiber networks

Hitachi and TRW have announced two separate agreements to collaborate in the development and manufacturing of InP modules. One venture will focus on PA modules for 3G handsets, while the other is targeting 40 Gbit/s fiber-optic transceivers and involves OpNext, a newly formed optical component company majority-owned by Hitachi (see *Compound Semiconductor* Sept/Oct 2000, p43).

PA modules for 3G wireless

Power amplifier modules will be built by Hitachi using InP devices manufactured by Velocium, the subsidiary of TRW focusing on InP- and GaAs-based products (see *Compound Semiconductor* June 2001, p 7). Both companies will participate in the design and development of the modules, contributing existing designs and developing new ones. The first PAs should be available to handset OEMs in early 2002, with production ramping up to meet the demand from the expected mass commercial launches of 3G services in the second half of 2002.

The new PAs are integral to the development of W-CDMA handsets for 3G, the next generation of wireless communications, enabling Internet access and high-speed data communications. The roll out of 2.5G and 3G services to replace the poorly received wireless access protocol (WAP) has been slower than expected.

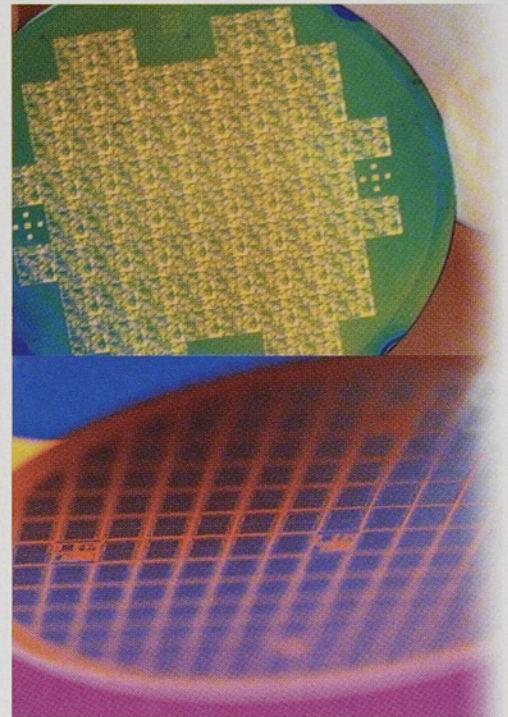
3G wireless services are expected to give great improvements over WAP services and hence boost ailing handset sales as subscribers upgrade. According to Gartner Dataquest, 3G phones will account for 10% of all wireless handset shipments by 2005.

InP offers a number of performance improvements over GaAs PAs, giving over 50% power efficiency and the improvements in signal quality that are needed for W-CDMA applications. "Hitachi's manufacturing capability, coupled with our advanced InP technology, will enable volume manufacture of wireless handsets with talk times and performance never before available," said Dwight Streit, Velocium's president.

InP devices for 40 Gbit/s transceivers

Velocium and OpNext will collaborate in the development and production of components for OpNext's OC-768 (40 Gbit/s) fiber-optic transceivers. OpNext currently produce 2.5 and 10 Gbit/s transceiver and laser diode modules. Velocium will supply InP-based devices such as amplifiers and laser drivers for the OpNext transceivers, planned for launch in 2002. First deliveries of the new Velocium components are expected later this year, with higher volume shipments building in 2002 as OpNext prepares for the implementation of 40 Gbit/s systems.

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Toyoda Gosei sees slowdown in revenues

Toyoda Gosei was recently downgraded by the analyst firm UBS Warburg, following indications from management that the company would miss its LED revenue and capacity expansion targets for the financial year ending March 2001.

The company's high-brightness LED business has slowed down significantly due to three major factors, according to analyst Chris Redl. First, Toyoda Gosei is taking longer than expected to roll out its white LED product, which is a key component in full-color handset displays. The Japanese handset market is fiercely competitive and is shifting very rapidly over to the new type of display. Second, Toyoda Gosei is being adversely affected by the global downturn in handset sales. Finally, the company suffers from its lack of sales teams in Europe and the US.

According to Redl, Toyoda Gosei was targeting a monthly production capacity of 75 million LEDs by the end of March 2001, but has only reached a level of 65 million units, with a capacity utiliza-

tion of between 50 and 60%. The company has indicated that LED revenues for the financial year ending March 2001 were ¥17.5 billion (approximately \$142 million), compared with guidance of ¥20 billion given in February of this year.

There is good news, however. Toyoda Gosei is working with at least three companies to develop white LEDs, one of which is Toshiba (see *Compound Semiconductor* April 2001, p67). Also the company has had a positive response to its products from both European distributors and US car-makers.

Furthermore, by increasing the overall brightness and efficiency of its products, Toyoda Gosei will be able to target low-end, high-volume applications such as electronic components, overseas handsets and automotive applications.

Positive patent news

Meanwhile, a recent court ruling in favor of Toyoda Gosei in its patent war against Nichia could have huge positive implica-

tions, says Redl. TG had sued Nichia in the lower courts over substrate technology that is used in some of Nichia's current products, and that TG considers proprietary. The lower courts stopped proceedings after patent officers had deemed that TG's patent claim lacked a proprietary nature. However, the Tokyo high court ruled in TG's favor, implying that TG has a chance of winning its lawsuit against Nichia.

"We feel this is a landmark ruling, as it could potentially lead to Nichia being forced to scale down its production, or pay massive compensation claims to TG," says Redl. "The view within the LED industry is that the Japanese government may be moving to force the two companies to settle out of court. In this case, we would see TG in an advantageous situation, as it has more efficient production technology." However, Redl points out that this lawsuit will take time to sort out, and there is also the prospect of more lawsuits to complicate matters still further.

LumiLeds Lighting launches multi-format Luxeon light sources

LumiLeds Lighting has revealed details of its new Luxeon products, a range of high-power LED sources featuring large area die that can be driven at high currents (up to 700 mA). The company says the new chips offer up to 10 times the output of standard LEDs.

LumiLeds plans to introduce a series of light sources containing Luxeon LEDs in various configurations and colors this summer. The Star is a single-light source available with or without optics, while the Ring combines six or 12 white devices with optics and supplies up to 194 lm. The Line source, containing 12 white LEDs, is also rated at 194 lm, while the Flood system provides up to 324 lm from a small board densely populated with white chips. The sources are equally bright or brighter in other colors; the red Flood emitter is rated at 792 lm.

"Until now, LED devices did not emit enough light to make an effective lighting fixture," said Mark Swoboda, vice-president of sales and marketing. "But with Luxeon producing anywhere from



Line and Ring light sources employing LumiLeds' Luxeon LEDs.

10 to 20 times more light, we're now in the right ballpark for [general] lighting."

LumiLeds is addressing color stability and reliability issues, including the perception that white LEDs lose 35% of their lumens after just 4000 hours. Failure mechanisms include epoxy yellowing, reflector cup and die-attach epoxy discoloration, phosphor degradation and reductions in LED die output. LumiLeds employs packages that do not contain

epoxy or unprotected silver lead-frames, or reflector cups that might discolor. In addition, the die-attach is separated from the LED, ensuring that epoxy degradation does not affect the light output.

As a result, long-term reliability data for the company's cyan LEDs show less than 20% degradation after 50 000 hours. LumiLeds believes that the white LEDs will maintain their high output for at least 25 000 hours.

Getting the whites whiter

LumiLeds has also looked at inconsistent lighting effects in white devices caused during conversion of blue LED emission by a phosphor.

The correlated color temperature, or CCT, defines this characteristic. A poor CCT value results in different shades of white, and conventional light sources have a CCT range of ± 50 K. Current white LEDs fall well short of this value with ± 500 K. LumiLeds says its new white devices are rated at ± 100 K, with ± 50 K expected in future.

GaAs — SILICON STYLE

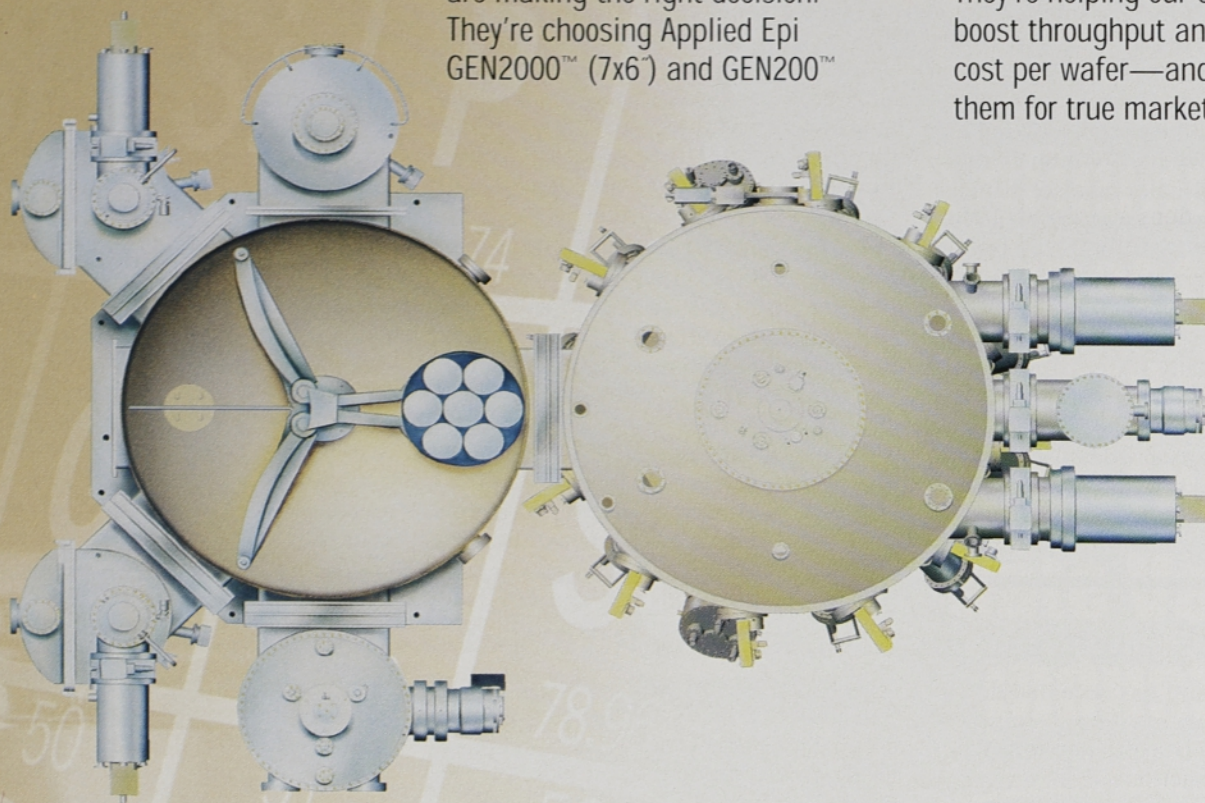
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Medical camera uses CdZnTe

eV Products has developed a CdZnTe camera for medical diagnostic applications in partnership with Anzai Medical of Tokyo, Japan.

The imaging system, which combines CdZnTe chips manufactured by eV Products with Anzai's small-field-of-view camera design, detects gamma radiation and provides images of internal organs. According to eV Products, the camera offers images with much higher resolution than comparable sodium iodide scintillation detectors.

CdZnTe has a density of 5.78 g/cm^3 , which makes it an excellent material for stopping high-energy gamma rays. As a gamma ray impinges, it creates an electron-hole pair in the CdZnTe material (nominal bandgap 1.56 eV) that can be weighted and converted to a signal. The detector is 5 mm thick, and absorbs up to

89% of the incoming 140 keV gamma rays from a ^{99}Tc source (technetium isotope with an atomic weight of 99).

The device used in the new camera is a metal-semiconductor-metal $\text{Cd}_{0.9}\text{Zn}_{0.1}\text{Te}$ chip patterned into 256 pixels, each spaced at 2 mm intervals. The active area measures $32 \times 32 \text{ mm}$.

According to marketing manager Chris Bickel, a key advantage is room temperature operation. "While high-purity Ge detectors offer better performance, they need to be cooled, which adds considerably to the cost," says Bickel.

"Our CdZnTe detector is designed to operate in the required temperature range [from -30 to 80°C] with little or no change in response, which makes it ideal for a number of applications, including direct contact with the skin of a patient," Bickel adds.

Cree files new patent suit against Nichia

In the latest round of patent litigation related to nitride-based devices, Cree is seeking the enforcement of US patent 5 686 738. This patent, entitled 'Highly insulating gallium nitride thin films', was issued to Boston University in 1997 and licensed to Cree. Boston University is a co-plaintiff in the action.

In its complaint, Cree has alleged that Nichia is infringing the US patent "by selling and offering for sale in the US certain semiconductor devices made from GaN thin films". The patent describes a method for the growth of near intrinsic GaN films and also n- or p-type films using electron cyclotron resonance (ECR)

microwave plasma-assisted MBE.

However, the claims of the patent describe devices comprising certain layer configurations, including a non-crystalline GaN buffer and subsequent crystalline-doped GaN layers. The claims detail deposition temperatures and layer thicknesses, but do not exclude alternative growth techniques to the MBE method described. Both Cree and Nichia use MOVPE to grow their devices.

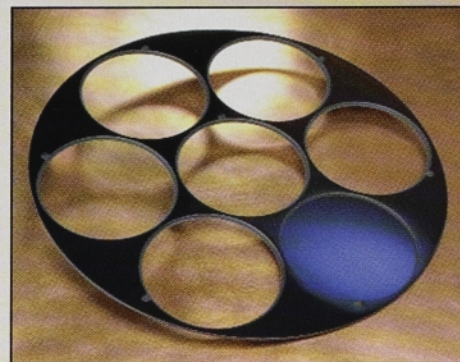
In another recent lawsuit between these two companies, the Tokyo District Court dismissed an infringement lawsuit filed against Cree by Nichia (see *Compound Semiconductor* June 2001, p10).

Diamond pn junction emits UV light

Researchers at the National Institute for Materials Science in Tsukuba, Japan, have reported UV emission from a pn junction formed from boron-doped (p-type) and phosphorus-doped (n-type) diamond (S Koizumi *et al. Science* 2001 **292**(8) 1889). The layers were grown epitaxially on 2 mm^2 single-crystal diamond substrates by microwave-plasma-enhanced CVD. A strong UV emission

peak at 235 nm, attributed to free exciton recombination, was observed when the forward bias voltage reached 20 V. This was accompanied by broadband visible emission, attributed to the poor crystalline quality of the boron-doped layer. By improving the quality of this layer, the broadband emission can be suppressed, making a diamond LED emitting monochromatically at 235 nm feasible.

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Nichia produce 30 mW violet lasers

Nichia is moving its NLHV3000 series of high-power violet laser diodes into volume production. These devices have a peak wavelength of 405 nm and a maximum optical output power of 30 mW, and are intended to increase the storage capacity of DVD players. The shorter wavelength produced by InGaN contributes to the five-fold increase in data storage capacity, from the current 4.7 gigabytes to more than 20 gigabytes, in next-generation DVDs. Also, the increased optical power output of the NLHV3000 series enables the laser to write data as well as just reading the discs.

Samco floats stock

In a move to raise capital to fund expansion, shares in Samco International were listed on the Tokyo stock exchange on May 30. Samco, which is headquartered in Kyoto and has research labs in California, plans to use the capital to buy buildings for a new factory in Kyoto. Samco's main products are tools for PECVD, reactive ion etching and UV ozone cleaning. In the half-year ended January 2001, 43% of the company's sales went into laser and LED production.

Rare earth ions change LED colors

Researchers at Osaka University have developed new technology that can adjust the color of light emitted from LEDs. According to a report in the Nikkei Business Daily, the LED is covered with transparent plastic containing rare earth complex ions. When light emitted by these ions is added to the light from the LED, the color of the overall light emitted is changed. For example, by covering an LED that emits white light with plastic containing europium ions, the result is red emission. Similar results were found with terbium (giving green light) and cerium (blue). Using the appropriate quantities of these three types of ions made it possible to minutely adjust the LED color.

UEC expands LED capacity, introduces new epiwafers

United Epitaxy Company (UEC) has developed a new range of epiwafers for optical communication applications, and intends to start mass production in July 2001. The products are AlGaAs VCSEL epiwafers, along with 1310 nm LED and Fabry-Perot (FP) laser diode epiwafers.

The AlGaAs VCSEL epiwafers cover the 780 to 850 nm range and are available with oxide-confined or ion-implant structures. 850 nm oxide-confined VCSELs fabricated using UEC's epiwafers have a 10 μ m aperture, 1 mA threshold current, 0.3 W/A slope efficiency and 35 Ω resistance. 1310 nm FP lasers with 3 μ m stripe width and 30 μ m cavity length have also been fabricated. These exhibit a typical threshold current of 12 mA, a slope efficiency of 0.37 W/A and a characteristic temperature of over 85°C.

Third LED plant to open soon

In further news, UEC expects that its third plant, located in the Tainan science-based industrial park in the south of Taiwan, will open shortly. The facility will be used for the volume production of ultra high brightness (UHB) AlInGaP LED chips. The company expects that the significant improvements it has made to high-volume epitaxy will help reduce production costs to NT\$0.1–0.2 per chip. In comparison, production costs for conventional LEDs are below NT\$0.1 (~0.3 cents). UEC expects UHB LEDs to replace conventional LEDs as costs fall and high-volume markets such as decorative lighting and outdoor displays continue to grow. The company aims to have a significant share of this market, which it expects to reach 2.5 billion chips by 2005.

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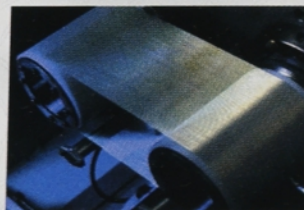
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Vitesse takes Versatile approach to modules

Vitesse is to acquire Versatile Optical Networks, a one-year-old start-up that designs and manufactures optical and optoelectronic modules, for approximately 10 million Vitesse shares (worth some \$220 million when the deal was announced in early June).

The acquisition is in line with Vitesse's strategic view that component suppliers must become module suppliers in order to be successful as the fiber-optic market continues to evolve (see page 75). Versatile's products include 10 Gbit/s long-reach transponders, 8 × 8 all-optical switches, and transponder arrays. Vitesse expects the transaction to be completed by the end of September, and plans to begin shipments at the end of the year.

"The Versatile acquisition brings us an excellent opto-mechanical design team with a highly desirable expertise base in manufacturing, automation, test and packaging," said Vitesse president and CEO Lou Tomasetta.

"Combined with Vitesse's analog and physical layer ICs and emerging InP manufacturing capability, we will now be able to provide a complete component

solution from the fiber to the back-plane."

Tomasetta gave more details about the acquisition in his presentation at the recent CIBC World Markets' annual Communications Food Chain conference.

"We've been talking about this space for about three years," he said. "It complements our expertise in physical layer components, which has been our core business. We will be able to provide literally all of the electronic components that will go into the various types of module."

Component modules

Versatile's products will use optical devices, such as lasers and InGaAs photodetectors, obtained from third-party suppliers, and Vitesse will continue to supply components to other module suppliers. The deal also fits with Vitesse's choice of InP technology for 40 Gbit/s components. "One of the important motivations for this acquisition is that it will give us an immediate outlet for an optimized, 40 Gbit/s (OC-768) module using our internal indium phosphide technology," said Tomasetta. Vitesse's recently announced InP process is discussed on page 4.

Tomasetta explained that modules will become the component that the OEMs purchase. "Customers are changing from buying components and building their own modules to buying the module as the component," he said.

"Unless you are an active participant in the module business – by that, I mean supplying the modules – you'll find yourself squeezed by a number of the large players such as Agilent, JDS Uniphase, Agere and Infineon. These companies are already in the module business, and can supply most of the components that go into the modules, or have access to the technology to build the components."

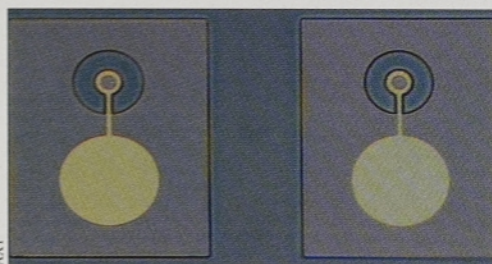
As the supply "food chain" continues to evolve, there will be important consequences for the revenue-generating capabilities of different suppliers. "In the recent past, ASPs were so high that everybody in the food chain could make 60, 70 or even 80% margins," said Tomasetta. "In a year or two, module suppliers will still be able to make high margins, but there won't be room for multiple layers of the food chain to make the same kind of margins they've made in the past."

AXT adds 850 nm oxide-confined VCSEL arrays to portfolio

AXT's VCSEL Technologies Division (Fremont, CA) has developed 850 nm oxide-confined VCSEL arrays in 1 × 12 and 1 × 4 configurations.

Available in volume production quantities, the arrays are based on the company's recently introduced oxide VCSEL designed for data modulation rates up to 3.125 Gbit/s (see *Compound Semiconductor* June 2001, p13).

The arrays' applications include short-



Two of the VCSEL devices in AXT's new array product.

reach optical interconnections and transceivers. This includes InfiniBand designs, which are based on a high bandwidth standard architecture to link processors and I/O devices. Each VCSEL operates in excess of 2.5 Gbit/s, and the 1 × 4 array modulates data at up to 10 Gbit/s (OC-192). The 1 × 12 array supports 30 Gbit/s data rates. The typical power output of each VCSEL is 1 mW, with output slope efficiencies of 0.45–0.50 mW/mA.

Nortel demonstrates first metro application with tunable laser

Nortel Networks demonstrated the first metro DWDM system to include a tunable laser at the Supercomm exhibition in Atlanta, GA.

A joint demonstration was held with Bandwidth9, a tunable laser manufacturer based in Fremont, CA. Nortel employed Bandwidth9's 2.5 Gbit/s tunable laser in

its OPTera Metro 5200 system, and tuning was achieved remotely using a PC.

"Tunable systems will be an essential requirement for future metro networks," commented Brian McFadden, president of Nortel's Metro Optical Group.

"Using tunable lasers in the OPTera Metro product portfolio will help to in-

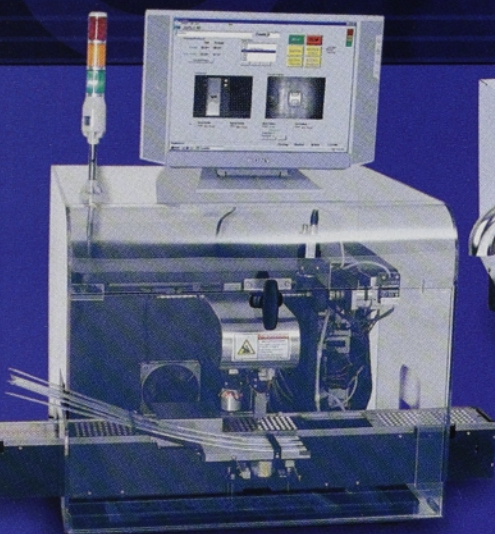
crease profitability by reducing inventory costs and enabling the delivery of optical services such as bandwidth provisioning, bandwidth-on-demand and also packet switching."

McFadden added that Nortel's system was also applicable to next-generation 10, 40 and 80 Gbit/s long-haul systems.



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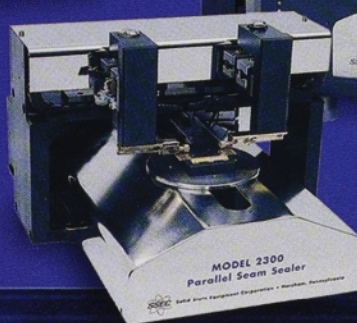
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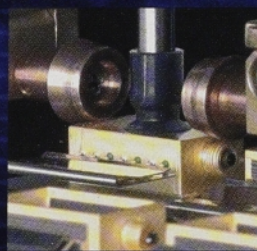
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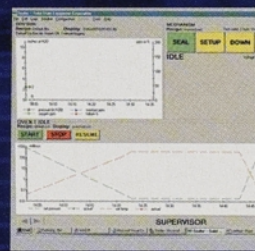
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Mitel reborn as Zarlink Semiconductor

Mitel Corporation, which manufactures analog, digital and mixed-signal ICs as well as a range of optoelectronic components and modules, has changed its name to Zarlink Semiconductor. Last December, Mitel announced it would sell its enterprise communication systems business, including the Mitel name, leaving a company focused on semiconductor products.

Zarlink has headquarters in Ottawa, Canada, as well as several facilities in Europe. The company manufactures VCSEL-based transceivers and other

optoelectronic components at its facility in Jarfalla, Sweden. Elsewhere, Zarlink manufactures communication ICs using its silicon bipolar and CMOS technologies.

One of the first announcements under the new banner is a joint venture with Applied Micro Circuits Corporation (AMCC) of San Diego, CA, to develop multi-channel 10 Gbit/s parallel fiber modules. The companies previously worked together on short-reach optical solutions operating at 2.5 Gbit/s per channel.

While 10 Gbit/s parallel modules are suitable for 40 Gbit/s transponders that

comply with the Optical Internetworking Forum standards, Zarlink intends to bundle twelve 850 nm VCSELs into a parallel fiber module for an aggregate bandwidth of 120 Gbit/s. This represents a fourfold increase in data rate for short-reach optical links used in scalable multi-chassis routers, switches and optical cross-connections, and central offices.

AMCC will provide physical layer, switch fabric, network processing and framer products. These include a 3.2 Gbit/s CMOS quad driver, and a SiGe TIA with integrated limiting amplifier.

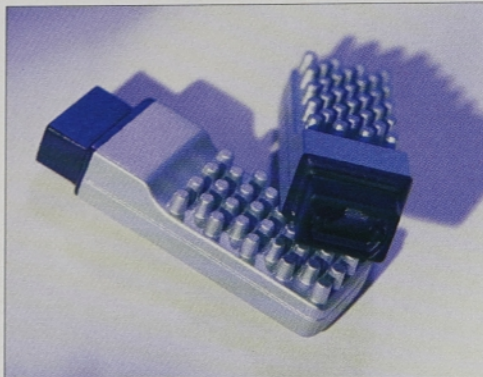
Cielo Communications launches 1310 nm VCSEL-based products

Cielo Communications has recently released two new products that feature 1310 nm VCSELs: a 10 Gbit/s serial transponder and a 2.5 Gbit/s per channel parallel array module.

The transponder is packaged in compliance with the 200-pin small footprint OC-192 transponder multi-source agreement, which is designed to reduce board space and power dissipation.

The transmit side features a jitter filter, high-speed serializer, 10 Gbit/s 1310 nm VCSEL and laser driver. The receiver side incorporates a PIN photodiode, transimpedance and limiting amplifiers, clock and data recovery circuits and deserializer. The transponder is targeted at standards-compliant optical networking markets and comes in versions compatible with OIF, Ethernet, SONET/SDH and Fibre Channel standards for 10 Gbit/s 1310 nm optical interconnects.

Also announced is the industry's first 2.5 Gbit/s per channel 1310 nm VCSEL-based array module. The modules, which



Cielo's 1310 nm VCSEL-based parallel array modules.

are available in eight- or 12-channel versions, are designed for use in OC-48 SONET applications, including dense optical networking and backplane interconnects. Cielo claims that the modules give a 60% reduction in power consumption and 75% size reduction over currently available products.

The modules utilize monolithic arrays

of directly modulated 1310 nm VCSELs to perform high-data-rate transmission in separate ultra-dense transmit and receive packages. Using the 8 or 12 transmit/receive channels at 2.5 Gbit/s per channel gives bandwidths of 20 or 30 Gbit/s respectively, over distances of up to 15 km. The arrays include independent signal detect and transmit disable functions on each channel to enable greater flexibility.

"Our 1310 nm VCSEL arrays are based on a disruptive technology that will significantly stimulate growth of a new generation of optical networks," said Mick Wilcox, product marketing manager for Cielo's array products. "Our product provides the densest OC-48 interconnect solution in the industry. Cielo's 1310 nm parallel optic solution will enable clean migration to a 1310 nm singlemode solution supporting distances up to 15 km."

Volume production of both the 10 Gbit/s transponders and the parallel array modules is expected in late 2001.

Agere announces 280 mW DFB Raman pump laser

Agere Systems has launched a 14xx nm DFB pump laser for use in Raman amplification systems that boost signal power in ultra high-capacity optical networking systems. The product has an operating power of 280 mW with a drive current comparable to high-power Fabry-Perot (FP) lasers. Agere claims this to be the most powerful 14xx nm DFB laser that is currently available. The laser supports

Raman amplification in both co-pumping mode (where the pump's optical power is transmitted in the same direction as the communication signal) and counter-pumping mode (where pump power is sent against the signal).

As part of the DFB design, the wavelength stabilization grating is incorporated onto the laser chip, removing the need for an external fiber Bragg grating. This con-

figuration keeps the relative-intensity noise (RIN) low and reduces wavelength shift with package temperature changes. The combination of both characteristics is critical to enable co-pumping, which distributes gain over the first few kilometers of the transmission fiber. Agere is now sampling the 14xx high-power DFB lasers, with production quantities expected in the third quarter of 2001.



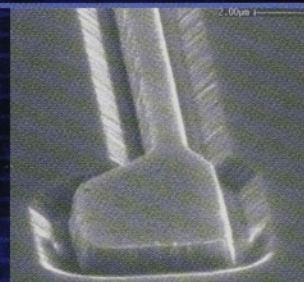
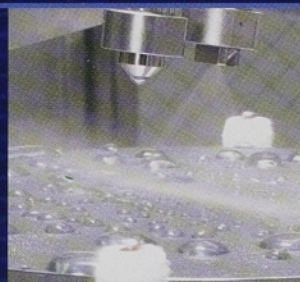
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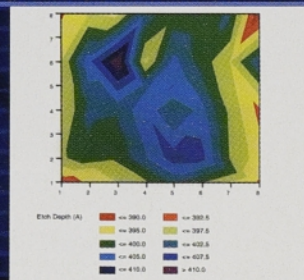
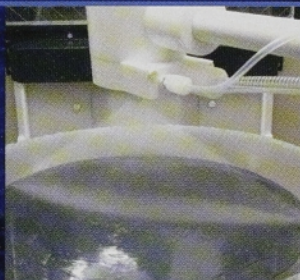
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FIBER NEWS

Ciena demonstrates new optical systems

Ciena of Linthicum, Maryland, demonstrated several new networking capabilities at the recent Supercomm 2001 exhibition in Atlanta, GA. These included a DWDM system incorporating very closely spaced channel spacing between wavelengths to increase capacity, and an optical networking system operating at 40 Gbit/s. In addition, the company exhibited an all-optical switching architecture, and interoperability of Ciena's switching range of platforms and DWDM systems at 10 Gbit/s.

Known as MultiWave CoreStream, Ciena's DWDM system is a flexible platform containing arrays of 850 nm VCSELs transmitters. Ciena has increased the channel density by employing fiber Bragg gratings to filter optical channels, resulting in a 12.5 GHz spacing between wavelengths. This compares with existing systems that typically feature either 50 or 100 GHz spacing. The system targets increased optical network capacity and economic scalability for existing 10 Gbit/s infrastructure.

Ciena also generated, received and processed multiple OC-768 (40 Gbit/s) data streams using the same dense channel arrangement in its Multiwave CoreStream metro optical product. CoreStream was designed with a modular DWDM architecture to enable upgrades, and a mix of 2.5 and 10 Gbit/s transmitters can be employed.

Quake wins further \$30 million in funding

Quake Technologies, a fabless semiconductor start-up with offices in San Jose (CA) and Ottawa (ON, Canada), has raised \$30 million in a second round of financing. Investors include Cisco Systems and Mitsubishi. Founded in April 2000, Quake develops mixed-signal, physical layer ICs for 10 and 40 Gbit/s optical networking applications. The company says the financial injection will be used to expand its R&D activities, and accelerate product delivery. "This financing will enable us to ramp up production for the introduction of products later this year," said Dan Trépanier, president and CEO.

MCE forms optoelectronic subsidiary

MCE Technologies has launched a start-up company to develop InP-based optoelectronic devices as well as broadband microwave and millimeter-wave components for optical networking applications. The new company, MCE OptoElectronics, will focus initially on integrated photo-receivers used in high-speed transceivers.

Manufacturing will leverage a 4 inch InP wafer processing line currently being set up at MCE Metelics, another company within the MCE Technologies group. MCE Metelics has 12 000 sq. ft of clean-room space at its facility in Sunnyvale, California, which includes silicon, GaAs and InP lines for the front-end processing of epiwafers obtained from external suppliers. Back-end procedures, such as packaging, will be carried out at MCE OptoElectronics' site in Ann Arbor, Michigan, where the company will spend the year developing products for introduction in 2002.

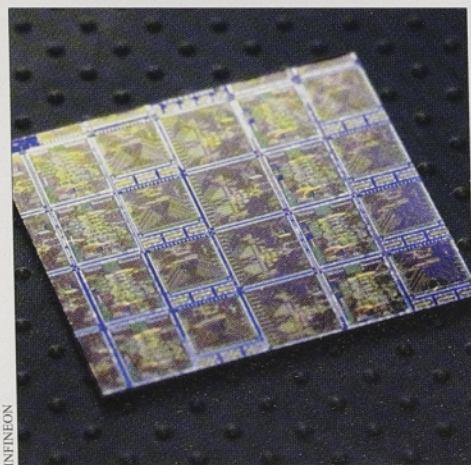
MCE Technologies is made up of six operating companies that offer an exten-

sive range of devices, components, and subsystems used in mobile and fixed wireless infrastructure equipment, and wireless broadband access, as well as fiber-optic networking, satellite applications and related test equipment. MCE OptoElectronics plans to employ various broadband RF and microwave technologies already available within these MCE companies.

"MCE OptoElectronics will initially concentrate on manufacturing components for the front-end of the fiber-optic transceivers, including integrated photo-receivers containing PIN diodes and HBT-based transimpedance amplifiers," said CEO Craig Linberg.

"In common with many manufacturers, we will also be looking to take advantage of InP technology to integrate more components, such as driver or limiting amplifiers, on chip. We also have millimeter-wave expertise through our company network that we can bring to broadband amplifiers."

Infineon unveils 40 Gbit/s SiGe chipset



Infineon's SiGe mux/demux chipset is designed for 40 Gbit/s operation.

Infineon has introduced what it describes as the industry's first 40 Gbit/s SiGe mux/demux chipset for SONET/SDH communication systems. The new chips are designed for OC-768 transmission systems used in emerging applications such as metropolitan-area networks.

"The optical networking market will boom in the next four years, and the OC-768 segment is expected to leapfrog

all other transmission technologies," said Christian Winkelmeyer, general manager of Infineon's high-speed communications business unit.

"We now have OC-768 SONET/SDH framing and mapping expertise, and the SiGe mux/demux chipset is a key component of Infineon's solution for 40 Gbit/s communication systems."

The company's chipset consists of 16 2.5 Gbit/s input channels multiplexed to a single serial 40 Gbit/s output data stream, supporting data rates of 39.8–43 Gbit/s for forward-error correction. The multiplexer also supports both NRZ (non-return to zero) and RZ (return to zero) formats, and the demultiplexer integrates clock and data recovery functions with an input sensitivity of 50 mV. Both chips operate from a single 5.5 V supply voltage.

Although companies such as Velocium and Vitesse are backing indium phosphide for next-generation 40 Gbit/s systems, Infineon has clearly sided with SiGe, along with AMCC – the latter recently launched an OC-768 transimpedance amplifier (see *Compound Semiconductor* June 2001, p29).

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Stanford signs foundry deal with RFMD

Stanford Microdevices and RF Micro Devices have signed a foundry supply agreement under which RFMD will manufacture RFICs according to Stanford Microdevices' proprietary designs. Production will be carried out at RFMD's 4 inch GaAs HBT fabrication facility in Greensboro, NC. The two companies will not exchange intellectual property in the course of the agreement, and there are no

plans for co-branding of any products. Stanford Microdevices is a fabless IC design company that supplies high-linearity power PAs, modules, LNAs, gain blocks, transistors, modulators, switches, mixers and up-/downconverters, plus multi-component modules for transmit and receive applications (see *Compound Semiconductor* November 2000, p49).

"We are very enthusiastic about this

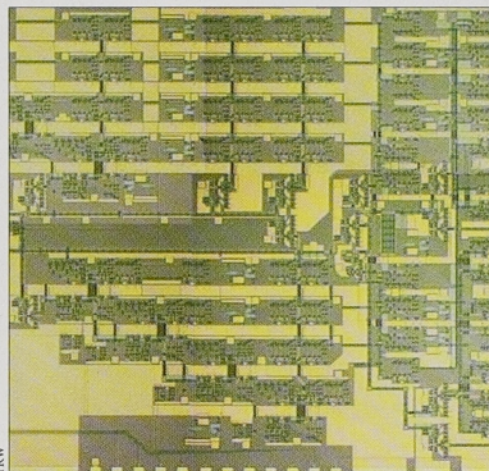
relationship," said Bob Van Buskirk, president and CEO of Stanford Microdevices. "It enables us to take advantage of RFMD's high-volume, low-cost HBT wafer-manufacturing capabilities. At the same time, the agreement will maintain Stanford Microdevices' proprietary design expertise in high-performance RF components for wireless infrastructure equipment."

TRW produces frequency synthesizer

TRW has used its InP device technology to produce a direct digital frequency synthesizer operating at 7 GHz, which the company claims is the world's fastest such IC. Developed under contract to the US Navy's Office of Naval Research (ONR), the circuit contains more than 3000 HBTs and operates up to three times faster than current synthesizers.

Digital synthesizers look set to benefit future military electronic systems such as radar by providing fast, accurate frequency and phase change information, which is needed to detect the position of rapidly moving targets. In addition, direct digital synthesis technology contributes to lower phase noise and improved system sensitivity.

"High-speed direct digital frequency synthesis will enable us to develop the Navy's next-generation electromagnetic systems employing Advanced Multi-function Radio Frequency Concepts (AMRF-C)," said Max Yoder, director of the Electronics Division at ONR. "AMRF-C is expected to provide the basis to combine communications, radar and electronic warfare functions into a single, integrated aperture. Direct digital frequency synthesizers provide better



TRW's new 7 GHz direct digital frequency synthesizer contains more than 3000 InP HBTs.

control over signal frequency and phase than conventional analog synthesizers."

"Our development of InP for commercial markets gives us the volume production we need to reduce the cost of this breakthrough technology, benefiting the Navy and positioning us to bring high-speed digital frequency synthesizers to telecommunications system developers," said Dwight Streit, president of Velocium.

Agere selects RFMD for GPRS modules

Agere Systems (Allentown, PA) has chosen a PA module manufactured by RF Micro Devices for use in its Class 8 general packet radio service (GPRS) handset. RFMD's RF3108 module is based on a triple-band GSM design for use in Class 10 applications. Manufactured using RFMD's GaAs HBT process, the module provides typical power-added efficiencies of 55% for the GSM900 band, 52% for the DCS1800 frequency and 47% for PCS1900 systems.

Asian interests

"Handset manufacturers, particularly in Asia, are showing increasing interest in technology platforms," said Joe Grzyb, director of RFMD's power amplifier product line. "This is due to the need for accelerated time-to-market, reduced cost, ease of assembly and an overall desire to reduce the reliance on design engineering resources, which remain in short supply. We believe this trend has recently accelerated as tier-one manufacturers have begun to outsource to Asian handset manufacturers in order to cost-effectively complement their supply strategies."

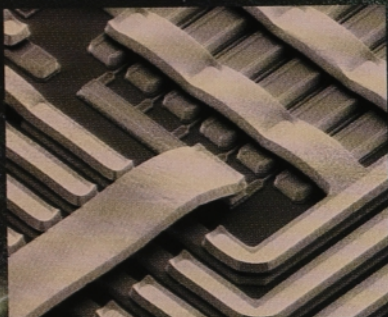
Endwave receives transceiver order

Endwave (Sunnyvale, CA) has received a multimillion-dollar order from DMC Stratex Networks to design and manufacture custom millimeter-wave transceivers. Operating in the 28, 29 and 31 GHz fre-

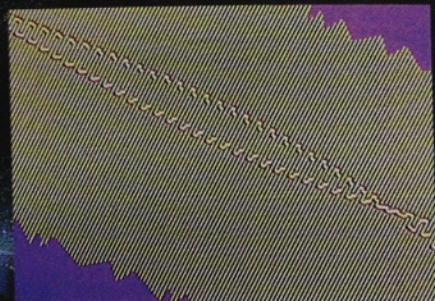
quency bands, Endwave's GaAs-based transceivers will be integrated into DMC Stratex's XP4 family of point-to-point wireless radios for use in cellular backhaul applications and last-mile broadband wireless access. XP4 radios are designed for low-cost wireless networks, and offer transmission capacities up to 45 Mbit/s in frequency bands up to 38 GHz.

"We are pleased to add DMC to our customer list, and believe this represents the beginning of a long-standing, mutually beneficial relationship," said Ed Keible, Endwave's president and CEO. "Our manufacturing capabilities and millimeter-wave engineering expertise are well matched to meet the company's diverse, volume supply requirements."

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Air bridge on high speed GaAs device, courtesy of M/A-COM



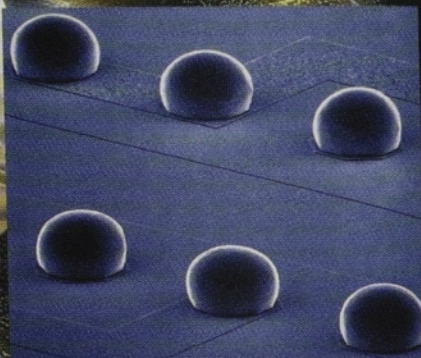
Saw filter, courtesy of AME Space



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Wafer bumping, courtesy of IZM/TU Berlin

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Filtronic proposes tie-up for UK GaAs fab

Filtronic has announced that it is in discussions with a "leading international aerospace and defense OEM" to form a joint venture company based upon the infrastructure located at its 6 inch GaAs fabrication facility in Newton Aycliffe, UK. Filtronic purchased the plant in September 1999 and set about a \$56 million conversion that gave the company 100 000 sq. ft of clean-room space for the production of a range of PHEMT-based products (see *Compound Semiconductor* May 2001, p87).

The plant opened in August 2000, but by February 2001 Filtronic was reporting substantial losses arising from its GaAs operation. These losses were attributed to the cost of maintaining a very large fab with a capacity far in excess of that required for Filtronic's internal use, coupled with the long time required to establish and qualify products with customers. Filtronic stated that it was looking for a

strategy to "reduce or eliminate the financial burden" of this group (see *Compound Semiconductor* March 2001, p30) – this latest move appears to be the culmination of this strategy.

Commercial and defense markets

Both shareholders in the proposed joint venture will benefit from access to an advanced compound semiconductor manufacturing plant and Filtronic's automated microwave electronics subsystems factory. Key products from the facility for Filtronic include GaAs PAs for 3G base stations, customized MMICs for millimeter-wave broadband wireless products, and photonic components. It is intended that the factory will supply Filtronic with complete amplifier and transceiver subsystems for both commercial and defense markets.

Products for defense markets will include devices for phased array radar

and electronic countermeasure systems, in addition to products being supplied by Filtronic for various defense projects such as EuroDass and Euroradar for the Typhoon avionics system.

According to Filtronic, it is intended that production at the plant will not be entirely captive and that the compound semiconductor devices will be made available to one or more selected third parties that do not compete with the principle shareholders.

Overall, a significant proportion of the output for both the GaAs fab and the microwave factory will be for commercial applications. This in turn will enable the military components to be produced relatively cheaply as they will gain from the economies of scale achieved in the commercial work, a benefit not always available when producing products for the military market, where volumes are small in comparison.

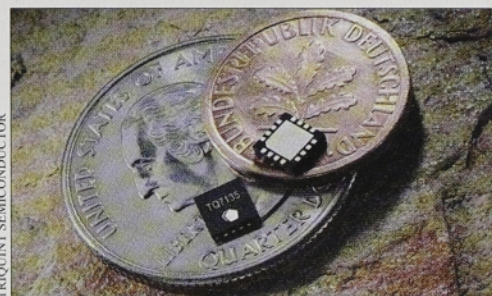
RFMD and TriQuint enter silicon germanium alliances

Two leading GaAs manufacturers, RF Micro Devices and TriQuint Semiconductor, have formed separate alliances with SiGe device manufacturers to develop RF wireless chips and to broaden their technology portfolios. RFMD is teaming with Agere Systems to manufacture chips for data-enabled digital cellular phones and other telecom products, while TriQuint and Atmel will jointly develop chipsets for CDMA handsets.

RFMD and Agere extend alliance

The Agere-RFMD alliance expands on an existing collaboration to bundle power amplifiers with other wireless chips into complete SiGe chipsets for digital cellular handsets, and wireless LAN and Bluetooth devices. The alliance also leverages Agere's silicon processes, and includes the creation of an RF center of excellence for chip process technology and design.

As part of the collaboration, RFMD will invest approximately \$58 million over 2 years to upgrade manufacturing clean-room space and purchase semiconductor manufacturing equipment, which will be deployed within Agere's manufacturing facility in Orlando, Florida. Production resulting from the new equipment



TriQuint and Atmel's first jointly developed SiGe product is a 3 V CDMA power amplifier.

will be allocated first to RFMD and subsequently to Agere. This is intended to secure silicon capacity for RFMD, while the companies say they will both benefit from combined operations and increased manufacturing volumes. RFMD also plans to deploy Si engineers at Agere's Florida facility.

"This alliance provides us with the silicon manufacturing capacity needed to expand our RF product portfolio beyond power amplifiers," said RFMD's Jerry Neal. "In addition, we believe this collaboration will enable RFMD to help define and develop next-generation silicon processes for wireless applications, while

providing a framework for both companies to collaborate on the development of new wireless products."

TriQuint and Atmel team up

TriQuint and Atmel (Heilbronn, Germany) will co-operate on the design and manufacture of integrated chipsets for CDMA handsets as part of their CDMA345 project. Atmel has a SiGe RF process designed for communications applications that operates at up to 82 GHz (see *Compound Semiconductor* Dec 2000/Jan 2001, p31).

The project has already led to the release of the first device. This is a 3 V SiGe CDMA power amplifier designed for use with IS-95/98 and AMPS-compliant phones (see figure and page 40). A CDMA RF transmit solution is also expected to be available for volume production later this year.

"TriQuint and Atmel engineers jointly developed each circuit block," said TriQuint's director of technology and business development, Dilek Barlas. "The performance of these circuits and the speed with which they have been developed has already demonstrated the value of this co-operation."

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Fiber-optic IC market to reach \$2.9 billion

Purchases of high-speed analog and mixed signal ICs used in optical networks will decline by 13% in 2001, according to a new report from Strategies Unlimited. This gloomy figure is tempered by the report's prediction that orders will stabilize by the end of the year. Subsequently, the market will resume its previous growth, reaching \$2.9 billion by 2005.

ICs for the fiber-optic market include laser drivers, amplifiers, clock and data recovery, MUX/DEMUX and devices to switch traffic in the electronic layer. According to the report, all semiconductor technologies will benefit from the pro-

jected market growth. Silicon and SiGe will continue to dominate at lower data rates, whilst GaAs and InP will lead in 40 Gbit/s applications, with emerging InP devices growing the fastest.

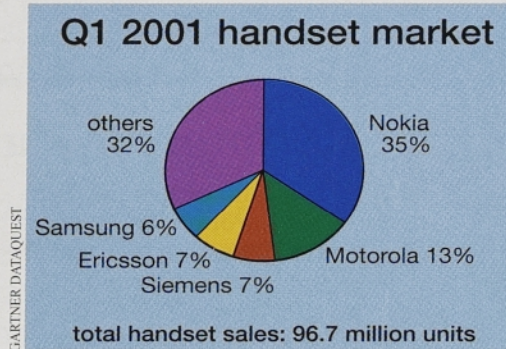
Two factors are cited as driving the predicted growth. The first is deployment of 40 Gbit/s (OC-768) transmission that will require new levels of performance from ICs. The second is the construction of high-speed metropolitan fiber rings bringing an increase in the number of optical connections requiring high-speed ICs. CMOS, SiGe, GaAs and InP are all competing to fulfill these needs.

The report also describes how this market growth and the move towards OC-768 is bringing about changes in the IC industry. Vitesse, Nortel, Conexant, TriQuint, Fujitsu and Anadigics continue to dominate in GaAs ICs, but InP is challenging GaAs with better high-speed performance. As a result, TRW, Vitesse and Nortel have invested significantly in InP technology.

"ICs for Optical Communications: 2.5 Gb/s and Beyond, Market Review and Forecast 2001" is available from Strategies Unlimited – for further information see "www.strategies-u.com".

Mobile phone sales exceed 96 million units

According to Gartner Dataquest, mobile handset sales are on track for 500 million units by the end of 2001, with 96 million units sold in the first quarter. Analysts have warned that changes in handset market dynamics will make market success more difficult this year. The market for new subscribers is decreasing and the replacement handset market is becoming the largest segment of total sales. Pessimism over the prospects for next-gener-



ation mobile terminals and services is also likely to make conditions difficult.

The first quarter of 2001 was an un-

usual one for the market as an unprecedented volume of fourth quarter 2000 handsets remained unsold. Gartner Dataquest estimate that the inventory overhang may have been as high as 30–35 million units.

Nokia continued to gain market share, passing 35% for the first time during the first quarter of 2001. During the same period in 2000, Nokia held 27.9% of the market. Siemens moved ahead of Ericsson in the first quarter of 2001 and now occupy the number three position.

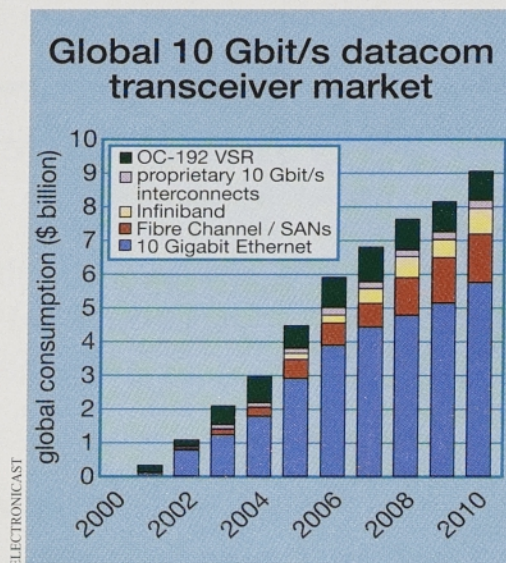
See "www.gartner.com" for further information.

Ten gigabit datacom transceiver market will reach \$9 billion by 2010

A new study from ElectroniCast forecasts that the market for 10 Gbit/s datacom transceivers will grow from \$157 million in 2001 to \$9 billion in 2010. From a low start of 100 000 transceiver units in 2001, the serious roll out of 10 Gbit/s links in 2003 will require 2 million units. Explosive growth will then continue for several years reaching nearly 7 million units in 2005.

The ElectroniCast report breaks down this market across five different applications: OC-192 very short reach, proprietary 10 Gbit/s interconnects, Fibre Channel, Infiniband and 10 Gigabit Ethernet. Suppliers of VCSELs and photodetectors will be key beneficiaries of this growth.

The report predicts that 10 Gigabit



Ethernet will have a strong position throughout, followed by 10 Gbit/s Fibre Channel in the latter half of the forecast. OC-192 very short reach will make an early impact, using low-cost 4 fiber parallel 10 Gbit/s transceivers. The portion of Infiniband requiring 10 Gbit/s transceivers begins to show significant growth after 2005. The first year of serious deployment will be 2002 with a value of \$1.14 billion. Very strong value growth will follow despite declining module prices, though this decline in price will begin to slow value growth beyond 2006.

"The 10 Gbps Datacom Transceiver Market Forecast" is available from ElectroniCast – for further information see "www.electronicast.com".



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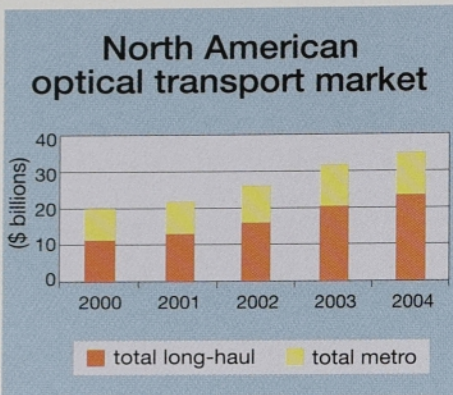
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MARKET NEWS

Growth slows in optical transport market, says RHK



New forecast figures from RHK show that growth in the North American optical transport market will slow from 67%

in 1999–2000 to 10% in 2001. This new figure updates a previous RHK forecast showing a 37% rise for 2001. The forecast predicts a rebound in 2002 as service providers deploy new transport products and long-haul WDM recovers from flat sales in 2001.

The total North American optical transport market will grow from \$19.6 billion in 2000 to \$34.9 billion in 2004. The RHK forecast analyzes the long-haul and metro segments of the market and shows the metro market growing at a compound annual growth rate (CAGR) of 8% to 2004, from \$8.1 billion in 2000. The projection for long-haul over the same period is a CAGR of 20%, from \$11.5 billion in 2000.

"Long Haul Transport and Optical Networks – North America" and "Metro Transport and Optical Networks – North America" are available from RHK – for further information see "www.rhk.com".

Profitable future in European fiber optics

Companies selling components for fiber-optic networks in Europe can look forward to billions of dollars in sales during the next five years, according to a new series of reports from Allied Business Intelligence (ABI). Explaining Europe's unique position, ABI senior vice-president of broadband communications, Marc Liggio, said, "With more recent deregulation and progress in the building of the European Union and a more conducive geography – the population centers are closely tied together – many carriers have seen the opportunity for fiber optics to serve the pan-European market."

The report forecasts that by 2005 the European market sizes in a number of areas will be as follows:

- Semiconductor amplifiers – \$138 million;
- Next-generation optical infrastructure – \$921 million;
- DWDM market – \$753 million;
- Broadband photodiodes – \$169 million;
- VCSELs – \$213 million;
- Fiber-optic receivers – \$1 billion;
- EDFAs – \$722 million.

"The European Fiber Optic Deployment Series" is available from ABI – see "www.alliedworld.com".

Strong growth for wireless data subscriptions

Gartner Dataquest is predicting that the North American wireless data market will grow from 7.3 million subscribers in 2000 to 137.5 million in 2005. This growth will be driven by the nationwide roll-out of packet data networks, increased usage of wireless devices to receive messages and e-mail, cheaper wireless data devices, and the development of company-specific applications to improve the productivity of mobile employees. The growth in wireless infrastructure and handsets will be significant for GaAs MMIC manufacturers.

Handsets will continue to be the most widely used access device with personal digital assistants gaining in popularity as wireless connectivity becomes standard. Application-specific devices such as games with wireless capability, and the addition of QWERTY keyboards to handsets, will also appear during 2002–2003, taking advantage of higher-speed services.

See "www.gartner.com" for further information.

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Osram Opto licenses light-emitting polymers

Cambridge Display Technology (Cambridge, UK) has granted Osram Opto Semiconductors a license to manufacture and sell light-emitting polymer (LEP) displays, in addition to lighting devices. Osram OS says its initial aim is to develop LEP products for mobile, cellular and automotive applications. The company has installed an LEP pilot line in San Jose, California and expects to bring a commercial display manufacturing plant on line in Penang, Malaysia during 2001.

Market research indicates that revenue from LEP (or OLEDs) for displays will grow very quickly from \$24 million last year to \$3.3 billion in 2005. OLEDs offer the potential for great design flexibility, including the ability to create displays on plastic substrates. Compared to LCD displays, OLED displays could benefit a



CDT's organic light emitters have been used by Seiko Epson to demonstrate a 30 000 pixel active matrix full-color cell phone display.

number of near term applications such as mobile phones, PDAs, digital cameras and camcorders, and later generations of PC and consumer products.

"Osram regards LEPs as a key innovation for legible displays with low power consumption and minimum size and weight," said Ruediger Mueller, president and CEO of Osram OS. "We are very pleased that Osram OS has taken this license," added CDT's CEO David Fyfe. "Osram has shown great commitment to the advancement of LEP technology by building a commercial production plant in Malaysia. Together with the commitments already made by CDT's partners, it is clear that a critical mass of well-resourced corporations has concluded that CDT's LEP technology holds the most promise for the future."

Spectra-Physics ramps up high-power laser production capacity

Spectra-Physics Semiconductor Lasers (SPSL, formerly Opto Power Corporation) of Mountain View, California is ramping its production capacity for high-power lasers with the installation of an additional MOCVD reactor. The com-

pany has also taken delivery of a new high-performance facet coater. The new equipment will enable SPSL to meet the increasing demand for lasers used in pumping, graphics, medical and industrial applications. The reactor will also support

high-volume manufacturing of the company's recently introduced ProLite line of high-power 808 nm single and multi-laser bar modules, in addition to the development of new higher power telecom pump chips.

DuPont and Toshiba boost OLED displays

DuPont Displays of Wilmington, Delaware is teaming up with RiTEK Display of Hsinchu, Taiwan to set up a high-volume production facility for the manufacture of polymer-based OLED screens. Employing proprietary technology supplied by DuPont and its wholly-owned subsidiary UNIAX, Dupont will deposit OLEDs onto RiTEK's glass panel substrates up to 370 x 470 mm.

Slated for operation in late 2002, the new facility will be built at RiTEK's current plant, which features an existing monochrome OLED line and is currently undergoing an expansion to include a full-color OLED line. According to RiTEK's CEO, D Wang, the new line will represent the first fully-automatic OLED mass production line in the world.

When operational, the plant will have a capacity for 35 000 large-area OLED panels per month. While initial production will be focused on monochrome displays on glass substrates, DuPont says it is developing full-color, active matrix displays which are based on a flexible plastic substrate.

Toshiba develops color OLED display

Japanese electronics giant Toshiba has developed what it says is the world's first prototype of a full-color polymer-based OLED display. Toshiba's panel is 2.85 inches across the diagonal and contains 25 344 pixels, in addition to supporting 260 000 colors. The company produced the display by applying a light-emitting polymer film onto a low temperature poly-silicon thin-film transistor array using a combination of its proprietary ink-jet printing and solvent-material technologies.

Toshiba originally developed the low temperature poly-silicon process to replace amorphous silicon used in its LCD displays, and says this approach is key to allowing the high carrier mobility required in large active matrix displays for OLEDs. Such matrixes contain a transistor to drive each pixel, and offer superior color, power consumption and picture quality compared to LCDs.

Toshiba's printing approach does not require vacuum deposition and allows easier manufacture of larger area displays, says the company. The display emits light in a wide viewing angle and dispenses with the need for back-lighting – which is required for LCD screens – meaning the screens have the potential to be thinner and lighter.

Commercial production is expected in April 2002, and initial markets will include cellular phones and PDAs, followed later by large displays for PCs.

IQE supplies InP HBT epiwafers to GTRAN

GTRAN has partnered with IQE for the supply of InP HBT epitaxial wafers for use in GTRAN's range of 40 Gbit/s fiber-optic components. The companies say that the collaboration has already resulted in a high-volume HBT wafer fabrication process that exhibits a cut-off frequency of 150 GHz and maximum oscillation frequency of greater than 200 GHz.

GTRAN, which has a headquarters facility in Westlake Village, CA and a product design center in Newbury Park,

CA, is currently developing 10 and 40 Gbit/s components such as transponders for SONET applications. At the recent Optical Fiber Communication conference, the company announced 1310 and 1550 nm transponders compatible with current multi-source agreement configurations for short and intermediate range applications. GTRAN has also developed its own InP device fabrication process for 40 Gbit/s devices, and has a foundry agreement with Global Com-

munication Semiconductors (see *Compound Semiconductor* April 2001, p16).

Commenting on the recent epiwafer supply agreement, IQE's chief technology officer Tom Hierl said: "Using MBE, we have been able to achieve the required base doping levels of $4.0 \times 10^{19}/\text{cm}^3$ necessary for these structures. We have proven this growth capability with both single and double heterojunction designs, using either beryllium or carbon as the base dopant."

Agility selects Brooks to boost productivity

Agility Communications has spent \$1 million to purchase several of Brooks Automation's Computer Integrated Manufacturing systems. The management software will be incorporated into Agility's manufacturing facilities to increase the yield and throughput of the company's tunable laser products. The software includes factory planning, dispatch management and equipment automation, in addition to fault detection programs.

"As Agility builds on the momentum it has generated in the rapidly emerging optical network market, we must ensure that we keep manufacturing costs to a minimum," said Jim Haynes, Agility's CEO. "This purchase immediately gives us an improved process and work-in-progress control in our facility and puts us in an excellent position for future expansion."

RSoft receives Navy support for software

The US Navy has awarded RSoft (Ossining, NY) a two year \$750 000 Phase II SBIR contract to develop advanced simulation programs that evaluate fibers and components used in the design of fiber-optic links. Based on the company's LinkSIM software (see page 99), new programs will be developed and made available commercially for a wide variety of applications. The Navy intends to

use the tool to design components and systems for applications such as Gigabit Ethernet and 10 Gigabit Ethernet.

"The LinkSIM product already enables optical communication links to be optimized, but we will be enhancing it to include sophisticated multi-mode simulations and critical analysis tools for maximum yield and performance," said RSoft's president, LuAnn Scarmozzino.

Emcore ships 15 000 six inch epiwafers

Emcore reports that its Electronic Materials Division has shipped 15 000 six inch HBT and PHEMT transistor wafers over a 12 month period. "The strong demand for our HBT and PHEMT wafers, coupled with our capability to offer high-

volume production, has enabled Emcore to meet its customers' requirements for high-volume, on-time delivery at a low cost," said Reuben Richards, president and CEO.

In more news, the company's Electronic Materials Division has also earned QS-9000 certification for its wafer manufacturing activities, adding to its status as an ISO-9000 supplier.

Epichem expands with new production facility in Massachusetts

Epichem has announced plans to build a new \$5 million facility in Massachusetts for the production of metalorganic compounds. The company opened its plant in

Haverhill, MA, in December 1997, but has found it necessary to build an additional facility due to the "rapid expansion of the compound semiconductor industry." Con-

struction will begin next month with a completion date targeted for April 2002. The two-level complex will have over 30 000 sq. ft of production and office space.

Recent orders for processing equipment

Marconi Optical Components has purchased a 954NT sputtering system from **KDF** of Rockleigh, NJ. Marconi will use

the four-target batch sputtering tool for use in both front- and back-side deposition, to manufacture GaAs devices at its production facility in Caswell in the United Kingdom.

Alpha Industries has ordered additional FCE-2700 evaporation systems

from **Temescal** (Fairfield, CA). The machines will be used to process RFICs for broadband and wireless applications at Alpha's facility in Woburn, MA. Temescal says it has sold 40 evaporator systems into the wireless and optoelectronic sectors so far this year.

Orders for MBE and MOCVD equipment

Procomp Informatics (Hsinchu, Taiwan) is further ramping up its production capacity with the purchase of several

additional **Aixtron** 2600 G3 reactors, to be delivered within 2001. These reactors make up part of the company's order for a total of 10 systems, and will be used in the manufacture of PHEMTs and HBTs.

Motorola has ordered several MBE reactors from **DCA Instruments**, to be

installed in Motorola's facility in Tempe, AZ. The company has ordered a DCA 450 MBE system for compound semiconductor growth, in addition to a DCA M600 MBE reactor and a UHV PECVD system for growing oxide materials. All systems are expected to be delivered this year.

PEOPLE NEWS

Greg Dougherty has been appointed as executive vice-president and chief operating officer of **JDS Uniphase** following the retirement of **Jay Abbe** who was formerly president and COO of the company's WDM, switching and thin-film business group. Dougherty has assumed responsibility for all day-to-day operations of JDS Uniphase. He had been serving as COO of the company's amplification and transmission business group and had previously served as COO of SDL Inc until its merger with JDS Uniphase in February of this year.

Abbe was CEO of Optical Coating Laboratories Inc (OCLI) prior to its merger with JDS Uniphase in February 2000, and served as president and COO of JDS Uniphase prior to the merger with SDL.

Optical component startup **Qusion Technologies** has named **Phillip Wallace**, former Anadigics vice-president of fiber communication products, as its new CEO. Wallace will be responsible for the overall development of the company, which recently opened a new facil-

ity in North Brunswick, NJ and closed a \$9.5 million first funding round. Former CEO and founder of the company Fred Rappaport remains in his role as chairman.

Multiplex, a vertically integrated manufacturer of optoelectronic components and subsystems based in South Plainfield, NJ, has appointed **Chris Peterson** to the position of vice-president of sales and marketing. Prior to joining Multiplex, Peterson spent 15 years with Mitsubishi Electronics America.

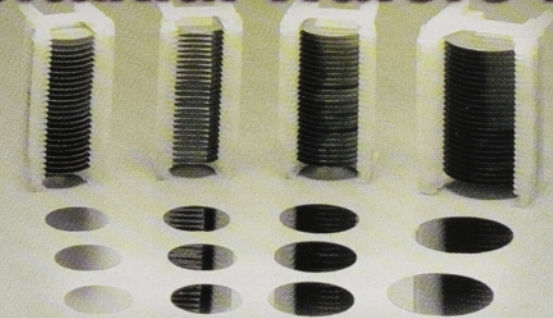
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Porous silicon enables high-Q inductors

Recent efforts to develop semi-insulating silicon substrates and fabricate high-Q inductors have involved the use of porous silicon structures, writes Bob Metzger.

As operating frequency ranges push beyond the 0.9–2.4 GHz bands, which dominate current applications and markets, one of the greatest challenges facing silicon for higher frequency operation is the lack of a truly semi-insulating substrate. Such substrates are critical to fabricating high-Q inductors – a crucial element in almost all monolithically-integrated RF devices.

Unlike GaAs or InP substrates, which can be made semi-insulating, silicon has typically been forced to rely upon the insulating properties of SiO₂ for isolation. While SiO₂ is an excellent DC electrical isolator, effective operation in RF applications requires the SiO₂ to be thick, in order to capacitively isolate it from the underlying conducting silicon substrate.

The challenge to implementing thick SiO₂ layers is two-fold. The first (physics related) challenge results from the difference in the thermal expansion coefficients of silicon and SiO₂. Thick oxides are typically grown in the 1050–1150°C range or deposited by a CVD process. Upon cooling the stresses generated as a result of the difference in thermal expansion coefficients can actually shatter a silicon substrate when the oxide exceeds a thickness of 50 µm.

The second challenge is based on economic and manufacturing considerations. The fabrication costs and the time required to grow (or even deposit by CVD) such thick oxides by any conventional techniques make the implementation of thick oxides unrealistic in a real manufacturing environment.

Enter porous silicon

A potential solution to both these issues is the use of porous silicon. In this material, the lattice has had a large number of its silicon atoms removed by an electrochemical reaction, producing a honeycomb-like structure that exhibits markedly different structural and electrical characteristics

compared to conventional silicon. In particular, porous silicon exhibits a resistivity of the order of 10⁶ Ω.cm, a value approaching the semi-insulating resistivity values achieved in GaAs and InP substrates.

Forming porous silicon

Porous silicon formation is typically carried out in an electrochemical cell using a 25% HF solution (HF:ethanol with a 1:1 volume ratio), with the silicon substrate acting as the anode and a sheet of platinum as the cathode. Anodization, which takes place at room temperature and at a current density of 50 mA/cm², can transform single crystal silicon into porous silicon at a rate of approximately 1–2 µm/min.

One of the greatest challenges facing silicon for higher frequency operation is the lack of a truly semi-insulating substrate.

Initial work on using porous silicon for RF applications focused on the oxidation of the porous silicon layer (Nam and Kwon). Because of the honeycomb structure, rapid thermal oxidation can be performed due to enhanced oxygen diffusion through the porous material: in less than one hour, an oxidized porous silicon layer of 30 µm can be achieved. Using such a layer, a 6.29 nH inductor was fabricated that exhibited a resonant frequency of 13.8 GHz and maximum Q of 13.3.

Such performance characteristics make this a suitable manufacturing process for silicon MMICs operating up to 12 GHz. However, the same thermal expansion coefficient constraints limiting the thickness of thermally grown oxides in single crystal silicon still exist in the case of oxidized porous silicon, limiting the total thickness of the oxidized layer to 50 µm.

Recent research (Kim *et al.*) has focused on leveraging the highly insulating nature of porous silicon. In fact,

it may not be necessary to oxidize the porous layers for RF applications, but merely rely on the insulating nature of the porous silicon itself. The authors prepared porous silicon layers ranging from 50–200 µm in thickness using conventional porous silicon formation on a heavily doped silicon substrate (0.007 Ω.cm). A 2 nm oxide layer was subsequently produced at 300°C to stabilize and passivate all the internal surfaces of the porous silicon.

The use of a highly-doped substrate allows the selective transformation of regions of the silicon substrate into highly resistive layers through the porous silicon process, while other regions of the substrate then become available for conventional silicon CMOS or BJT fabrication.

Pushing silicon RF performance

Spiral inductors with L values of 5.7 nH have been fabricated using the above method. These exhibited maximum Q values of 29 at 7 GHz, and a resonant frequency of greater than 20 GHz. It was observed that the resonant frequency increased with porous silicon thickness, and saturated when the thickness exceeded 120 µm. This was accompanied by a corresponding decrease in total capacitance as the porous silicon thickness increased, with Q increasing monotonically with thickness beyond the 200 µm level.

Values such as these show that porous silicon structures have the potential to push the RF operating window for silicon MMICs well into the 20 GHz range, offering real competition in a regime that many consider the exclusive domain of GaAs and InP.

Further reading

C Nam and Y Kwon 1997 *IEEE Microwave and Guided Wave Letters* **7**(8) 236.
H Kim *et al.* 2001 *IEEE Electron Device Letters* **22**(6) 275.



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Uncooled 980 nm pump laser modules

Fiber-optic systems designers are increasingly concerned with cost, size and power consumption of EDFAs, particularly in metropolitan and cross-connect systems. Thus, highly-efficient pump laser modules that require no active cooling are of great interest. T Pliska and colleagues from Nortel Networks Optical Components in Zurich, Switzerland (*Elec. Lett.* 2001 **37**(1) 33) describe the operation of ridge wave-guide lasers at

980 nm. These devices exhibit an efficiency that is only weakly dependent on increasing temperature.

The authors subjected a submarine-qualified G05 InGaAs/AlGaAs laser packaged in a butterfly module to temperature testing without active cooling. At 10°C, the fiber output power was 250 mW, with a wall-plug efficiency of 35%. When the temperatures are increased to 75° and subsequently 100°C,

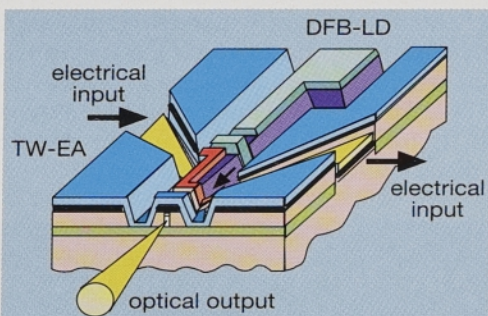
output powers of 150 and 95 mW were obtained, respectively. Under these conditions, the shift in the peak emission wavelength as a function of temperature is only 0.6 nm over a 90°C temperature range. The authors attribute the excellent stability and high power performance to the diode's fiber Bragg grating, which is instrumental in maintaining a high level of reliability across the entire range of operating conditions.

Low cost taper photodiodes with more than 50 GHz bandwidth

Detectors employed in very high data rate optical networking applications feature side-illuminated photodiodes to increase the efficiency-bandwidth product. This represents an improvement compared to top illuminated devices, but at the cost of expensive, sophisticated packaging.

In a recent paper (*Elec. Lett.* 2001 **37**(5) 516), S Demiguel *et al.* describe a new side-illuminated detector that employs a double-stage taper photodiode. The device integrates etched waveguide input facets and anti-reflection coating on wafer.

Conventional contact lithography is used, and the photodiode mesa and tapers are fashioned with RIE. The AR coating is applied on-wafer and patterned with simple chemical etching, which allows on-wafer testing for improved yields and



Taper photodiodes formed in a low cost process exhibit polarization-independent behavior and a bandwidth exceeding 50 GHz.

lower fabrication costs.

The device and tapers are grown on Si substrates by MOVPE. The photodiode consists of a monomode input waveguide

with three thin InGaAsP layers (1.05 μm bandgap wavelength) embedded with a 700 nm thick InP layer.

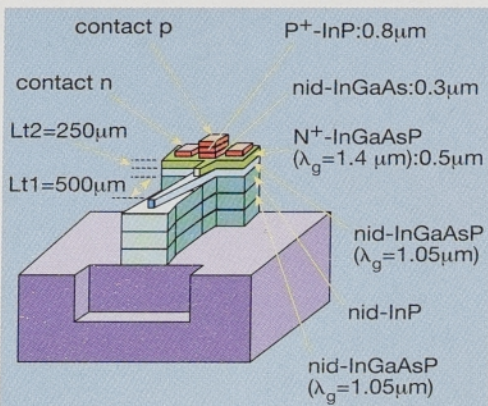
The impinging light is first coupled to a monomode taper where the power is confined to an InGaAsP (1.5 μm bandgap) layer, before being directed to the second multimode InGaAsP taper which has a bandgap of 1.4 μm . The higher bandgap material acts both as an optical matching layer and n-type contact.

At an input wavelength of 1500 nm, the responsivity as a function of the first and second taper length (L_{t1} and L_{t2}) was 0.46 A/W for $L_{t1} = 500 \mu\text{m}$ and $L_{t2} = 250 \mu\text{m}$. This combination led to a polarization figure of less than 0.1 dB for the device. At 50 GHz, the taper photodiode reaches the -1 dB power compression point above +12 dBm.

Travelling wave lasers exceed 50 GHz

Electroabsorption modulators (EA) integrated with DFB lasers represent a key development in high capacity optical networks. However, much wider bandwidths will be required and the limitation caused by device capacitance needs to be overcome for bit rates over 40 Gbit/s.

The authors, from NTT Photonics Laboratories in Japan (Y Akage *et al.* *Elec. Lett.* 2001 **37**(5) 299), describe a novel travelling wave design that integrates the EA and DFB laser with a bandwidth that can be tuned to well over 50 GHz. The device was fabricated on



A travelling wave design has been used for the electrode in an integrated EA-DFB laser to extend the bandwidth to 50 GHz and beyond.

Fe-doped InP to form a co-planar feeding electrode. The InGaAsP/InGaAsP MQW absorption layer of the modulator and the MQW of the DFB are monolithically integrated, and 2 μm wide stripes (etched by RIE) form the co-planar travelling waveguide in the modulator section.

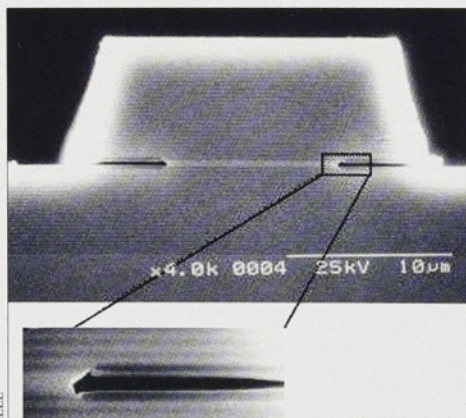
Compared to conventional EA-DFBs with a lumped element electrode, the small signal frequency response falls off more gradually in the new design. Centered on a wavelength of 1552 nm, the optical output power of the emitter was 20 mW, and the extinction ratio of the EA was 21 dB at -3 V bias. The bandwidth is expected to exceed 100 GHz by optimizing the structure.

Selectively etched VCSEL apertures

VCSELs operating in the 1.3–1.55 μm range can be obtained using wafer fusion or metamorphic growth of AlGaAs DBR mirrors. The AlGaAsSb/AlAsSb materials system also offers an attractive option for InP-based monolithic VCSELs, due to the high refractive index of the AlGaAsSb mirrors. However, forming oxide apertures in these devices is difficult due to the slow oxidation rate of AlAsSb.

E Hall and colleagues from UCSB describe the selective etching of AlAsSb DBRs and strained AlGaInAs QWs that make up the active region (*Phot. Tech. Lett.* 2001 **13**(2) 97). Citric acid and hydrogen peroxide was used to attack the active region, leaving the mirrors untouched and forming regions that confine the current and optical mode in the same manner as oxide apertures.

VCSELs with 50 μm apertures were produced with an emission centered on



SEM image of VCSEL structure showing how the active region has been undercut by 6 μm after etching with citric acid and hydrogen peroxide. The mirror periods (inset) are untouched.

1540 nm. Etching experiments showed that reducing the aperture size improved the external quantum efficiency from 9 to 13%. The threshold current was reduced to 13 mA for a 33 μm diameter device (50 μm pillar and 8 μm undercut).

Tunable laser nears power of DFB lasers

To replace DFB lasers in DWDM systems, tunable lasers must provide the same power output. S Debrégeas and co-workers from Opto+ (*Phot. Tech. Lett.* 2001 **13**(1) 4) have demonstrated a two-section DBR laser emitter that achieves 20 mW coupled output power over a 16 nm tuning range.

The device consists of a 1.45 μm quaternary Bragg section to ensure a large index variation for the grating with applied current, and a 30 nm 1.45 μm quaternary for the grating, separated by 120 nm of InP. This ensures a large side-mode suppression ratio of >40 dB. This region is then butt-jointed to the active region, which consists of six 8 nm thick compressively-strained quaternary layers and 10 nm barriers.

The device achieves 20 mW across the 1557–1573 nm range, equivalent to 40 channels with 50 GHz spacing.

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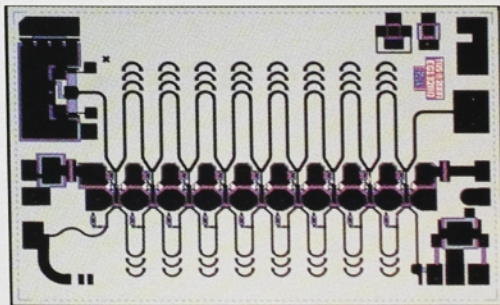
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OPTO PRODUCTS

TriQuint broadband PA targets OC-192

Hillsboro, OR. TriQuint has unveiled a driver/receiver broadband amplifier for 10 Gbit/s DWDM applications. Based on a GaAs PHEMT process, the company's TGA1328 device operates from DC to 20 GHz. The amplifier is also suited to 12 Gbit/s applications that incorporate forward error correction. Flexible operation is provided as either a receive amplifier (17 dB gain), or a modulator driver with an 8 V peak to peak output drive, which affords designs that suit long haul, medium haul and metro fiber systems.

Typical operating conditions include a jitter value of less than 2 ps. For driver applications at 8 V, the power dissipation is 1.2 W, and two cascaded stages are

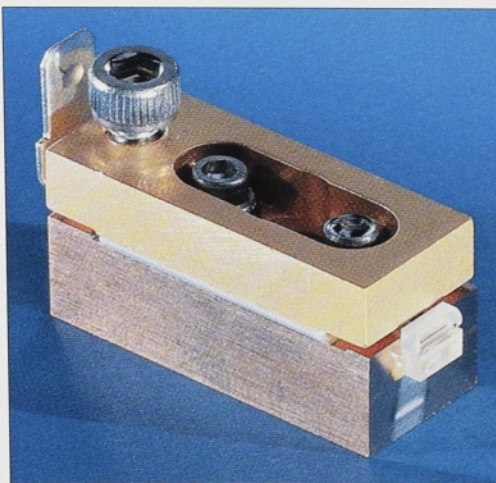


designed to drive 0.5 V input to 8 V peak to peak output. Pre-production quantities are available now at a cost of \$285 in die form (1000 quantities). Volume production is expected in the third quarter.

www.triquint.com

Coherent unveils 5 W diode laser

Santa Clara, CA. Coherent Inc Semiconductor Division (CSD) has introduced a broad-area 810 nm emitter that produces 5 W under CW operation. The new device is an addition to CSD's existing family of aluminum-free near-infrared (790–813 nm) laser diodes and lends itself to integration into direct diodes for thermal, medical and industrial applications. The laser also serves as a pump source for Nd-based diode-pumped



solid-state lasers. Featuring a 500 μm single-stripe structure and mounted on an industry-standard (10.5 mm $\times$ 25 mm) conduction-cooled package, the drive current and compliance voltage are less than 6 A and 2 V, respectively. The spectral line-width is typically less than 2.5 nm, and the beam divergence is 35° $\times$ 10° (both quoted FWHM).

www.coherentinc.com

Agilent offers L-band laser module

Palo Alto, CA. Agilent Technologies has unveiled a new high-power (+13 dBm) DFB laser source module covering the ITU grid (100 GHz spacing) in L-Band DWDM applications. The 81663A employs the company's 816xA VXI plug and play driver, which reduces test time prior to installation.

The new modules contain Agilent's tunable lasers, which reduce inventory and maintenance costs, in addition to providing full remote control via the company's plug and play driver. The module features an output power of 20 mW and is available for \$7350 in the US.

www.agilent.com

Celeritek amplifier drives modulators

Santa Clara, CA. Celeritek has developed a new driver amplifier for external lithium niobate modulators targeting 10 and 40 Gbit/s applications.

The CMM2030-BD wide-band pre-driver amplifier is based on a GaAs PHEMT process and offers an output power of 23 dBm. The wide-band operation allows coverage from 30 KHz to 32 GHz, with a linear gain response of 11 dB.

In addition, a reduced internal jitter figure makes it well suited to high-speed data applications. When used with the company's CMM3020-BD amplifier, an output voltage of 7.5 V peak to peak is achieved. Samples are available in gel packs and priced at \$90 in quantities of 5000.

www.celeritek.com

WIRELESS PRODUCTS

Toshiba cell packs combine functions

San Jose, CA. Toshiba has expanded its family of Cell Pack RFIC packages. Cell packs combine components and are designed to offer multiple functions for mobile RF and Bluetooth devices, eliminating the need for discretely mounted wide-band amplifiers, mixers, attenuators and SPDT switches. The series now includes three new wide-band amplifier packages for low voltage operation, and separate packages for crystal oscillator and SPDT switch functions. Each pack helps to reduce component count and board space.

Toshiba's wide-band amplifier packs, designated TA4011FU/AFE, TA4012FU/AFE and TA4016AFE, are housed in compact SMD packages, and are suited to PDA, cellular phone, portable computer, set-top box and tablet PC applications. For crystal oscillator functions required by all portable communications devices, the company's TA4014FT/FE and TA4015FT/FE packages (6 pin TU6 or ES6) reduce noise and improve stability. For switching, Toshiba's TG2210FT MMIC package targets SPDT functions for Bluetooth devices at 2.4 GHz. Manufactured using the company's GaAs process and packaged in a TU6, this pack features 30 dB of isolation and an insertion loss of 0.4 dB.

www.chips.toshiba.com



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Motorola's SiGe:C device hits market

Phoenix, AZ. Motorola's Semiconductor Products Sector has introduced its first SiGe-based product for the merchant market – an LNA with on-chip bypass switch. Using the company's 0.35 μm RF BiCMOS process, the C-doped SiGe process requires the addition of only one masking step.

The MBC13720 LNA features an on-chip bypass switch to improve the dynamic range, leading to low insertion loss receiver designs, in addition to saving board space and manufacturing costs. Operating from 400–2400 MHz, applications include PCS 1900 MHz cellular phones, as well as 900 and 2400 MHz ISM band designs. Production orders are expected by August.

www.motorola.com/wireless-semi

New 2.5G InGaP HBTs from Anadigics

Warren, NJ. Anadigics has introduced two new InGaP HBT power amplifiers for use in multi-mode, multi-band CDMA handsets that support 2.5G applications. The AWT6105 is specifically designed for cellular



CDMA, CDMA-1X and AMPS applications in the 824–849 MHz range. The AWT6106 targets PCS, MA and CDMA-1X applications operating at 1850–1910 MHz. Both devices combine all of the required components for full compensation and 50 Ω input/output matching. Both the AWT6105 and AWT6106 are 3.5 V DC devices with 6 mm $\times$ 6 mm package footprint, 1.6 mm

profile and low leakage current. The AWT6105 demonstrates 37% PAE in the CDMA bandwidth and 45% in the AMPS bandwidth, while the AWT6106 provides 35% PAE.

www.anadigics.com

RFMD LNA employs bypass switch

Greensboro, NC. RF Micro Devices' RF2369 RFIC functions as a front-end LNA designed for digital cellular applications at 3 V. The device also features a bypass switch that provides an adjustable bias current that can be set externally. This allows a trade-off in RF performance versus current consumption. Typically, the low bypass loss in the switch is 2 dB, which meets IS-98 requirements (including intermodulation distortion testing) using only two gain states and a single logic control line. In high-gain mode, the device exhibits 15.5 dB gain, 11.5 dBm IIP3 and a 1.6 dB noise figure. Manufactured using RFMD's GaAs HBT process, the 2369 is currently shipping at \$0.81 per 10 000 units or more.

"RFMD's customers have requested that a low bypass loss function be added to the LNA to enable a simpler, more robust and cost-effective way of controlling their receiver gain states," said Mike Coady, marketing manager for digital cellular products.

www.rfmd.com

Conexant develops PA for handsets

Newport Beach, CA. Conexant has developed a new PA for W-CDMA mobile handsets. The CX77115 employs the company's proprietary SystemSmart platform to meet the efficiency and spectral linearity requirements of W-CDMA standards. The handset uses information received from the base station to determine how much power is necessary to complete a call, and adjusts the power in the PA accordingly for the minimum amount of current drain. In addition, the power amplifier does not require a regulated reference voltage supply, eliminating the need for a power management IC.



Based on a 50 GHz GaAs HBT process and packaged in a 6 $\times$ 6 mm impedance matched "micro-module", the CX77115 is sampling now with volume production scheduled for the third quarter of 2001.

www.conexant.com

RF Solutions' PA targets 5.8 GHz band

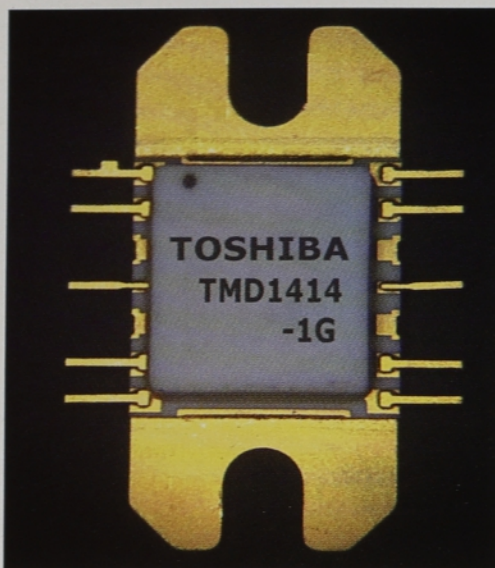
Atlanta, GA. RF Solutions has unveiled a 5.8 GHz PA for broadband wireless access applications. Based on TriQuint's GaAs MESFET process, the RFS1003 is designed for transmit applications in the 5.1–5.9 GHz frequency band. With a P1dB output of 29 dBm, the device can be used as the final stage for fixed wireless applications requiring high transmit linearity.

Limited samples are available now with production volumes expected around the fourth quarter. The company says future 5.8 GHz devices will include down/up-converters and LNA amplifiers/switches.

www.rf-solutions.com

Toshiba VSAT and W-CDMA MMICs

San Jose, CA. Toshiba has added two new MMICs that reduce component count and lower the tuning costs of wireless applications, which include very small aperture terminal (VSAT) satellite communications and W-CDMA power



sockets. The TMD1414-1G is a 1.5 W Ku-band (14.0–14.5 GHz) VSAT amplifier housed in a small semi-hermetic sealed ceramic package internally matched to 50 ohms.

The company's first 3 W S-band

(2.05–2.23 GHz) MMIC for the W-CDMA market is designated the TMD2121-3A. The device's high RF output power also makes it suitable as a final output amplifier for repeater and microcell applications. With –52 dBc IM3 performance in two-tone tests at a single carrier level of 17 dBm, the TMD2121-3A offers the requisite linearity for demanding modulation schemes. Mass production of both devices is expected in June.

www.chips.toshiba.com

TriQuint broadens HBT PA portfolio

Hillsboro, OR. Two new PAs have been introduced for cellular handsets employing the TDMA standard. TriQuint's new GaAs HBT-based TQ7125 and TQ7625 chips provide tri-mode TDMA (IS-136/54 standard) operation, resulting in coverage in more geographic markets.

Operating from a single 2.75 V supply, these new devices also eliminate voltage regulators from the phone, lowering costs and reducing board space. The TQ7125 is an analog and TDMA PA with an output power of 29.5 dBm and PAE of 47%, in addition to an adjacent channel performance figure of better than 29 dBc. The TQ7625 chip is a TDMA PCS PA with an output power of 28.0 dBm and typical efficiency of 40%. Both devices are available in 3 × 3 mm leadless packages.

TriQuint has further broadened its product portfolio with the announcement of a CDMA power amplifier based on SiGe, the first device to spring from a joint development with Atmel (see page 25). The TQ7135 is a 3 V, two-stage HBT for use with IS-95/98 and AMPS compliant phones. The efficiency is 40% and gain 28 dB. Two power modes (94 and 72 mA) are designed to minimize quiescent current in the device, which features a 4 mm × 4 mm footprint.

www.triquint.com



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GaAs remains a hot topic at Mantech

Temperatures reached 100°F in Las Vegas during the 2001 GaAs Mantech Conference. Cooler climates were found inside the meeting rooms where, despite the recent chill in macroeconomic conditions, GaAs remained a hot topic. Marie Meyer reports.

The GaAs industry may be in a slump, but there was little evidence of that fact on display at the 2001 GaAs Mantech Conference, which was held on 21–24 May in Las Vegas, Nevada. The continuing maturation of the GaAs industry, combined with the allure of the venue, contributed to the record turn-out of some 500 visitors, with 100 companies taking part in the exhibit.

Supply chain issues

Last year GaAs fabs were bedeviled by the most fundamental of problems: a shortage of GaAs wafers. The crisis was brought about in part by the phenomenal growth in consumption of GaAs devices, and the well publicized gallium shortage (see *Compound Semiconductor* December 2000, p43). But, as Scott Davis of Sumitomo Electric explained, there were also some interesting, less obvious contributing factors, stemming from the transition to 6 inch GaAs in 1999. According to Davis, the more aggressive wafer suppliers were so eager to win a strategic position with first 6 inch fabs that prices fell to unsustainable levels – as low as \$400/piece in the second half of 1999. At about the same time, suppliers began to notice that yields on 6 inch wafer production were not as high as hoped. “The combination of low prices and yield problems made short-term prospects for profitable business poor,” said Davis. “This led to slower investment in new 6 inch production equipment.” As a result, when demand began to rise, the wafer suppliers were unable to meet it.

When making this point Davis used the phrase “apparent demand” to distinguish it from actual consumption of wafers. Davis noted that there is a significant amount of “double counting” throughout the industry, with all the major wireless handset vendors planning to increase market share, and each device manufac-

Wafer expansion plans

- Sumitomo Electric is increasing capacity 215% from 27 000 4 inch equivalent wafers at the end of 2000 to 58 000 4 inch equivalent wafers at the end of 2001.
- Hitachi Cable is expanding 130% in 2001 to a total capacity of 45 000 4 inch equivalent wafers per month.
- Freiburger plans a 70% expansion in 2001.
- AXT plans a “substantial capacity increase” with a facility in China in 2001.

SUMITOMO ELECTRIC

turer planning to supply the power amplifier for each of those phones. And, of course, “every wafer vendor intends to expand their business at all of the major device fabs”. Reality, of course, has turned out to be not so rosy, and Davis said that the shortage of wafers experienced last year has now turned into rising inventories for device manufacturers and cancelled orders in the first half of this year.

Mixed outlook for GaAs wafers

Davis also noted that supply chain issues are intervening in the LEC vs VGF debate. It is generally held that wafers grown using the VGF technique (or one of its variants) offer superior results for epitaxial structures because of their lower dislocation densities. However, there is still some debate on this issue, and LEC might be seen as still having an edge in terms of its cost and the greater maturity of the technology. But, Davis noted, the long lead times that are required to ramp up LEC production are an additional disadvantage of LEC technology. Most LEC

crystal growth uses high-pressure chambers that require extensive safety testing before they can be brought on line, stretching the total lead-time for commissioning a new LEC puller out to nearly a year. In contrast, the lead-time for new vertical growth furnaces is 4–6 months.

Currently the GaAs wafer supply situation is a “good news, bad news” scenario. The good news is that the shortage is over. “Capacity for 4 and 6 inch wafers is expected to be more than adequate to meet market needs in 2001 and beyond,” said Davis. This is due in part to the fact that the gallium supply situation is rapidly improving (see *Compound Semiconductor* April 2001, p4), as well as the fact that several major GaAs wafer producers have embarked on ambitious expansion plans (see box). The bad news is that relief is also coming from a very unwelcome corner – GaAs fabs are delaying or canceling wafer orders in light of the slowdown in the wireless business. But, Davis reported, the construction of new facilities by the wafer manufacturers is still going through – albeit with a moderation of the rate at which new capital equipment is being installed – so that the suppliers will be ready to respond when the market picks up again.

Recycling GaAs wafers

In a separate presentation, Marty Brophy of TriQuint reported another measure that could make a positive impact on the supply chain: recycling of processed GaAs wafers. TriQuint is working with the Swiss company Picopolish to demonstrate that scrapped GaAs wafers can be stripped and repolished. While this process is common for producing “mechanical” wafers that can be used for equipment testing and other experiments, TriQuint is exploring whether this method can produce prime wafers for use in its production process. Brophy reported that

less than 10 μm of thickness is lost in the recycling process, and the wafers show low defect levels and no metallic contaminants such as gold or titanium due to strip and/or etch residues. No noticeable effect on parametric test results or device yields has been detected when the recycled wafers are processed for the second time. TriQuint and Picopollish intend to continue this work using much larger quantities of wafers to discover whether there are any subtle effects that haven't been revealed by these early trials.

GaAs vs silicon

In the plenary session, Y K Chen of Bell Laboratories reviewed the choice-of-technology issues in the high-speed IC area, one of the critical technologies for optical networks. Here, compound semiconductor devices serve as technologies that enable higher data rate networks to be implemented, but eventually silicon narrows the performance gap and moves in on the market. The section beginning on page 48 gives a more detailed explanation. The 2.5 Gbit/s market has already been "siliconized" and the same is now happening in the 10 Gbit/s market. The 40 Gbit/s market, however, provides many exciting opportunities for compound semiconductor technologies, including the first high volume application of InP circuits.

Another GaAs vs silicon battle is being waged in the area of power devices for wireless infrastructure markets – meaning base stations and related equipment, as opposed to handsets. Here the competition comes from silicon LDMOS (laterally diffused metal oxide semiconductor). Lynelle McKay of Motorola reported that "every base station power amplifier design team in the world is currently debating the "LDMOS or GaAs?" question". Not too long ago, it seemed that the fight was already lost. In the mid-1990s LDMOS was shown to provide superior linearity perfectly suited to the relatively low-frequency, linear-cellular modulation formats in use at that time. However, the deployment of 3G cellular in the next few years may present an opportunity for GaAs to make up lost ground. These networks will have the highest frequency operating system of any mobile scheme to date. Most of the world, led by Europe, has allocated the 2.52–2.67 GHz band. The US is still contemplating the option of using a lower frequency range, but it

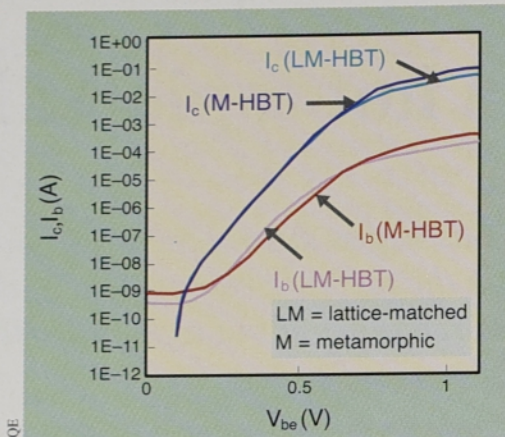


Fig. 1. Gummel plots for large-area metamorphic and lattice-matched single HBT devices.

is generally believed that the FCC will eventually come down in favor of synchronizing with the rest of the world. If so, GaAs will have a significant advantage because of the higher frequency. The decision is an important one and will be watched very closely, because although LDMOS can operate at up to 2.6 GHz (far higher than previously thought), efficiency is greatly compromised above 2.2 GHz.

In the meantime, power GaAs suppliers are trying to reclaim lost market share by reducing prices to achieve parity with LDMOS on a \$/W basis. McKay reported that the prices of power GaAs devices have dropped by more than 50% in the last year.

MEMS applications

Olga Blum Spahn from Sandia National Laboratories discussed the promise of GaAs-based MEMS structures. At present, the potential size of the MEMS market is only poorly understood. Spahn noted that when commercialization possibilities do open up, III-Vs should be considered as a candidate material system. They provide two major advantages over silicon: a very rich process chemistry, with numerous selective etch options; and the ability to integrate with optoelectronic devices. Spahn said, "The general scepticism surrounding the mechanical properties of compound semiconductors is largely unfounded...while not as strong as silicon, they are sufficiently robust for most MEMS applications."

Also in the MEMS area, S C Shen of the University of Illinois reported results from low-voltage MEMS switches fabricated on GaAs using a five-mask layer process that is compatible with standard

GaAs MESFET processing. Low-insertion-loss, high-isolation MEMS switches are considered to be one of the most attractive RF applications of MEMS technology. Achieving low actuation voltages is the key. In this report the minimum operational voltage was 9.5 V compared with typical reports that are in the 30–50 V range.

Metamorphic devices

The next weapon that the III-V industry can wield against silicon is InP technology. But, as Bill Hoke of Raytheon told the audience, a 4 inch InP wafer currently costs more than \$1000, compared with \$450 for a 6 inch GaAs wafer. Moreover, since 6 inch InP wafers are not available, fabs are not able to employ the newest, most sophisticated processing tools. As the diameter of InP substrates is increased, the fragility of InP may become a bigger issue, particularly for processes requiring backside thinning and via holes. Therefore achieving "InP-like" performance out of structures grown on GaAs wafers using metamorphic buffer layers is an attractive prospect.

Hoke reported that microwave measurements on an MHEMT device with a 0.13 μm gate and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ channel layer yielded an extrapolated peak f_T and f_{max} of 235 GHz and 210 GHz, respectively. Metamorphic devices may even provide some design flexibility that isn't possible in InP-based devices. Hoke gave as an example an MHEMT that contains 30–40% indium in the channel and barrier layers. This composition is attractive for increasing the breakdown voltage of the high-gain, high-frequency, low-noise performance of the InP HEMT. This structure cannot be obtained by pseudomorphic growth on GaAs or InP substrates due to combined strain from the barrier and channel layers. A comparison of power-density results at 35 GHz shows that MHEMT devices exhibit a clear improvement over InP HEMTs.

HEMTs are not the only devices that can be produced on metamorphic wafers. Dimitri Lubyshev of IQE reported on the growth of metamorphic HBT structures on GaAs substrates that exhibited DC characteristics comparable to conventional HBTs grown lattice-matched to InP substrates. Figure 1 on page 42 shows Gummel plots for metamorphic HBTs (M-HBTs) and conventional lattice-matched devices (LM-HBTs). Lubyshev

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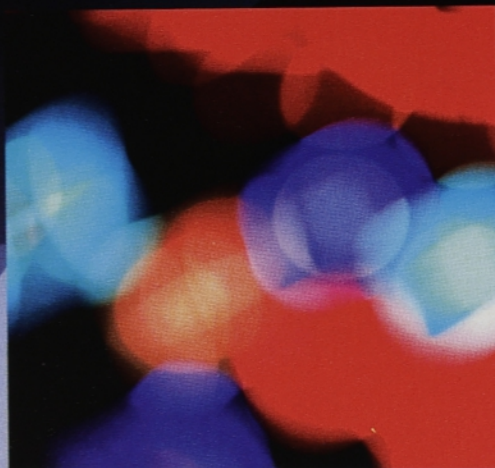
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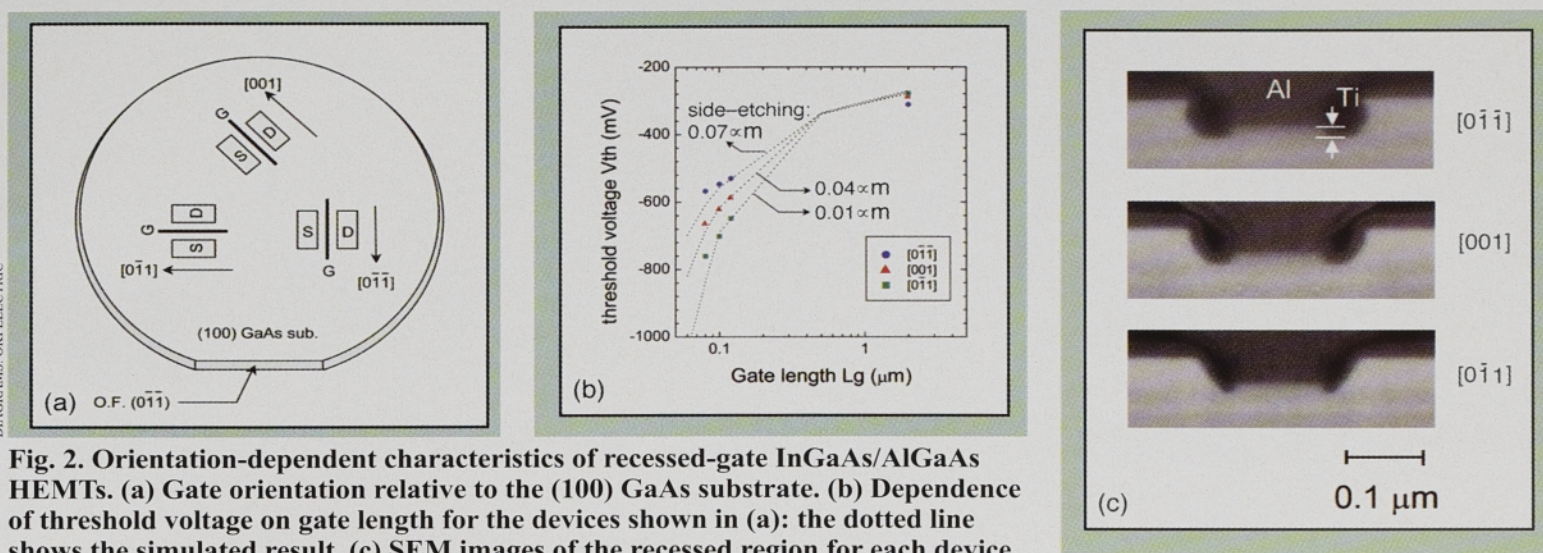


Fig. 2. Orientation-dependent characteristics of recessed-gate InGaAs/AlGaAs HEMTs. (a) Gate orientation relative to the (100) GaAs substrate. (b) Dependence of threshold voltage on gate length for the devices shown in (a): the dotted line shows the simulated result. (c) SEM images of the recessed region for each device.

reported that there was no indication of p-n junction degradation due to interfacial roughness or diffusion of the Be dopant.

Orientation dependence

In a very interesting presentation from Oki Electric, Tomoyuki Ohshima discussed the effect of the gate orientation relative to the substrate for pseudomorphic InGaAs/AlGaAs HEMTs. For FET devices it is understood the electrical characteristics of the device are gate-orientation-dependent because of the piezoelectric effect (a well-understood phenomenon wherein the influence of the source and drain regions on the channel grows as gate length is reduced). Oki has also observed a relationship in HEMT devices. Figure 2 shows the dependence of threshold voltage on gate length for HEMTs with three different orientations. Threshold voltage decreases as the gate length is reduced, due to the short channel effect. However, the extent of the effect does seem to be related to substrate orientation. Ohshima observed that this is not due to the piezoelectric effect because the threshold voltage did not change before and after the deposition of the silicon nitride film. Instead, it appears to be related to the dependence of etching rate on crystal orientation. Cross-sectional SEM analysis reveals that the profiles of the recessed walls vary significantly, from nearly vertical in the case of the [0-1-1] device to sharply sloping in the case of the [0-11] oriented device. Oki observed that other characteristics of HEMTs such as cut-off frequency (f_T), transconductance and gate-to-drain breakdown voltage were also orientation-dependent.

New tools and techniques

Several of the Mantech presentations dealt with new tools for processing and inspection. Yaozu Wang reported on a yield-enhancement methodology applied to Anadigics' new 6 inch GaAs fab using an August Technology NSX system coupled with a defect correlation program that was developed in house. The NSX is an automated inspection tool that can be used to run full wafer inspection and to monitor defects at the critical process steps for MESFETs, HBTs and HEMTs. It correlates the defects-to-die sort yield and parametric results at probe testing, hence improving the yield by reducing the critical defect density. Wang noted that when inspections are done using manual methods, the quality of the results depends largely upon the ability and experience of the inspection operator, and the data gathered are difficult to correlate with yield results.

Paul Miller of TriQuint discussed a dry replacement for conventional wet, solvent-based techniques for metal lift-off process steps. The tool used was a system produced by Eco-Snow that generates a stream of solid CO_2 particles. In traditional GaAs device manufacturing, interconnect formation uses evaporated or sputtered metal deposited over patterned resist. The bulk of resist and metal is then removed by a wet solvent lift-off process, followed by a high-pressure DI water or solvent spray to remove residual metal. However, the Eco-Snow system relies primarily on a physical mechanism for the removal of residues, eliminating the possibility of metal residues being left behind.

S K Jones from Marconi Caswell dis-

cussed importing a familiar technique from the silicon industry: process and device modeling and simulation using TCAD (technology computer-aided design). In its annual roadmap for the silicon semiconductor industry, ITRS reports that the use of TCAD can deliver annual cost reductions of 20–35%. Nevertheless, Jones said, "While device modeling is used widely in the III-V industry, process modeling is still rather scarce." He explained that Marconi adapted commercial software tools from the silicon industry for use in developing its new 6 inch GaAs PHEMT process. Device geometry and topography were modeled through sequential deposition and etch stages, with the metal evaporation, (PE)CVD nitride deposition, and wet and dry (plasma) etch steps being the specific processes modeled. No attempt was made to model the lithography, due to the lack of detailed experimental calibration required for accurate models of the resist exposure and development. Jones explained how the process modeling was used to choose between three gate processes on the basis of a cost/benefit analysis, with a combined e-beam and optical lithography process being the winner.

Bonding to wafer carriers

Finally, a presentation from Austrian processing equipment manufacturer EV Group and the Max Planck Institute of Germany discussed different kinds of wafer bonding for GaAs processing. Reversible wafer bonding, done using either wax or an adhesive heat or UV release film, is used during backside thinning and lithography. The GaAs wafer is

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coated uniformly with wax and bonded to a carrier substrate such as quartz or Si that improves mechanical strength, while the wax protects the active surface of the device. This is referred to as "reversible" bonding because the device and carrier wafers can be de-bonded once the back-side processing is complete.

Permanent or direct wafer bonding (DWB) can be used for integration of heterogeneous materials, such as GaAs on Si. In the process developed by the EV Group "spin-on-glass" (SOG) layers are used as the bonding material, as shown in figure 3. One of the biggest problems in mating silicon with GaAs is the thermal mismatch – the thermal expansion

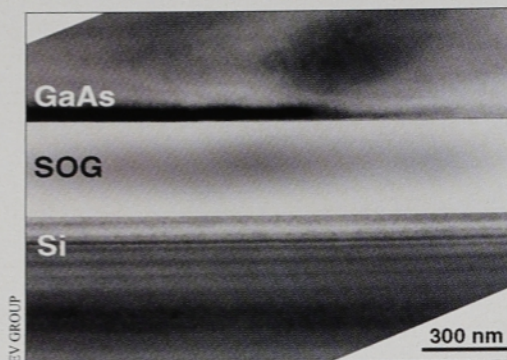


Fig. 3. Cross-sectional TEM image of a GaAs/SOG/Si bonded wafer.

coefficient of GaAs is twice that of Si. Therefore the performance of these

wafers during annealing is a topic of concern. The results presented showed good results for temperatures up to 280 °C – above that, they de-bond or shatter. However, after the GaAs portion of the bonded wafer is thinned to 40 µm via grinding and then polished by CMP to a final thickness of 5–10 µm, the bonded pairs could be heated to more than 400 °C. At this point the contribution of the back-thinned GaAs wafer to the thermally induced stress on the heterostructure becomes negligible.

The next GaAs Mantech conference will be on 8–11 April, 2002 at the Sheraton Hotel & Marina, San Diego, CA.

Technology choices for high-speed ICs

The speed of an electronic circuit is limited primarily by the cut-off frequency of the transistors used to build it. The common figures of merit are the current gain cut-off frequency, or f_T , and the maximum oscillation frequency, f_{max} . Analog circuits are usually evaluated by f_{max} , while f_T is a good indicator of the switching speed of logic circuits.

There are many technologies that can be used to implement the high-speed ASICs (application specific integrated circuits) that are required for optical networks. As a rule of thumb, the transistor technology chosen must provide f_T and f_{max} better than four times the bit rate of the network in order to achieve the required switched speeds and proper system margins. In other words, OC-192 networks, which operate at a bit rate of 10 Gbit/s, require ASICs that are fabricated from a material system that can provide an f_T and f_{max} of at least 40 GHz. However, it is also possible to use novel circuit technologies, such as distributed design, and the use of multiple phase half-rate clocks to reduce the cut-off frequency requirement to twice the bit rate.

The f_T of field-effect transistors, such as Si MOSFETs, GaAs MESFETs and GaAs or InP HEMTs, is limited by the carrier transit delay in the gate region. This transit time is determined by the lateral dimension of the gate electrode and by the electron velocity in the host material – giving compound semiconductors an intrinsic advantage. But silicon manu-

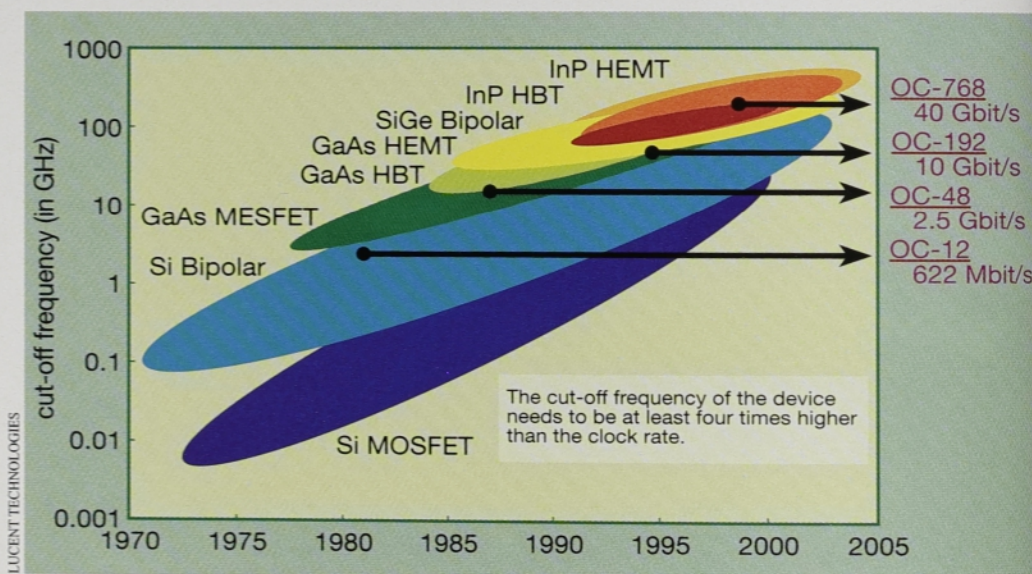


Fig. 4. Technology roadmap for lightwave electronics.

facturers can fight back by employing ever-more sophisticated fine-line lithography tools. For the other major category of transistors, bipolar devices, the cut-off frequency is determined mainly by the vertical layer thickness and less by the lateral dimensions.

Figure 4 shows the trends in cut-off frequencies for IC technologies over several decades, as indicated by the best f_T data reported by research laboratories as well as the typical f_T data in production lines. The pattern that emerges shows that the more advanced technologies are significantly faster than CMOS at the outset, and these speeds improve over time.

However, CMOS improves at a faster rate, due largely to the greater amount of resources brought to bear on the problem, and the aforementioned decreases in the lithography line widths.

In the real world, this translates into silicon muscling into markets that were established using compound semiconductor technologies. For example, OC-48 networks, which operate at 2.5 Gbit/s, were launched in the late 1980s using GaAs MESFETs and silicon BJTs because at that time they were the only production-worthy technologies with f_T values of 10 GHz or more (recall the four-times rule-of-thumb mentioned previ-

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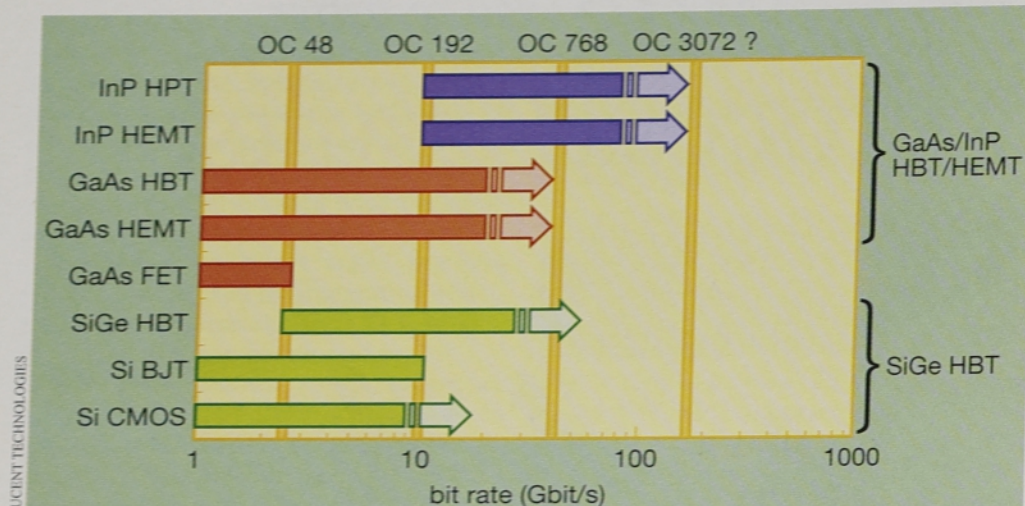


Fig. 5. IC technologies for lightwave communications.

ously). But, as CMOS technology improved in the late 1990s, most of the OC-48 ASIC market was taken over by silicon circuits that could now offer not only the necessary f_T , but also lower cost, lower power consumption and higher integration capabilities.

Today's market is dominated by OC-192, which has a 10 Gbit/s data rate. Most of the ASICs for these systems are implemented in GaAs and SiGe technologies with 0.5 μm line widths. But encroachment by advanced 0.16 μm CMOS technology has already begun – the narrower

line width making up for silicon's lower intrinsic speed.

What lies ahead? Currently 40 Gbit/s ASICs for the next-generation OC-768 networks are still in the early stages of development. As shown in figure 5, there are many candidate technologies for this regime – and, as of now, silicon CMOS is not one of them. In fact, there is no single technology that is capable of performing all the circuit functions and meeting all the performance requirements of a 40 Gbit/s transceiver. Thus we will see several ASIC technologies combined into transceiver modules. For 40 Gbit/s ASICs it is preferable to use a bipolar technology, either InP or SiGe, to realize low-power, high-speed digital circuits with high transistor counts, while employing GaAs or InP HEMT technology for analog functions that require low noise amplification and high-voltage driving capability.

Based on a presentation by YK Chen, Lucent Technologies' Bell Laboratories.

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Princeton Lightwave shows its power

After operating in stealth mode for almost a year, Princeton Lightwave has now revealed an impressive range of high-power InP-based lasers, writes Peter Gwynne.

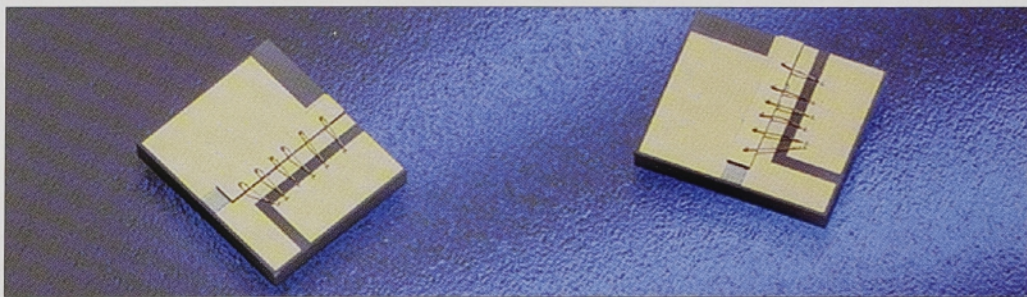
For several months after its founding in May 2000, Princeton Lightwave Inc (PLI) hid its light under a bushel. Then, starting in March this year, the company from Cranbury, New Jersey started to take that light, and the optical products related to it, into the open. The company has announced a series of new high-performance active components based on indium phosphide, designed for applications in long haul and metro networks.

"We're looking at a number of different areas, including modulators and semiconductor optical amplifiers," says Pamela York, vice-president of corporate development at PLI. "At present, we're focusing on achieving the highest power levels for pump lasers. We are selling to telecom companies and their system suppliers, to component manufacturers, and to chip-on-carrier customers. PLI is committed to being an industry leader."

A start-up with products

Despite its low profile, the company has been selling its WaveRider broadband gain chip since its inception. The InP laser chip, which is supplied as a chip-on-carrier subassembly (see photo), is designed to be incorporated into customers' external cavity lasers (ECLs) to form broadly tunable source lasers. ECLs, in which wavelength tuning is provided by adjusting the external cavity in a variety of ways, are commercially available from companies such as Iolon, Blue Sky Research and New Focus (see *Compound Semiconductor* April 2001, p24). PLI says that the WaveRider product permits customers to reduce the size of their products and the complexity of their manufacturing process. According to York, PLI had revenues of "several million dollars" last year.

The WaveRider was officially announced in March, along with two other new families of products. The WaveHarp



Chip-on-carrier sub-assemblies are used for all three of PLI's product lines.

is an advanced distributed feedback laser that emits up to several hundred mW of power in a narrow spectral band. By integrating the grating on the laser chip, this approach eliminates the need for an external fiber Bragg grating to achieve wavelength stabilization, thereby reducing costs. At the CLEO meeting in May, PLI claimed a record output power of 340 mW for a 1550 nm DFB laser coupled into a singlemode optical fiber.

WavePower pump lasers, meanwhile, are available at 14xx nanometers for Raman amplifiers and 1480 nm for EDFAs. The pump power of up to 500 mW in a module provides higher amplifier gain and more robust amplifiers.

The WavePower platform provides PLI with a route into an extremely promising market that, by giving customers longer transmission distances without optical regeneration, promises more bandwidth at lower network costs. Indeed, the company recently announced it had become the first to reach the one Watt power level from a single narrow-stripe pump laser chip. "Last year's record was 700 mW," points out senior analyst Vladimir Kozlov of RHK, a company that analyzes the telecommunications industry. "They aim to provide existing products at lower cost with higher power," adds Jay Patel, a senior analyst at The Yankee Group. "If delivered, the expertise they claim could be pretty significant."

The market for such pump lasers is also significant. "This will be one of the fastest growing segments in the next few years," Kozlov says. "PLI is really targeting the sweet spot, and the product should be substantially better than what's available on the market today."

Roots at Sarnoff

That market potential owes much to PLI's roots in the Sarnoff Corporation, a wholly owned subsidiary of SRI International that is the part of the old RCA Laboratories not bought by GE. Sarnoff produces, incubates and commercializes electronic, biomedical and information technologies. "Sarnoff was one of two federally funded organizations in the United States being paid to develop ultra-high power lasers," recalls York, who spent time on Sarnoff's staff. "Our high-power laser technology seemed a good opportunity to spin off. We had really tremendous results with high-power lasers around 1480 nm, and few companies seemed able to deliver the power levels we can provide."

That promise persuaded Sarnoff to spin off PLI as a privately held venture-backed company. Moving out with it were York, four other co-founders, and plenty of intellectual property. "We are unusual for a start-up in that we have an extremely broad background in technology developed at Sarnoff," says John Connolly, a co-founder who is now PLI's vice presi-

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dent of engineering. "About 27 patents moved into the company from Sarnoff."

The breadth of the start-up company's technology stemmed from an exclusive license from Sarnoff for active components. The license comprises developments in lasers, detectors, modulators, semiconductor optical amplifiers and other active components, as well as advanced device and fabrication technology for an InP-based integration platform.

Facilities and personnel

The new company had other assets, in terms of people and infrastructure, on which it has continued to build in the past year. Its vice-president of research, for example, is Dmitri Garbuzov, a renowned laser physicist who trained at St Petersburg's Ioffe Physico-Technical Institute with Zhores Alferov, winner of a share of last year's Nobel prize in physics. Raymond Menna, who oversees materials growth, trained under another Nobel laureate, Daniel Tsui, who shared the physics prize in 1998. Menna has five crystal growers at his disposal. Altogether, PLI's staff of 50 includes a 25-person engineering team, of which 60% have PhDs. Nancy Morris, the fifth co-founder of PLI, has over 20 years experience in active optical components and materials technology gained at Laser Diode Inc and Sarnoff Corp.

Pam York also notes that PLI has excellent facilities. The company's 90 000 sq. ft of space, expandable to 150 000 sq. ft, includes state-of-the-art automation and modular tooling for batch manufacturing and rapid retooling for new product lines. "We have two reactors, in which we can do 500 wafer starts per week," says York, who was a crystal grower.

Technology choices

Initially, the leadership of the new company faced the issue of which technology to pursue, and decided to focus on indium phosphide. "Every wavelength that you need for telecommunications can be done in InP," explains Connolly. "It enables the merger of active and passive technology that will be the key when moving forward with optical integrated chips."

Another early decision involved the wavelength on which the firm should concentrate. The question was this: should PLI work in the 980 or 1480 nm range? "Even though we had the world's power record at 980 nm, that market was fairly

crowded, and the engineering had already been done," explains Connolly. "We felt we could really improve the power capability in the 1480 nm wavelength range." In fact, high output power is a key feature of PLI's products. "The primary focus that we took to start the company was the power capability that we always prided ourselves on at Sarnoff," says Connolly. "As you move power levels up, the number of dollars per photon will fall, driving down the cost of the network."

PLI also made the conscious business decision to enter the marketplace at the high end. "We'll be able to compete across numerous market segments," Connolly says. "Our technology allows us to compete at the high end of the market, while our automated chip-on-carrier line provides the opportunity to go downmarket."

Market opportunities

The commercial space in which PLI operates is already becoming crowded. Potential rivals include Furukawa Electric (currently the market leader for 14xx nm pumps), Corning, JDS Uniphase and Nortel Networks. However, the market shows signs of expanding rapidly. According to RHK, the markets for 1480 nm and 14xx nm pump lasers and for tunable source lasers will both grow very rapidly in the next three years. PLI seems ready for the challenge. "The company has been in a stealth mode," says Patel. "But it has a market message now. This is the right timing for the company."

Future growth

What comes next? The company expects to triple its head count by the end of the year, and also has high ambitions for its technology and products. "We're really pushing integration, both hybrid and monolithic," says York. "We see hybrid integration really coming on strong over the next two years. We think monolithic integration is several years out, although we're pushing it as fast as we can; it will make a huge difference."

"We really have a cost advantage with our manufacturing facilities," York continues. "With low cost and high performance we have the ability to be a major player. We have the capacity to deliver tens of millions of chips, and hundreds of thousands of modules."

Peter Gwynne is a freelance technology writer based in Massachusetts.

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Exotic compounds, new solutions to old problems and record-breaking device performance were just some of the things discussed at IPRM'01. Colombo Bolognesi reports.

The Thirteenth International Conference on Indium Phosphide and Related Materials (IPRM) was held May 14–18 in Nara, Japan. A new attendance record was set with some 470 participants, including 210 from outside Japan.

This year's IPRM conference program was rich with exploratory work on novel electronic/optoelectronic materials, including GaInNAsSb/GaNAs QWs, InMnAsSb/InSb heterostructures, GaInNP, TlInGaAs/InP double heterostructures and GaAs_{1-x}Bi_x which features a temperature-insensitive band gap.

Optical devices

Arakawa *et al.* from the Furukawa Electric Company reported the use of CBr₄ to perform *in situ* etching of InP in MOCVD reactors. Using SiN stripe masks at a temperature of 600°C, it was found that InP is easily etched while AlGaInAs layers can be used as effective etch stop layers. For InP the etch rate was found to be proportional to the CBr₄ flow in the chamber and etch rates varied with group III element. In etched the fastest, followed by Ga then Al. The etched surfaces were smooth enough for epitaxial regrowth with a reduced defect density and a lower residual oxygen concentration, as observed by SIMS measurements.

Lee *et al.* from Osaka University reported temperature-stable TlInGaAs/InP double heterostructure (DH) LEDs grown on (100) InP substrates with a Tl composition of 6%. The DH LEDs were operated up to 340°C near 1.58 µm and exhibited an electroluminescence temperature coefficient of -0.09 meV/K. The improved temperature stability could turn out to be an important asset for WDM laser diodes.

A new type of electroabsorption (EA) modulator for high bit rate WDM applications was proposed and simulated in a presentation by Wakita *et al.* from Chubu

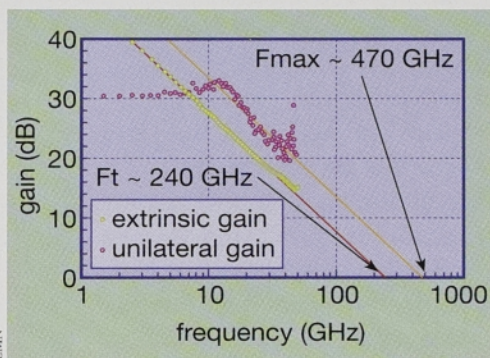


Fig. 1. Gain versus frequency for a 70 nm × 100 µm gate HEMT on the IEMN optimized layer structure.

University. The device consists of a transverse p-i-n structure using a strain-compensated AlGaInAs MQW stack grown on InP. This allows the field to be applied in a direction parallel to the stack layers. The structure is believed to allow greater incident optical power levels since the carriers generated flow parallel to the layers instead of escaping the MQW stack

Endoh *et al.* from Fujitsu reported the fastest transistor ever built – a 25 nm gate InP HEMT with an f_t value of 396 GHz.

by crossing the barriers as in classical modulators. The predicted device performance includes a phenomenal 3 dB bandwidth of 250 GHz and a driving voltage of less than 2 V for a 20 dB extinction ratio.

Takeuchi from NTT presented work on an ultrafast EA modulator integrated with a DFB laser in both lumped and traveling-wave electrode configurations. The traveling-wave EA-DFB exhibited a bandwidth of over 50 GHz as well as 40 Gbit/s eye diagrams.

Ougazzaden *et al.* from Agere demonstrated tandem EA modulators suitable for 40 Gbit/s transmission over long distances using return-to-zero modulation.

DC extinction ratios of 28 and 22 dB were measured at -3 V for 120 and 80 µm long devices, respectively. The 3 dB bandwidth for the 80 µm device was 40.5 GHz and a dynamic extinction ratio of 13 dB was achieved with a 2.5V_{pp} drive at 40 GHz.

Electronic devices

In the field of HBTs, a group from Simon Fraser University reported InP/GaAsSb/InP DHBTs with both f_t and f_{max} values greater than 300 GHz. These operated at record current densities in excess of 500 kA/cm².

Mathew *et al.* from The University of California at Santa Barbara (UCSB) reported transferred substrate AlInAs/GaInAs/InP DHBTs with $f_t = 165$ GHz and $f_{max} = 300$ GHz. UCSB also reclaimed the fastest ECL static frequency divider record in a post-deadline paper.

A couple of very impressive papers from l'Institut d'Électronique et de Microélectronique du Nord (IEMN, France) revealed that better scaling can further improve the characteristics of sub-100 nm gate HEMTs built on metamorphic and/or InP substrates. The group showed results from a "standard structure" and an "optimized structure", both grown by MBE.

The standard structure consisted of a 20 nm InGaAs channel (53% In), with a 5e12 cm⁻² Si delta-doping plane separated from the channel by a 5 nm InAlAs spacer layer. A 12 nm InAlAs (52% Al) top barrier was capped with a 10 nm n⁺ InGaAs layer.

In the optimized structure, the top barrier was reduced to 8 nm and Al content raised to 65%. The Si delta-doping plane was increased to 6e12 cm⁻² with a 3 nm spacer. The In content of the channel was raised to 65%.

Both structures gave well behaved HEMTs, with the standard structure giving an f_t of 270 GHz and f_{max} of 260 GHz for a 60 nm gate finger. The optimized

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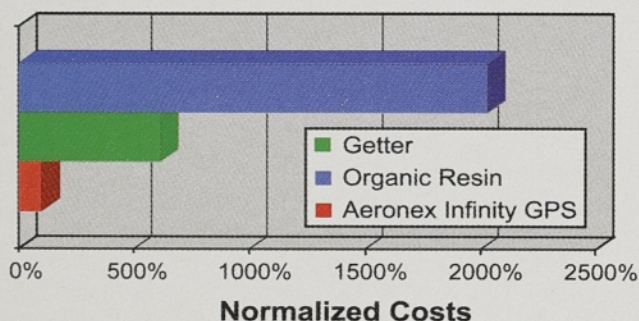
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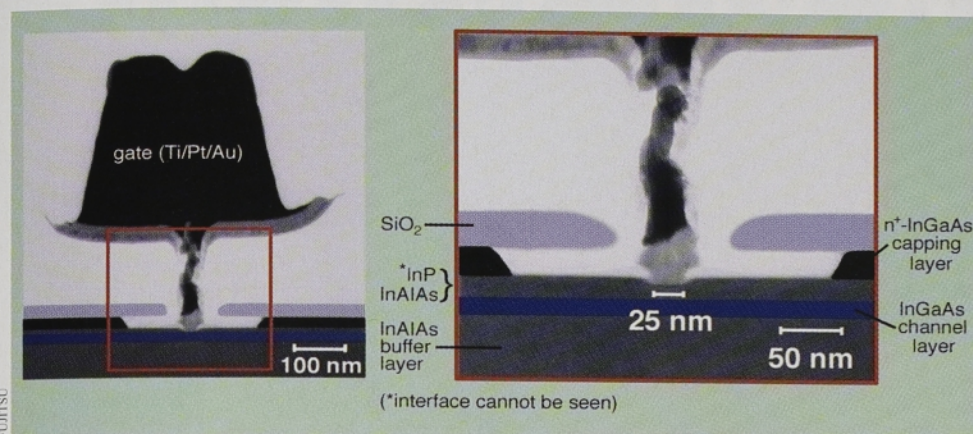


Fig. 2. Cross-section SEM image of a 25 nm T-gate HEMT, enlarged at right. Source and drain electrodes are not seen in this image.

structure gave an f_t of 240 GHz and an f_{max} of 470 GHz for a 70 nm gate finger (see figure 1).

Endoh *et al.* from Fujitsu reported using a similar layer structure (see figure 2) to the IEMN group to fabricate the fastest transistor ever built. This HEMT had a short-circuit current f_t of 396 GHz. The device featured a 25 nm gate and operated at V_{DS} of 1 V with a $2\mu m$ source-drain separation.

Are we running out of indium?

The evening rump session theme was "InP-based materials and device research for the Internet era". This attempted to plot a course of development for InP research towards 2010. The rump panel speakers were Sawada (Sumitomo), Nelson (IQE), Oki (TRW), Kasukawa (Furukawa), Subbanna (IBM) and Wada (FESTA).

Sawada launched the evening discussion by stating that his company faces market demands for higher quantities of InP substrates with larger diameters and improved flatness and cleanliness. The discussion soon migrated to the question of whether or not the world supply of indium metal can sustain the InP industry. The bad news was, it appears from the discussion, that the world may run out of indium within the next 20 years. The better news is that InP substrates consume only about 1% of indium worldwide, while the major user of indium metal is indium tin oxide (ITO). The supply of indium for InP technology may, in the long run, depend on the ability to recycle ITO. Thinking back on that discussion and recalling Marie Meyer's survey of gallium supply problems (see *Compound*

Semiconductor Dec 2000/Jan 2001, p43) may tempt one to play devil's advocate and ask whether God really intended us to work with III-Vs at all after he gave us silicon – heresy!

Nelson (IQE) painted a bright financial picture for InP devices with an estimated \$50 billion market by 2005. Nelson also suggested that metamorphic buffers on larger area, cheaper GaAs substrates might be a clever way to work around the indium supply problem. This comment prompted a query from Agilent's Tom Low who pointed out that some devices are temperature sensitive and benefit from the higher thermal conductivity of InP compared to GaAs. This further raises the question of how the thermal properties of metamorphics compare to InP substrates.

Oki (TRW) provided an interesting point of view with his perception of the over-capacity in the cell phone and fiber-optics market, quoting the number of companies working on tunable VCSELs as 60. His expectations are that as the industry matures, many of these companies will disappear or be absorbed into larger units.

Subbanna (IBM), who chose to make a career in the realm of silicon, rocked our fragile InP world with news of 120–200 GHz SiGe HBTs built on 8 inch sturdy, cheap, and crystallographically near-perfect silicon substrates. In terms of reliability, Subbanna pointed out that Si has no clear failure modes like those of III-Vs, and that defect diffusivity in Si is some 10 orders of magnitude lower than those found in GaAs at 150°C.

The full technical program of the Thirteenth IPRM can be found at www.knt-ec.com/IPRM01/program.html.

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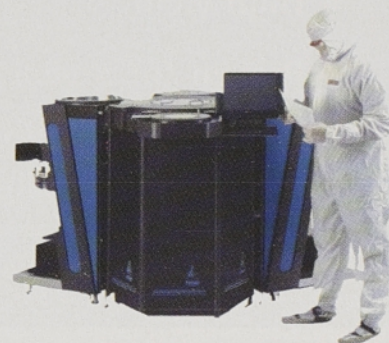
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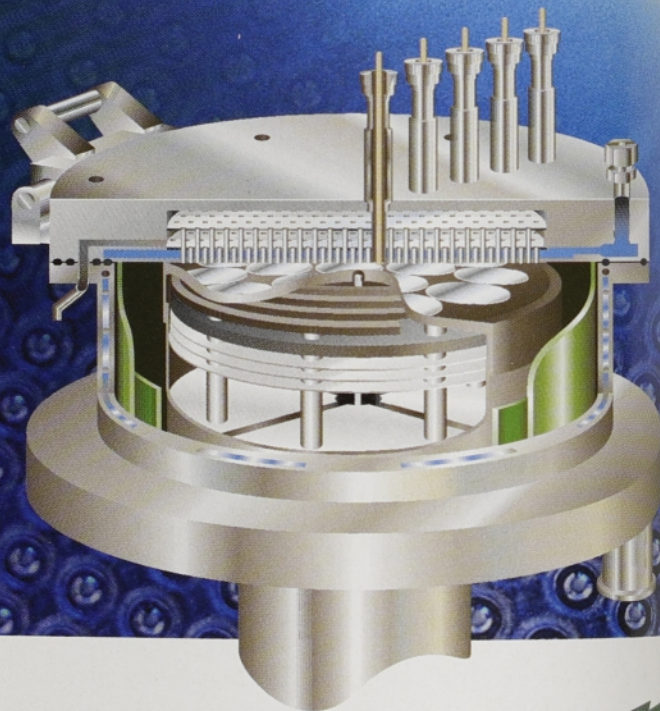
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NASA takes the helm of US SiC research

Well known for its SiC research and development activities, NASA also fulfills a crucial role in transferring SiC technology to the commercial world and helping to co-ordinate the US SiC program. Martin Grado-Caffaro reports.

Military and aerospace environments are frequently hostile, subjecting equipment to large temperature variations, high mechanical stresses and high EM radiation exposures. Electronic components capable of operating effectively in these conditions are crucial to the military and aerospace industries. Applications requiring high temperature, high power and radiation-resistant operation include microwave communications, high-power radar, engine ignition and sensing systems, and space-based electronics. Silicon and GaAs devices do not work effectively at high temperatures. Above 350°C, silicon requires cooling equipment to maintain its electronic properties, adding size and cost to circuitry. GaAs-based devices found in solid state microwave communications and radar electronics also suffer at high power densities and high temperatures.

Silicon carbide

Silicon carbide has a large bandgap and high breakdown voltage, properties that make it a good material for devices that may need to operate in the military and aerospace environments. The ability of devices made from SiC to operate at high temperatures and powers (see figure 1), while at the same time being radiation hard, have made them the subject of intense research by military and aerospace agencies throughout the world. NASA Glenn Research Center (GRC) in Cleveland, Ohio is one such agency.

SiC at NASA GRC

SiC research forms part of the High Temperature Integrated Electronics and Sensors (HTIES) program within the Instrumentation and Control Division (ICD) at NASA GRC. The purpose of ICD is the development of electronics, photonics and controls technology for aerospace applications. Facilities at the



Fig. 1. A SiC blue LED chip being tested at 600°C.

disposal of the HTIES team include a SiC MOCVD epitaxial growth laboratory equipped with an Emcore Discovery 75 vertical flow reactor and an Aixtron 200/4HT horizontal flow reactor, both specifically designed for SiC growth. Also available are comprehensive materials and electrical characterization laboratories and a 1500 sq. ft clean room for fabricating prototype devices.

NASA GRC has an in-house SiC research program going back over 25 years, and they can claim a number of firsts, including:

- The first large-area epitaxial growth of SiC on silicon wafers in 1982;
- The first kilovolt and multi-kilovolt SiC rectifier devices in 1991 and 1993, respectively;
- The invention of dopant control by "site competition epitaxy" in 1993;
- The identification of micropipes as crystal defects that provoke premature electrical breakdown in SiC power devices, also in 1993.

Developments in epitaxy

Site-competition epitaxy is a growth process where Si and C compete with the dopant atoms for available substitutional lattice sites on the growing SiC crystal surface. Nitrogen acting as a donor and aluminum acting as an acceptor compete with carbon and silicon, respectively. Nitrogen concentration in the grown

epilayer is proportional to the Si/C ratio during growth. Aluminum acceptor concentration is inversely proportional to this ratio. This technique has been applied to create very low-doped epilayers for the first 6H-SiC 2000 V and 3C-SiC 300 V diodes, and to fabricate JFETs able to operate at 600°C in air for 30 hours.

Another growth-related breakthrough has come with the granting of a patent in April 2001 for a method of growing atomically flat semiconductor surfaces. The method involves etching device-sized arrays of mesas into the wafers. By controlling growth conditions, crystal growth is limited to the side of each atomic step. The crystal at each step grows sideways until the step reaches the edge of the mesa, leaving behind an atomically flat surface. Mesas up to 0.4 mm² have been flattened out by this sideways growth. One benefit of this method is that mesas containing screw dislocations are left unflattened and thus can be isolated as unsuitable areas for further processing. The ability to process devices on flat, dislocation-free material will improve device reliability and performance.

NASA and commercialization

One of NASA GRC's missions is to facilitate the uptake of SiC technology outside of the military and aerospace arenas. Currently it is the military/aerospace demand that is pushing SiC and other

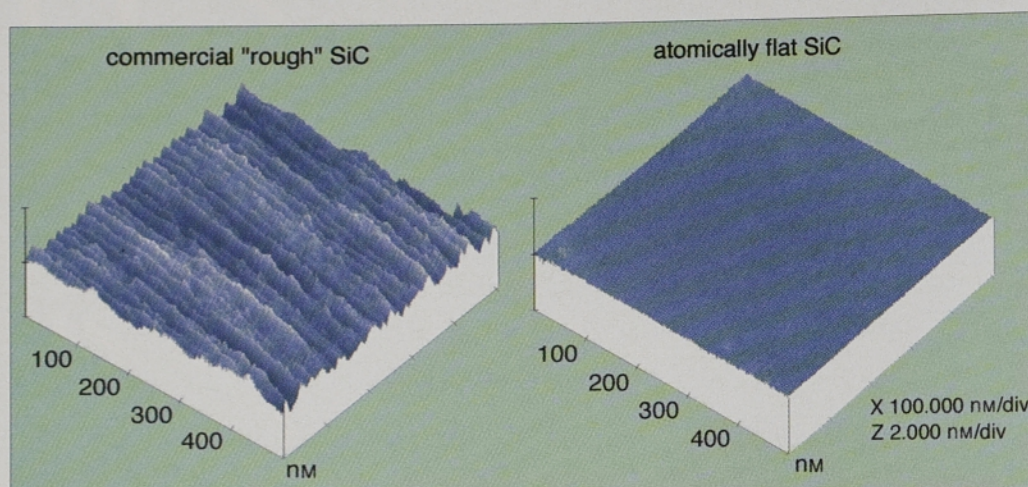


Fig. 2. AFM images from the surfaces of SiC grown by a standard method, and NASA's patented method for producing atomically flat surfaces.

wide bandgap technologies. Getting the technology into the much larger and potentially very profitable commercial marketplace is proving difficult. Device performance – mainly hampered by poor defect control – is as yet not sufficient to make SiC an obvious choice for many applications. Presently there exists no obvious large volume commercial application to drive the development of SiC technology.

One notable success in this role as facilitator has been the acceptance by industry of NASA's base technology for epitaxial growth of SiC as a de facto standard. As Jih-Fen Lei, chief of ICD explains, "the site competition process enables better control of the doping level (from 10^{14} to 10^{20} cm $^{-3}$) and enhances the durability of the fabricated device". The adoption of this and other processes by a number of companies working alongside NASA GRC has brought some success stories. Lei continues, "GE has demonstrated the world's first 500°C amplifier, and Kulite Semiconductor took advantage of the deep etching technique developed by GRC. This led to the joint development and demonstration of the world's first SiC-based pressure sensor in an engine compressor under a NASA-funded project". Other industrial partners to whom technology has been transferred are Westinghouse, Motorola, Cree Research, Boston Microsystems, Northrop Grumman, ATMI (for crystal growth) and Sienna Technologies (for sensor and packaging applications).

MEMS: a promising niche for SiC
Micro-electro-mechanical systems (or

MEMS) have carved themselves an important niche in the aerospace industry and are becoming prolific across the whole electronics industry. Traditionally based on silicon, MEMS have become a strategic area at NASA GRC, driven by the need to perform sensing functions in hostile environments where the properties of silicon make it unsuitable. SiC has become the material of choice because of its mechanical and electrical stability in hostile environments.

Much SiC research to date has focussed on the 6H-SiC polytype as a material for high-power, high-temperature electronics. The difficulty of depositing the 6H polytype onto any other material has limited its development as a material for MEMS. Attention has turned to the 3C polytype because of the ability to epitaxially grow this material on single crystal silicon substrates. Because SiC is resistant to the common Si etches, such films are suitable for bulk micromachining. Polycrystalline SiC can be deposited onto polysilicon or silicon dioxide sacrificial layers to enable surface micromachining of SiC MEMS.

Glennan Microsystems Initiative

Work on SiC MEMS at NASA is facilitated by the Glennan Microsystems Initiative (GMI), a public/private partnership between NASA GRC, Case Western Research University, and other government agencies and private sector companies. These include Air Force Research Laboratories, Battelle, Steris Corp, General Electric and the Cleveland Clinic Foundation. Companies involved in GMI gain access to funding, expertise, research

results, prototyping facilities and help with early commercialization. To date the initiative has supported \$4 million in research projects and will support a further \$17 million worth of projects through to 2003.

The main goal of GMI is the development and commercialization of innovative microsystems for harsh environments. In this instance, harsh is defined as high temperature, corrosive and high mechanical loading through shock and vibration. As a result, most projects feature SiC as the base structural material.

"One important component in the commercialization of SiC MEMS will be the development of a multi-user SiC surface micromachining process called MUSiC, which will provide access to SiC devices through a process quite similar to the multi-user MEMS processes (MUMPS) based on Si," says Walter Merrill, executive director of GMI. MUSiC promotes the general philosophy of GMI by making prototyping and small-volume manufacturing more economical by providing access to a multi-user process. Multiple users with similar goals share overhead costs for small volume production. In a single process run, designs from different users are fabricated on the same multi-project wafer. The foundry then dices the wafer and sends each user the relevant chips. This approach to small volume prototyping is already well established in silicon and SiGe microelectronics through services such as Europractice and even large companies, including IBM, offering multi-project wafer runs.

Co-ordinating SiC projects

NASA's relationship with the outside world where SiC is concerned can be viewed as one of technology transfer and co-operative research with universities, government agencies and industry. NASA GRC works with DARPA, US Naval, US Air Force and US Army Research Laboratories, all of them with interests in SiC. NASA acts very much as a co-ordinator for all these activities. As Lei points out, "NASA GRC has been solicited by the Air Force, Navy and Army to help them to set the direction for their related programs and provide evaluations for the industry proposals."

Martin Grado-Caffaro is a scientist and writer based in Madrid, Spain. E-mail "m.grado-caffaro@sapienzastudies.com".

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The evolving market for optical components

*The current slowdown in the optical components market could signal a period of industry consolidation, but there are still plenty of opportunities on the leading edge of performance and cost reduction, says **John Lively**, director of optical components research at RHK Inc.*

Although the optical components market has seen explosive growth in recent years, a dramatic slowdown hit the market starting in the first quarter of 2001. A report published in May 2001 by RHK's optical components research team forecasts that demand for optical components for DWDM networks (including active and passive devices) will decline by roughly 10% this year versus 2000 revenues, and 2001 revenues will total only \$4.5 billion this year. The report identifies the reasons for the decline as over-purchasing of critical components in 2000 (which led to a build up of excess inventory), and a slowdown in 2001 spending on DWDM long-haul networks by North American carriers.

Long-term evolution

A key question now facing the optical components industry, however, is how it will evolve in the long term. The recent RHK study predicts that the most likely future is that market demand will return to positive growth starting in 2002, with growth rates in the range of 25–35% in 2003–2004. But what will happen to the composition of the industry during this transition from “hypergrowth” to more “normal” growth? Looking at how other industries have evolved is one way to see what could happen in the optical components industry. A comparison with the personal computer (PC) industry would suggest that the optical components industry is headed for a period of industry shakeout and consolidation, while a comparison with the aircraft industry suggests the status quo may prevail for some time to come.

Before attempting to predict where the optical components market is heading, it is instructive to examine just what the market consists of and how the market has reached its current state.

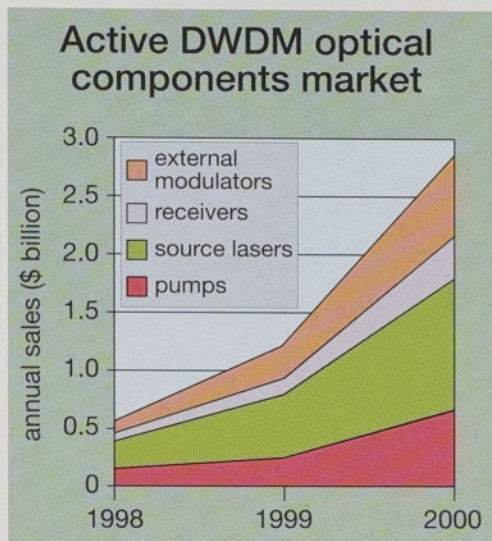


Fig. 1. Sales figures for different categories of active optical components used in DWDM systems.

Semiconductor-based optical components can be roughly divided into three major application segments:

1. DWDM optical transport: this has been the fastest growing market segment in recent years, and products in this group include source lasers, photodiode receivers, and pump lasers.
2. SONET/SDH optical transport: as with DWDM, this technology also requires source lasers and detectors.
3. Core and edge IP routers: these also require source lasers and receivers, which are typically packaged as transceivers or transponders.

The components used in these market segments are based on InP and GaAs devices, with the majority fabricated from InGaAs/InP structures. The high-speed, high-bandwidth capability of these devices has been a critical enabler of the rapid capacity expansion of DWDM optical networks. For example, the number of wavelengths carried on a single fiber increased from a single wavelength in 1994 to four in 1995, and by 2001 had

reached 176. In addition, over the same time period, the transmission speed of each individual wavelength increased from 2.5 Gbit/s to 40 Gbit/s. The combined effect of the increase in wavelength number and transmission speed has been to increase the potential maximum capacity of a single fiber by a factor of 10, every two to three years, for the last six years.

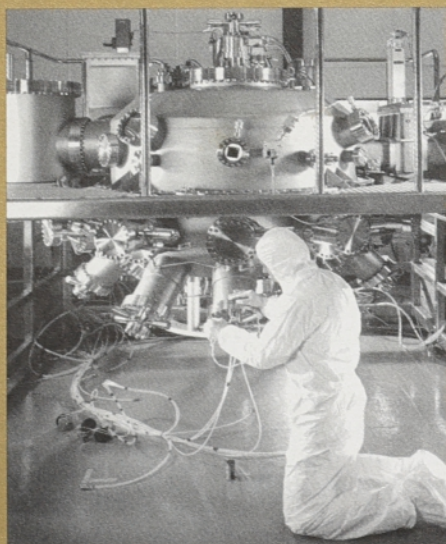
Hypergrowth and expansion

The explosive growth in DWDM network capacity was accompanied by a period of “hypergrowth” in demand for the optical components used in those networks. Figure 1 illustrates the historical growth in active optical component sales in the DWDM market, which have been broken out as pump lasers, source lasers, receivers, and external modulators. Since 1998, the aggregate market has increased from just over \$500 million to \$3.0 billion. The other major optical network market, represented by SONET/SDH, has also experienced very strong growth.

While not as rapid as DWDM, SONET/SDH component sales increased by more than 60% from 1999 to 2000. Figure 2 shows the sales breakdown of both active and passive optical components in 2000, representing a total revenue of \$6.3 billion, of which two-thirds was generated by active devices.

The impact of this hypergrowth in market demand on industry structure was dramatic. As demand accelerated, severe component shortages appeared. Existing suppliers realized profit margins in the 40–50% range. This combination of rapid growth and high margins attracted a number of new entrants to the industry, which ranged from established, related industries like semiconductors and industrial optics, to specialized military and government optics contractors, as well as venture-capital-funded start-ups. The

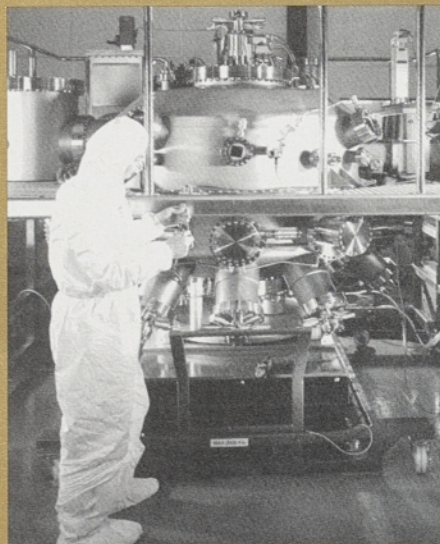
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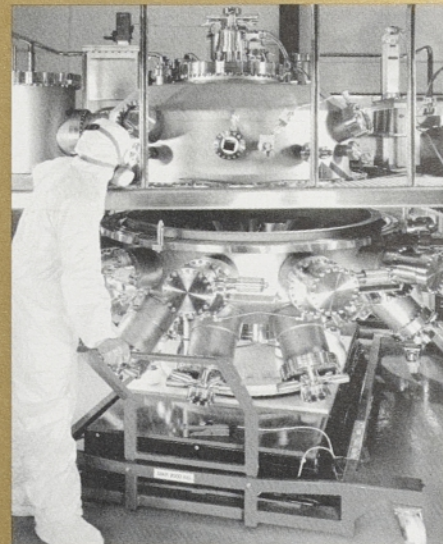
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3 *The trolley is lowered at the touch of a button and the entire lower section of the growth chamber is wheeled out for easy cleaning and source loading.*

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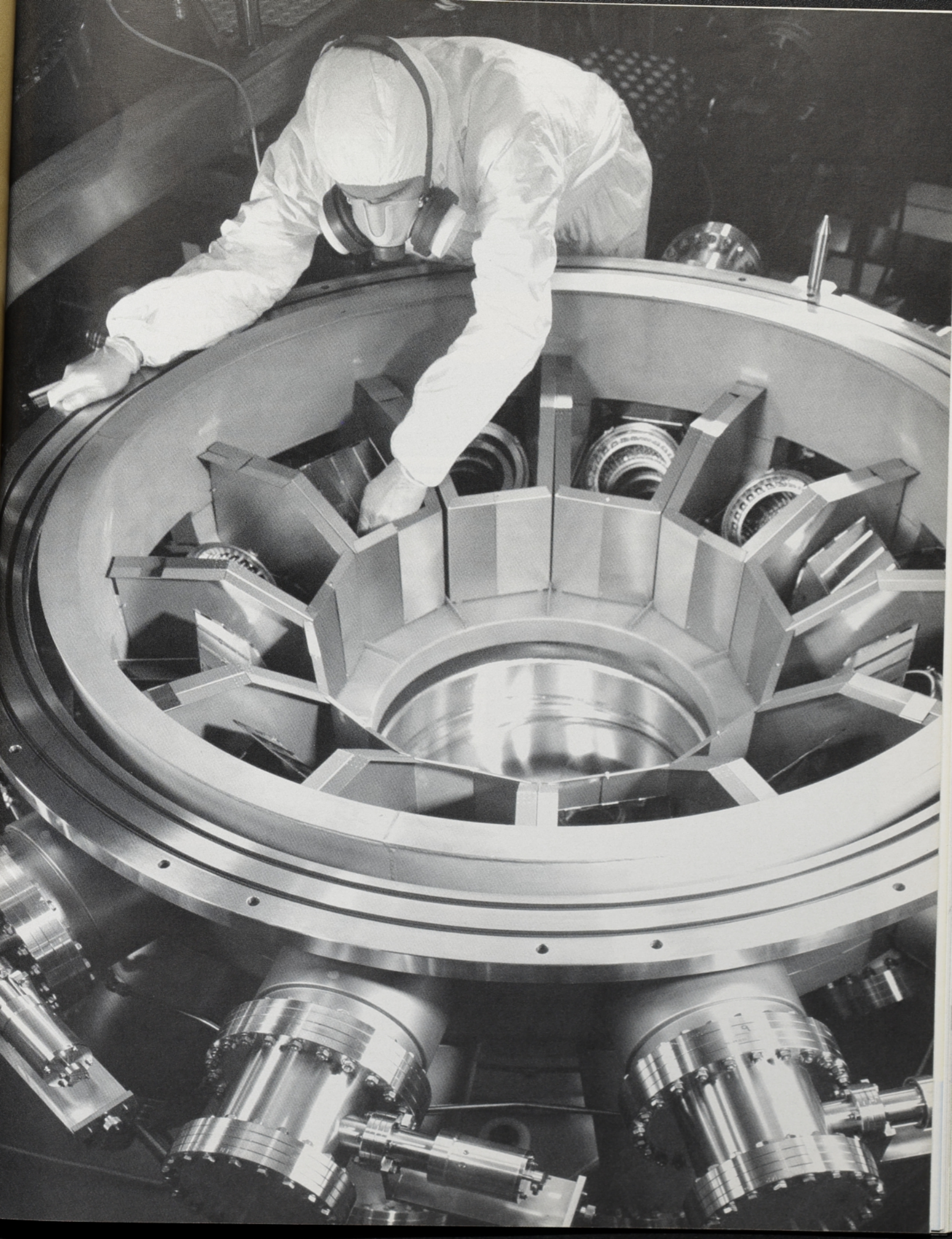
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number of the latter is quite impressive – over 50 start-ups exist in Europe alone, and probably well over 200 worldwide.

An industry transition?

As previously noted, in the first quarter of 2001 the music suddenly stopped: system demand growth slowed, and large inventories of purchased parts slowed components sales to a crawl. Such a sudden and large drop in market demand often signals a transition point in the evolution of an industry. This is particularly true with respect to new “disruptive” technologies; a term which certainly describes DWDM optical networks. We can get some ideas for what this could mean for the optical components industry by examining how the composition and structure of other industries has changed as a result of disruptive technologies.

One recent example of a disruptive technology is the PC. Not only did it replace the mainframe as the tool of choice for many applications, but it also opened up a whole new range of applications that the mainframe could not address, such as the home computer and small business computer markets. The parallels between the current optical components industry and the PC market period of 1978 to 1984 are striking. During that time, the PC market grew at a CAGR of greater than 100%, and over 150 PC manufacturers came into existence. The early market-share leaders were technological innovators: Apple and IBM. However, in 1985 and 1986, market demand slipped just as new capacity became available. Market growth plummeted to a CAGR of less than 10%, resulting in massive over-capacity, price wars, and widespread industry consolidation. In 1985, Apple Computer, the darling of the early-1980s tech stocks, laid off almost half of its work force.

However, as bad as things seemed then, all was not lost. The PC industry is still around. After the rapid decline in growth during 1985–1986, PC market growth stabilized, leveling off during the 1990s to a growth rate of about 20% per year. During those intervening years there was significant consolidation, as the 150 would-be manufacturers of PCs were reduced to a dozen or less. Apple and IBM were displaced as market leaders by Dell and Gateway; these companies focused on streamlining their manufacturing and distribution systems, rather than

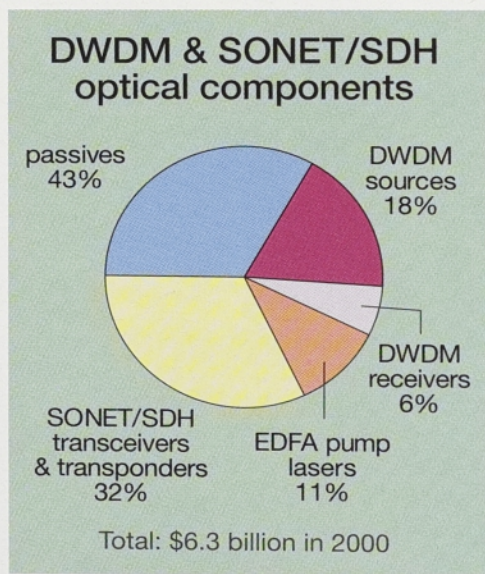


Fig. 2. Total sales of optical components for DWDM and SONET/SDH applications reached \$6.3 billion in 2000, of which over two-thirds was for active components.

technological innovation. The course of this industry transition is generalized in figure 3. The number of manufacturers and industry capacity increases at a ferocious rate during an initial period of rapid market acceptance and wild optimism from investors. Very often, this gives way to an industry shakeout, or period of consolidation, when many companies either merge or fail. After this relatively brief

This highlights an important lesson for optical components suppliers and investors alike: there will always be high-growth opportunities associated with leading-edge technology, even during periods of reduced overall market growth.

and difficult transition period, the fewer, larger remaining suppliers enjoy a period of more balanced supply and demand, and more rational competition.

While the PC industry was going through this evolution, components and subassemblies used by PCs were going through major changes as well. If one views the PC as an analog to an optical network, then optical components are analogous to PC subassemblies such as the disk drive. Over the period from 1980 to 1988, 5.25 inch rigid disk drive shipments increased from zero to some

eight million units, an increase somewhat reminiscent of the explosive market growth experienced by optical components over the last several years. In 1989, shipments began to decrease, and in 1995 less than 1 million 5.25 inch disk drives were shipped. The market for rigid disk drives did not go away of course. Instead, faster, higher density, smaller diameter drives were developed. Each new generation experienced a few years of very fast growth, followed by a rapid decrease in demand as the next generation reached the marketplace. This highlights an important lesson for optical components suppliers and investors alike: there will always be high-growth opportunities associated with leading-edge technology, even during periods of reduced overall market growth.

Of course, for every clever analogy, there is usually a counter-example, and this case is no exception. Some industry experts, including RHK's own chief analyst, Dr John Ryan, believe the aircraft industry offers a better analogy to the optical components industry. The aircraft industry has undergone tremendous consolidation at the aircraft manufacturer level, until only a few remain, while at the same time the parts suppliers of the aircraft industry have remained numerous and fragmented. This analogy suggests the optical components industry structure could remain unchanged – with a plethora of small, niche-focused start-ups surrounding a half-dozen or so broadly based suppliers – even as a wave of consolidation sweeps through the telecom carrier and optical transport system levels of the industry.

High-growth opportunities still exist
Will the optical components industry evolve in the manner followed by the PC industry, and enter a period of consolidation? Or will it more closely resemble the aircraft industry, with a plethora of smaller start-ups coexisting with a half-dozen larger, more broadly based suppliers? Only time will tell.

Regardless of which evolutionary path the industry takes during its transition from hypergrowth to a more normal growth phase, it is safe to say there will continue to be high-growth opportunities for leading-edge optical components, where the “leading edge” is defined in terms of both performance and cost reduction.

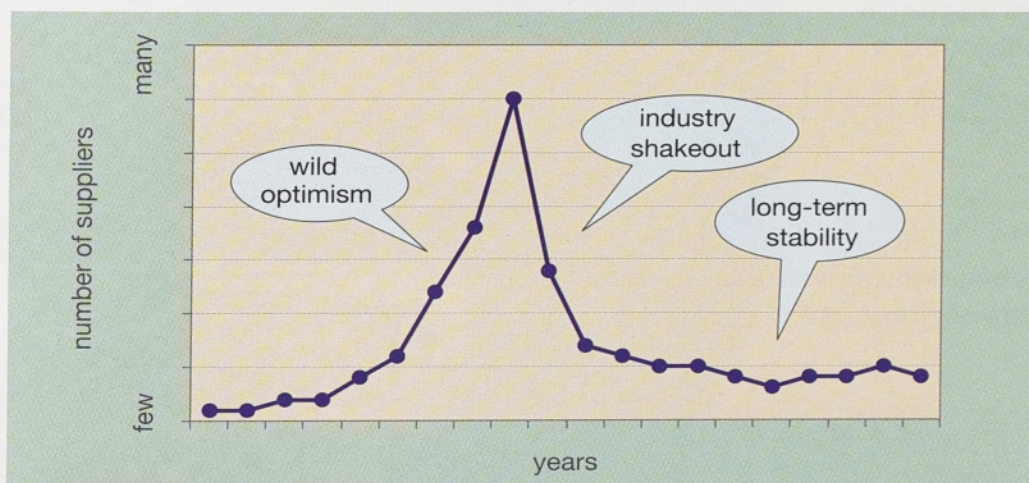


Fig. 3. The impact of disruptive technologies on industries: wild optimism is followed by an industry shakeout, which leads to a period of relative stability.

The performance-related opportunities are tied to system trends, such as the transition to 40 Gbit/s transmission; the need for more channels, which require higher pump powers; and the introduction of tunable laser sources, to reduce complexity. In turn, these component trends

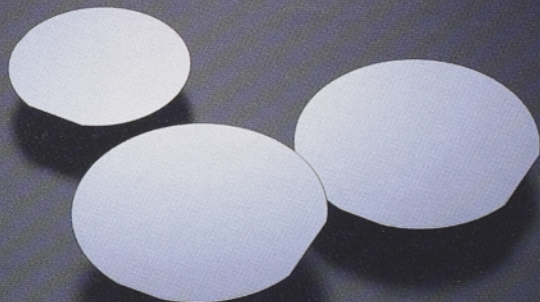
are being pursued through a variety of semiconductor device improvements, such as higher levels of on-chip integration, the development of 980 nm VCSELs, and the use of MEMS that are coupled with VCSELs to implement tunable laser sources.

Current cost-reduction efforts lag behind the leading edge of performance by several product generations because of the industry's focus on rapid product development over the last three years. As a result, there are now many opportunities in manufacturing, integration and automation. Other cost-reduction-related opportunities are tied to innovative product designs, including the use of less expensive uncooled lasers, parallel optics, and plastic housings, which are being developed for the metro market.

By focusing on the right opportunities, and investing rationally, optical components companies can weather the current storm, and position themselves to enjoy the period of more rational growth ahead.

John Lively is the director of optical components research at RHK Inc, a market research firm based in South San Francisco, California. This article is based on a presentation given at the 2001 Key Conference, held March 5-6 in Key West, Florida.

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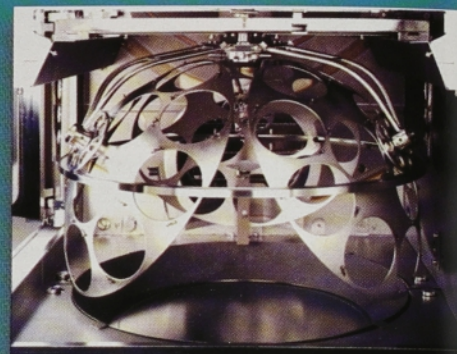
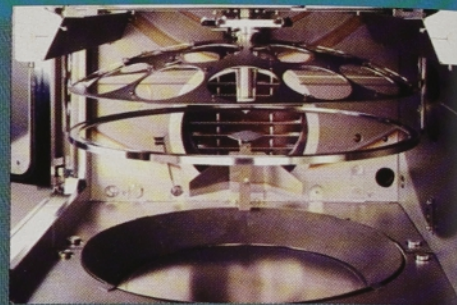
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The economics of photonics manufacturing

*After a period of “brute force” capacity expansion, the photonics industry is now entering a demand-driven growth phase that will see the development of a mature supply chain, according to **Eric Chen** and **Donald Lu** of JP Morgan H&Q Equity Research.*

The photonics sector is destined to become a major force in the world economy. Although the market demand for photonics components and systems is potentially massive, it is our view that the current manufacturing approaches employed in the photonics business are too inefficient for the industry to address all of the available markets. Contrasting the photonics supply chain to the infrastructure of “Silicon Valley” yields some useful insights.

In the silicon semiconductor industry, device manufacturers rely heavily on the suppliers of equipment, design tools, and even pure intellectual properties. Together, these companies form the holistic semiconductor supply chain. For investors there are Intel, which makes semiconductor devices, and Applied Materials, which provides semiconductor capital equipment. Both companies can be suitable investment vehicles to cash in on the opportunities in semiconductors.

On the photonics side, the picture is far from clear. The technology supply chain remains underdeveloped. If JDS Uniphase is poised to become the Intel of photonics, where is the Applied Materials of photonics? Analyzing this question is important, and not just for companies such as ours that are always looking for great investment vehicles. It is also important for the overall health of the photonics industry.

Recipe for disaster

We believe that the current processes employed in photonic device manufacturing are prohibitively inefficient to support a profitable growth business over the long run. Take the industry leader, JDS Uniphase, as the representative company, and assume that JDSU's manufacturing economics are typical for a photonics manufacturer. Each employee at JDSU generates roughly \$110 000 of revenue per year. Considering the mix of low-cost

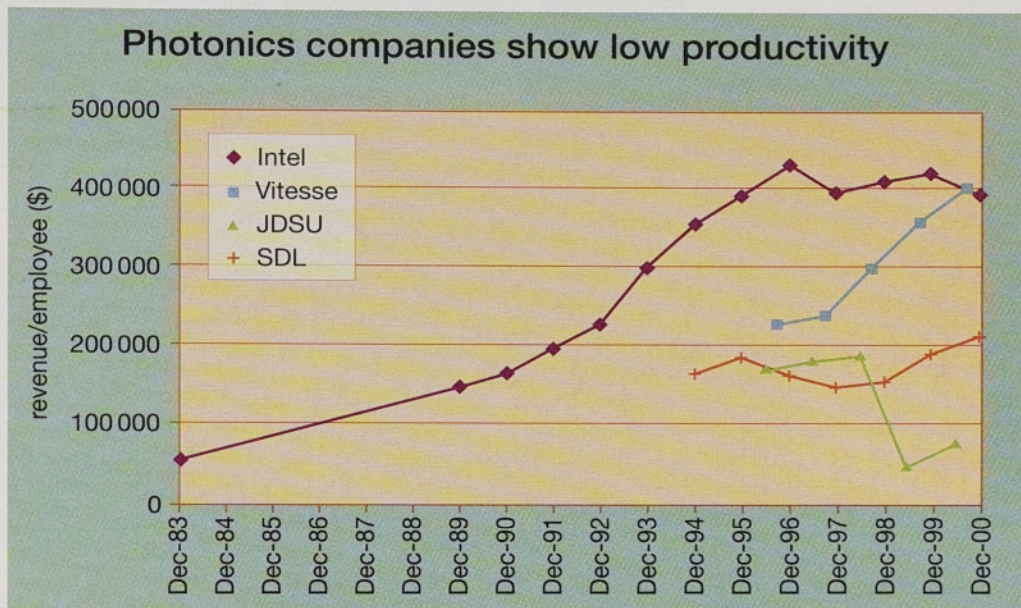


Fig. 1. Revenue productivity of selected semiconductor and photonics companies, derived from company reports.

Comparison of photonics and semiconductors

Technology traits	Semiconductors	Photonics
Repeatable building block	Transistors, gates	None
Uniform material base	Silicon	None
Dominant manufacturing process	CMOS	None

Table 1. A comparison of technology traits in the photonics and silicon semiconductor industries. The latter is characterized by three unifying principles that do not have analogues in photonics manufacturing.

labor employed by these companies, this can be a reasonably profitable business model. It suggests that there are approximately 125 000 people involved in making photonics communication products in the world today.

Now consider the future. The market research firm RHK estimates the market for fiber-optic components will grow ~35% per year until 2003. We will extend this forecast by assuming a 25% growth rate after 2003, and we will further assume that the component average selling price (ASP) will decrease 25% per year.

Under this scenario the current model of employee productivity says that nearly 34 million people would be needed in the photonics business by the year 2011 (more than the entire population of Canada!), and each employee would generate only \$4000 of revenue a year. Clearly this is an unsustainable business model.

The only way to fix the model is to change one of the assumptions: either unit and ASP growth rates for devices, or the manufacturing economics. We believe the latter is more likely to change than the former. Again, the silicon industry pro-



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vides an example. In 1983 Intel generated \$52 000 in revenue per employee. Sixteen years later in 1999, Intel had increased its revenue per worker to \$420 000 (see figure 1). This was done despite the fact that ASPs decreased 25% per year over the same period. The main driver for this remarkable improvement in productivity has been the relentless effort of the semiconductor industry to increase wafer size, to improve yield, and to implement highly automated manufacturing processes.

The photonics industry pales in comparison, a direct reflection of the highly labor-intensive process of photonics manufacturing. For an example drawn from the compound semiconductor industry, look at the difference between Vitesse and SDL. While Vitesse has almost doubled its revenue productivity in the last four years, achieving "Intel-like" numbers, SDL has seen basically flat revenue per employee. During this period, both companies greatly improved the yield and productivity of their III-V semiconductor operation. In addition, Vitesse also benefited from outsourcing the manufacturing of CMOS products. What dragged down SDL was its expansion into the highly labor-intensive business of module assembly – not an uncommon problem in photonics manufacturing.

Photonics manufacturing tools

Analogies between photonics manufacturing and the silicon industry can be helpful, but they can also be stretched too far. The most notable difference is that the photonics device sector is severely fragmented, with each market segment finite in size and thus unable to support its own specific enabling technologies. In contrast, as shown in table 1, there are three unifying principles that underlie more than 90% of the worldwide semiconductor industry, namely: core "building blocks" in the form of transistors/gates; a single material system, silicon; and a dominant manufacturing process, CMOS. There are no analogous items for the photonics industry. In our view, this has served to dampen the growth of a monolithic photonics-manufacturing sector and has caused the photonics industry to "import" tools from other areas.

There are four main types of "front end" processes for making the majority of photonics components: (1) semiconductors, encompassing both Si and III-Vs; (2) thin-film technology; (3) microelectro-

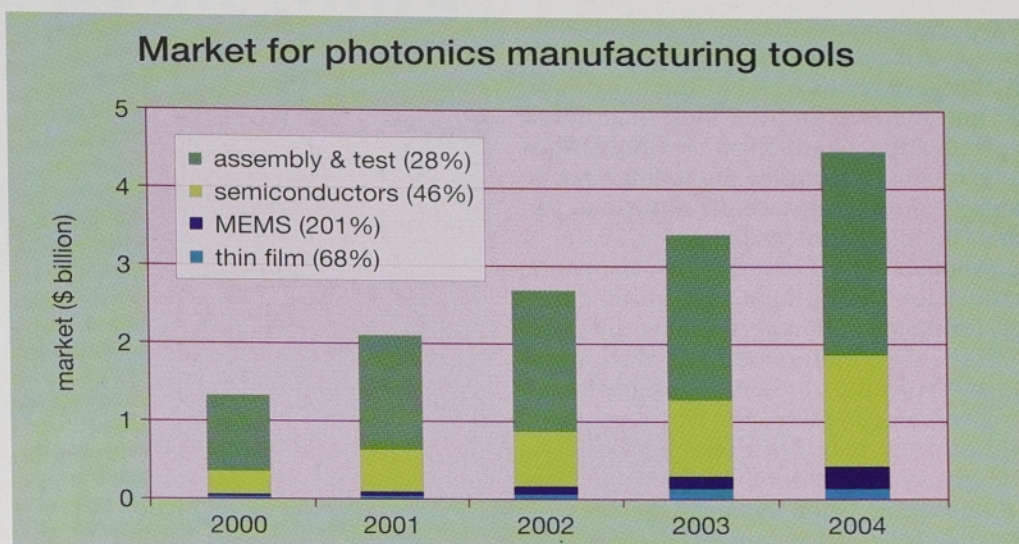


Fig. 2. Projected annual revenues of different types of photonics manufacturing tools. Percentage figures indicate compound annual growth rates from 2000 to 2004.

mechanical systems (MEMS); and (4) micro-optics. Packaging and testing form the "back end". The tool set required for each of these technologies is obviously different from each other.

We have compiled our own industry model, broken into four distinct segments: semiconductors, MEMS, thin film, and module assembly and test. We have chosen to ignore the software, materials, and micro-optics segments because they are too embryonic or fragmented to quantify at this time. While the total market for photonics manufacturing tools is expected to reach almost \$4.5 billion in 2004, the market suffers from fragmentation, with the largest segment being automated assembly and test, which is projected to become a \$2.6 billion market in a few years (see figure 2). The second largest segment, semiconductor tools, will reach almost \$1.5 billion in 2004, with a CAGR of 46%. The thin-film and MEMS tools segments are the fastest growing, but they make up a relatively small portion of the total market.

Supply and demand

The optical communications components and systems markets experienced phenomenal growth in the last few years, driven by the need of carriers to rapidly expand and upgrade their infrastructure to meet the anticipated explosive growth in bandwidth demand. Estimates for the annual growth rate vary, but 25–33% is a useable benchmark. Meanwhile, the ASP of optical components is declining. Therefore, the unit growth of the optical component market

is even more pronounced, potentially exceeding 50% per annum.

Until late 2000, the optical component market had to live with rampant supply shortage. The backlog of optical systems was as long as six months in early 2000. Financially, the supply shortage has contributed to a unique distribution of profit margins among different participants in the supply chain. Photonics component companies seemed to enjoy significantly higher profit margins than their system OEM customers (see figure 3). We believe that the shortage of photonics manufacturing capacity contributed to this disparity.

Supply constraints

What is the cause of these supply constraints? It is certainly true that demand growth has caught the industry by surprise. But once the situation was grasped, it proved surprisingly difficult to ramp up new production capacity for optical components – surprising because given the rich stock valuation of the component companies and the eagerness of venture capitalists to open their wallets for optical start-ups, capital was not a limiting factor. Instead, we would blame the following factors:

- Lack of scalability in the current manufacturing processes;
- Shortage of technical talents for both engineering and manufacturing;
- Absence of standardization throughout the supply chain.

Almost every photonics component has some manual processes in its production. Despite the high-technology nature of the

products, manufacturing of optical components is most often compared to shoe making, in terms of labor intensity, lack of automation, and the lack of process optimization. Component assembly, fiber attachment (also called pig tailing), packaging, and testing are all notorious for their high labor intensities.

Another culprit is variability. In mature industries like silicon, the variance in performance parameters among different parts is well understood and well managed. Typically, a system is designed with this variance in mind, and sufficient margin of error is built in to accommodate the idiosyncratic behavior of each part. In photonics, such system-level design practice is still immature, leaving the system performance dependent on the variability of each component. The variations are due in part to the manual labor involved in making the components, which in turn makes system-level assembly difficult to scale.

The situation is further exacerbated by the difficulty of codifying knowledge in this field and the resultant dependence on artistic experience. Many photonics manufacturing processes require a certain art and experience that can only be obtained through practice and remain difficult to communicate. For example, an experienced coating engineer could easily increase the yield of thin-film coating by 100%, compared with a novice.

Finally, the optical component market lacks standards. For example, the form-factors of thin-film dies vary among different vendors. This is widely recognized as one of the main inhibitors of manufacturing scalability throughout the supply chain, pertaining not only to the components, but also to the modules and systems. Some of this, in our view, stems from fundamental technological issues, while some of it is a reflection of the current economics in the early stage of the industry's maturity, which, we believe, can change rather dramatically over time.

Three growth phases

The good news, in our view, is that some of the aforementioned effects that have inhibited the growth of the photonics manufacturing tool industry will disappear in the near future. These transient effects include vertical integration, extreme secrecy and lack of standardization. In our opinion, these transient effects will diminish as the photonics industry goes

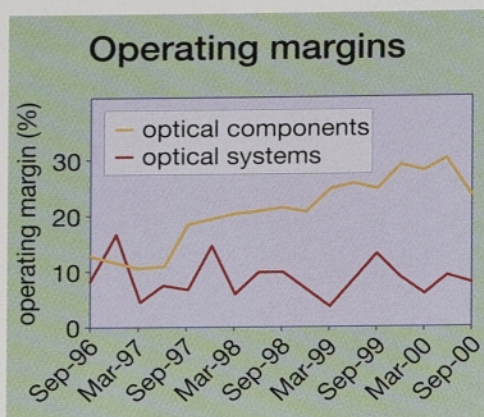


Fig. 3. Operating margins for optical component and optical system manufacturers, obtained from company reports. All operating margins are revenue weighted. Optical component companies include JDS Uniphase and SDL, while Nortel, Lucent, Alcatel and Tellabs are examples of optical system companies.

through the current painful trough period. In other words, the trough of the photonics industry could be the genesis of the photonics manufacturing tool industry.

We further hypothesize that the growth of the photonics industry has three phases: the brute-force phase, the synergistic phase, and the lockstep phase.

The brute-force phase

To cope with the supply shortage, photonics companies embarked upon what we will refer to as the "brute force" style of

Once supply catches up with demand the industry's dynamics will be fundamentally altered as a demand-driven scenario emerges. In this environment, a successful company has to be either primarily a technology leader or a cost leader.

capacity expansion. This is characterized by rapid building of manufacturing plants, widespread hiring of low-cost manufacturing personnel, and purchasing of basic, non-integrated tools.

Process engineering innovations, automation, and standardization are largely absent from this type of expansion since all of these factors have to take lower priority than time to capacity. Time to capacity is such an essential competitive factor in the supply-constrained industry setting, that we believe it may cause manufacturers

to sidestep industrial engineering issues.

To us, the brute-force phase of capacity expansion is rather unenlightening because it does not change the economics of the photonics industry, nor does it alter the industry structure from its current state. Specifically, it does not foster the development of an organic supply chain, including a sophisticated supplier base. In short, brute-force capacity expansion retards the maturation of the sector. If a company is able to expand its capacity with relatively minimal capital investment and sell almost everything it makes at an attractive margin, why should the company worry about increasing productivity?

Demand and supply reach balance

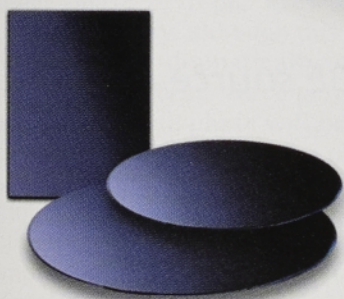
A major change in the photonics industry is on the horizon: we believe that supply and demand have come into balance sooner than many expected, especially given the recent downturn in the economy. For the first time in its young life, the photonics industry will have to cope with a supply glut.

In the brute-force phase described above, manufacturing and process issues have held a relatively low priority, muting growth of the photonics infrastructure and providing opportunities only in isolated pockets. However, once supply catches up with demand (which is, after all, the goal of brute force capacity expansion) the industry's dynamics will be fundamentally altered as a demand-driven scenario emerges. In this environment, a successful company has to be either primarily a technology leader or a cost leader.

In our view, it will be difficult to remain in the middle. The technology-driven company will likely continue to focus its resources on improving product performance and, to some extent, cannot afford to be distracted with manufacturing process issues. For commodity producers, on the other hand, cost and supply chain management become overwhelmingly important concerns because pricing will likely approach marginal cost. After the move to regions with low-cost labor, the only other fundamentally viable approach to cost reduction is through improvements in manufacturing efficiency.

We believe that at this critical juncture we will see the emergence of a sophisticated, robust infrastructure in the photonics industry that is analogous to the tremendously sophisticated semiconductor equipment market that we see in the

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Three growth phases in the photonics industry

Growth phase	Growth of photonics enabling technology (PET) companies	Status of photonic device market (PDM)	Interaction
Brute force	Muted opportunities are limited to "pockets"	Supply-constrained	PET growth suppressed by supply constraints in PDM
Synergistic	Accelerated growth out-performing PDM	Balanced supply and demand	Synergistic growth of both PET companies and PDM
Lockstep	Tracking PDM	Mature	PET dictated by stable capital intensity in PDM

Table 2. The photonics industry has spent the majority of its short history in the brute-force phase, but is now being forced to transition to a new growth phase, termed synergistic, which will see the development of photonics enabling technology (PET) companies. (PET companies are those that supply equipment, materials, tools and general methodologies to the photonics industry.)

silicon industry. Since this infrastructure will play a critical role in enabling the future growth of the photonics market, we have chosen to describe it as "photonics enabling technologies", or PET. PET companies are those that supply equipment, materials, tools and general methodologies to the photonics industry.

The synergistic growth phase

We believe that the rewards associated with an outsourced technology supply base will quickly materialize and power another phase of rapid growth in the photonics industry, although this time the growth will be dramatically different from that of the brute-force period. This subsequent growth phase will be characterized by rapid changes in the photonics business model, including:

- Rapid cost reduction, hence rapidly declining ASPs;
- Improved manufacturing efficiency and scalability;
- Reduced labor intensity combined with increased capital intensity.

As photonics companies outsource manufacturing technologies, they will gradually migrate toward higher value-added activities, such as:

- Deeper, more proprietary technologies;
- Innovative component design;
- Module and system-level engineering.

In our view, the PET industry will experience extremely rapid growth around this time. Its growth rate will be the compounded effect of two drivers: first, the gradual but growing trend toward outsourcing, and second, the growth of the photonics market itself, empowered by the

newly developed merchant supply of enabling technologies and the attendant benefits. Realizing that the two industries, photonics and its suppliers, will be mutually stimulating, we intend to label this part of the photonics and PET industries' life cycles the "synergistic growth phase."

The lockstep growth phase

After the rapid growth of the synergistic phase, we believe that the industry structure and dynamics between photonics companies and the PET players will likely stabilize. Technologies will standardize, manufacturing platforms will consolidate, and the benefits of outsourcing will fully materialize. At this point, we would then

We believe that we will see the emergence of a sophisticated, robust infrastructure in the photonics industry that is analogous to the tremendously sophisticated semiconductor equipment market that we see in the silicon industry.

expect the PET market to start tracking the photonics industry in terms of growth. We will label this phase the "lockstep growth phase." To get a feeling for how the industries will behave during this period of time and beyond, one only needs to study the current state of the semiconductor capital equipment industry. The market for semiconductor equipment has largely tracked the semiconductor end markets, with 22% of semiconductor revenue spent on capital spending year in and year out for more than a decade now.

Conclusions

Naturally, we would like to know exactly where we are in the industry's three-phase life cycle (summarized in table 2). We believe that the photonics industry has spent the majority of its short history in the brute-force mode, with only some embryonic activities in PET. Since the industry is transitioning from a supply-constrained situation to having more balanced demand and supply, it is natural to postulate that the PET market may be entering the synergistic growth phase, making this the high time for us to identify the investment opportunities in PET.

At this point in time, the detailed segmentation analysis leads us to believe that investment opportunities in PET are largely limited to automated assembly and test, and specialized semiconductor process tools. While the thin-film and MEMS segments will also experience high growth, these sectors are too small to support independent investable companies. In the area of assembly and test, Newport, a merchant supplier of automated alignment and welding stations, is a potential investment vehicle.

In the semiconductor segment, equipment companies focusing on compound semiconductors, such as Aixtron, Emcore and Riber, also offer investment opportunities. Other notable players include Thermo VG Semicon (part of a much larger company) and Applied Epi (currently evaluating an IPO), as well as materials suppliers such as AXT, IQE and Picogiga.

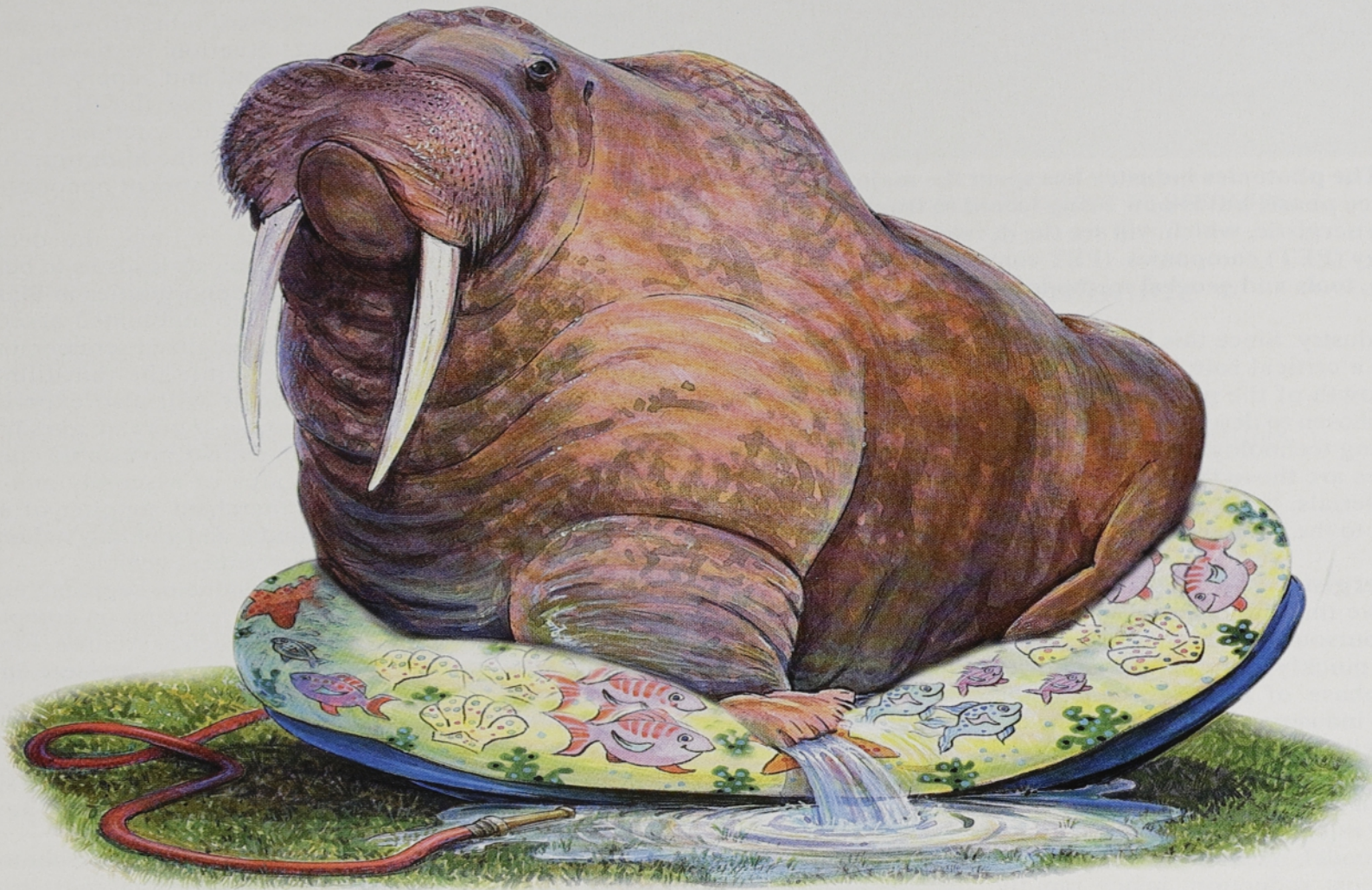
An interesting aspect of the photonics manufacturing field is that most critical processes in use have been imported from other technology areas. Thus it is likely the major players that will emerge in the photonics infrastructure will have a heritage of serving other markets. Among other things, this means that there will be few "pure play" investments.

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This article is based on a JP Morgan H&Q industry report entitled "The Pick and Shovel of the Photonics Gold Rush" by the same authors.

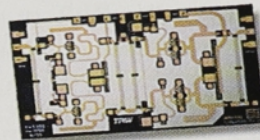
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Optical networking components gear up for 40 Gbit/s and beyond

The next generation of optical networks will place heavy demands on components. Ira Deyhimy of Vitesse Semiconductor examines how InP is meeting the challenge.

Today's optical networking infrastructure handles the bulk of communication traffic in the developed world. Voice, data, wireline, or wireless traffic ultimately traverses the optical network at some point. At the heart of the optical network infrastructure is the "optical subsystem", which converts the aggregated digitized traffic between the optical and electronic domains.

Certain common functions appear in the optical subsystem, regardless of transmission protocol or whether the signaling is between continents or within equipment cabinets. These generic functions include the optical-to-electrical conversion, the deserialization or serialization of the digitized data, and protocol-specific framing and de-framing of the data used to encapsulate or strip the data from the overhead associated with the protocol being used. As an example, in the case of Ethernet, this function is called the media access controller (MAC).

The demand for greater volume of traffic motivates higher serial transmission data rates, and in turn, gives rise to technology alternatives. OC-48 (~2.5 Gbit/s) has traditionally been served by GaAs MESFET and silicon bipolar technologies, and more recently by CMOS. Higher standard transmission rates, OC-192 (~10 Gbit/s) and OC-768 (~40 Gbit/s) are being addressed by several technology alternatives, such as GaAs, SiGe, and InP.

GaAs MESFETs

Historically, Vitesse Semiconductor has applied high-speed digital GaAs technology to develop multiplexers and demultiplexers for the physical layer of OC-48 optical networks. The company's MESFET-based process runs on 6 inch GaAs and requires only 16 mask layers. The gate lengths are 0.25 μm and the MESFETs exhibit f_t values of 80 GHz.

	opto/electronics	physical layer	framers	processors	switch fabric
1.06 Gbit/s-2.5 Gbit/s	GaAs	CMOS	CMOS	CMOS	CMOS
2.5 Gbit/s OC-48	GaAs	GaAs CMOS	CMOS	CMOS	GaAs CMOS
10 Gbit/s OC-192	GaAs	GaAs	CMOS SiGe	CMOS	CMOS SiGe
40 Gbit/s OC-768	InP	InP	CMOS	CMOS	CMOS

Fig. 1. The different technologies utilized across the different functions, as networks progress from 2.5 to 40 Gbit/s.

However, with advancements in a wide range of process technologies, the OC-192 physical layer components now going into production are not only being implemented in GaAs, but also in SiGe and even in 0.13 μm CMOS (see figure 1). The competition amongst various materials and technologies is fierce in the pursuit of 10 Gbit/s applications. The stringent performance requirements for the physical layer components needed in next generation optical networks, operating under the OC-768 standard (40 Gbit/s), will eliminate many of these technologies as potential solutions.

InP increases the speed

Though they are sufficiently fast for 10 Gbit/s operation, AlGaAs/GaAs HBTs with an f_t of 60 GHz and SiGe HBTs with an f_t of 90 GHz will not be fast enough to support the bandwidth and error correction requirements for 40 Gbit/s operation. The only current alternative is an InP-based HBT, where a 1.0 μm device exhibits an f_t of 160 GHz, a value high enough to make these devices suitable for 40 Gbit/s applications. Another advantage

of InP HBTs is their lower supply voltage requirement. The emitter-base turn-on voltage is only 0.7 V, compared to 1.4 V for GaAs HBTs. This will allow InP HBTs to operate at lower voltages, and therefore consume less power. The lowering of operating voltages becomes extremely important as overall module operating voltages are pushed down to 3.3 V. In addition, InP HBTs, where both the emitter and collector are implemented in InP, exhibit breakdown voltages in excess of 10 V, far higher than SiGe devices. This makes InP HBTs compatible with the high breakdown voltage requirements of laser drivers and modulators. These considerations indicate that InP-based technology will be the best – and perhaps only – technology capable of supporting 40 Gbit/s systems.

Modules as components

Even as standards evolve and system requirements expand, most optical networks share many commonalities. All these systems require an optoelectronic layer that converts signals from optical to electrical or electrical to optical, to move

data in and out. Next comes the physical layer as described above, followed by the framing layer that frames or deframes according to the particular protocol being used. After framing the data is processed, then the switching fabric takes the stream of data and switches it to a different channel and passes it out again. Currently, within each of these layers, is a myriad of components. Typically, OEMs incorporate these components into modules that in turn are sold to those manufacturers implementing optical networks. However, within the near future, driven by market needs, cost reduction and performance improvements, the "components" will no longer be the elements within the modules, but the modules themselves.

Greater integration

In order to maintain high growth rates in the optical networking arena, it is no longer sufficient to simply supply to OEMs devices such as MUX/DEMUXs. Such devices are used by the OEMs to fabricate physical layer modules that go into the line cards of an optical networking module. Large OEMs such as Lucent and Nortel have in the past designed and fabricated custom layouts for the production of physical layer modules. This effort results in minimal added value to the overall optical network. In future, these OEMs may focus more on overall systems integration from the module level, and the development of network engineering software. While ever faster devices will be required (as in the case of MUX and DEMUX), many of the functions need to be reduced to compact assemblies, or in some cases even single chips. In the near future, the components being supplied by manufacturers such as Vitesse will actually be the entire module – a single black box that contains all the electronic and optical components together, forming an optical transponder module (see figure 2).

InP-based modules

Currently, systems are migrating from OC-48 (2.5 Gbit/s) to OC-192 (10 Gbit/s) and in the next few years to OC-768 (40 Gbit/s). As this happens, the fundamental component within the physical layer will no longer be represented by such elements as a MUX or clock and data recovery (CDR), but rather by the transponder module. This implies that the current approach of choosing the best

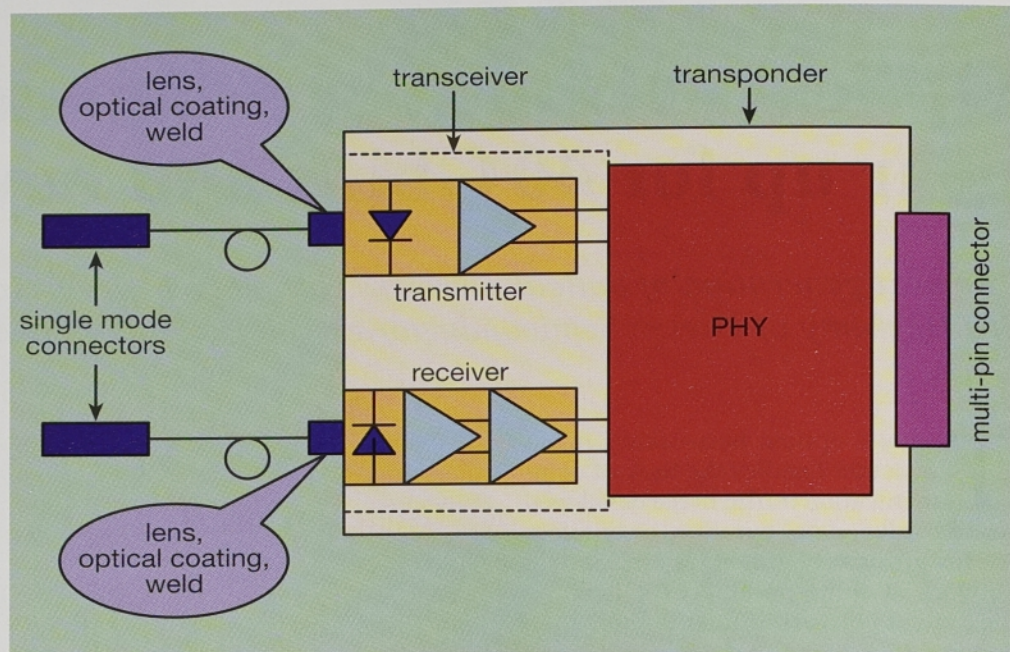


Fig. 2. In the future, a single black box that contains all the optical and electrical components will form an optical transponder module.

technology or material for a MUX or CDR will need to be replaced by an approach using a single technology capable of supporting a wide range of functions, including lasers, electronics and detectors. Fortunately, many of these optical components, in particular the lasers and detectors, are already being implemented in InP-based materials. Currently, InP is the only material that can also support the electronic portion of a 40 Gbit/s system, therefore making it ideally suited to large levels of on chip integration containing a wide range of different InP-based device types.

Jumping the processing hurdles

However, the process technology to fully implement a transponder module using InP-based materials does not yet exist. While excellent detectors and lasers are currently being fabricated in this material system, only a relatively small level of integration has been demonstrated with InP-based transistors. In an environment of volume manufacturing in which a high level of transistor integration must be coupled into a single InP chip with optical components, the process development will be a great challenge. But in the long run, Vitesse believes that this is the only way to succeed. Module suppliers that are only assemblers of sub-components will not be able to compete on performance or

cost in the face of competition from those manufacturers that view the module as the fundamental component.

Challenges for assembly

Beside the material processing challenges are the mechanical aspects of assembly and alignment of the sub-components of the module. Currently, many modules are assembled by hand, and require *in situ* calibration and adjustments. While this approach may work for production runs limited to a few hundred modules, future requirements will dictate that tens of thousands of modules be fabricated. Manual assembly will need to be replaced by automated systems, a challenge every bit as great as the implementation of a robust, manufacturable electronic/optical integrated InP-based process.

The roadmap toward a fully integrated transponder will therefore evolve in step-wise fashion. Initially just the detector and amplifier would be fabricated in a single chip. This would be followed by the modulator and the driver, then perhaps a component that consists of the modulator, driver, and the waveguide amplifier. The vision is of a transceiver module with a high-speed serial connection to the outside world where MUX/DEMUX, CDR and related functions are carried out, and an optical module with detectors, lasers and modulators. Eventually this would lead to a fully integrated transponder module.

Optical modulation

A variety of optical modulation techniques are available, the choice of which depends on factors such as the distance the optical beam transverses between electronic conversions, and the data rate.

The simplest modulation technique is direct modulation of the current through the laser diode. This technique is typically used for relatively short distances and low data rates. Other devices used for higher data rates and/or longer distances include electro-absorption (EA) modulators and lithium niobate (LiNbO_3) modulators. EA modulators utilize the effect of an electrically induced shift in the absorption band edge of a semiconductor material. LiNbO_3 modulators utilize an electrically induced phase-shift in the optical beam, which is generally applied in a Mach-Zehnder interferometer configuration.

LiNbO_3 vs InP modulators

Currently the highest performance at high data rates is achieved using LiNbO_3 modulators. These modulators have the

disadvantage of being bulky and requiring large voltage swings ($\sim 7\text{--}8\text{ V}$) which are increasingly difficult to produce at higher data rates (e.g. 40 Gbit/s). Among alternative approaches for modulation at high data rates, InP is emerging as a strong candidate.

The development of either semiconductor-based EA modulators, or LiNbO_3 modulators operating in a differential mode by

In the near future, the "components" being supplied by manufacturers such as Vitesse will actually be entire modules.

taking advantage of the different transport characteristics of these devices when fabricated in alternative crystallographic directions, are two possible solutions.

However, the key challenge in the implementation of InP-based devices for these applications lies not in the individual performance capabilities of the devices, but in the ability to integ-

rate sufficient numbers of transistors, along with optical components, in a cost effective manner. The successful development of such a process will open the way to a low-cost, high throughput, module manufacturing capability that will support 40 Gbit/s optical networking systems.

Conclusion

InP is a very attractive candidate for developing components for the "optical subsystem" at 40 Gbit/s and higher. This material has the potential of data rates well beyond 40 Gbit/s, and is applicable to the electro-optical conversion devices (lasers, detectors and modulators), as well as the electronic serialization/deserialization components.

Ira Deyhimy is vice-president of Product Development and a co-founder of Vitesse Semiconductor Corporation, Camarillo, California. This article is based on a presentation at the 2001 Key Conference, held 5-6 March in Key West, Florida.



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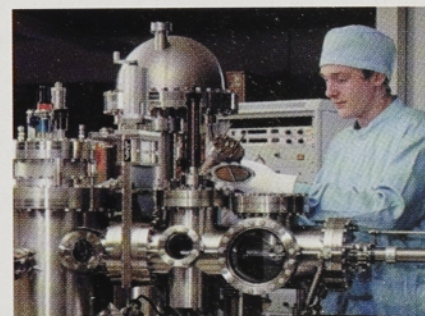
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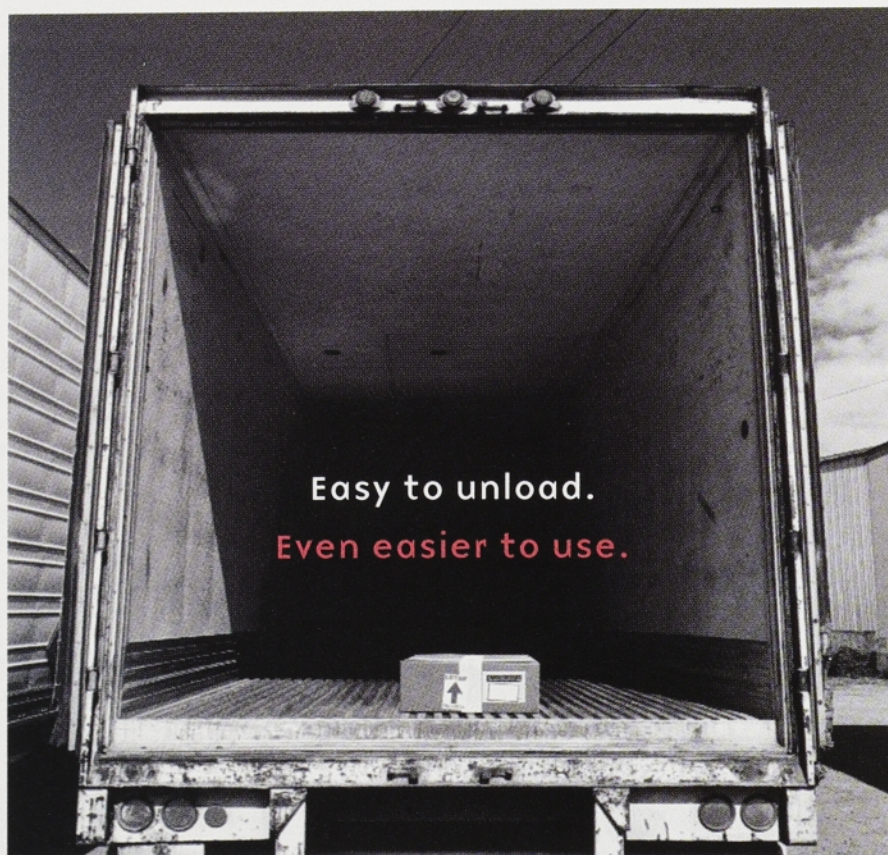
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OEICs: commercialization at last

Applying the lessons learnt by the silicon industry will be crucial if optoelectronic integrated circuits are to make the transition to high-volume production with high yields, repeatability and further miniaturization, writes Michael Lebby of Ignis Optics.

Optoelectronic integrated circuits (OEICs) have gone through dramatic changes in the past two years. Much of this has come as a result of changes in investment dynamics. In 2000, optimism about investments in optical components skyrocketed, as reflected in the fact that roughly \$2 billion was invested in that year. This large amount of capital (a great deal of which was funneled by way of venture capital (VC) investments), coupled with extreme optimism, resulted in relaxed evaluation criteria during the process of due diligence. In such an environment the competition for technical talent was both ruthless and expensive. In addition, many competing startups were funded, including some 30–40 MEMS companies, 20–30 optical systems companies and 30–40 optical device companies. This behavior was not exclusive to the VC or start-up environments. Established companies generated a frenzy of acquisitions at often-inflated values, acquiring companies that had not yet developed products or revenue streams.

The bubble bursts

With radical reductions in stock prices, and the realization that business plans and earnings do matter, the perspective in 2001 is much more prudent and sobering. As a consequence, VC investments in this area will continue, but with far more scrutiny. Many of these start-ups will need to formulate more viable business plans, or else disappear at higher funding rounds. Critical to their success will be the experience of their management team coupled with the ability to nimbly address market demands and execute on their business plans.

The issues now driving VC investment in the optical market are very much the same ones found in the IC market, namely: integration, automation, volume,

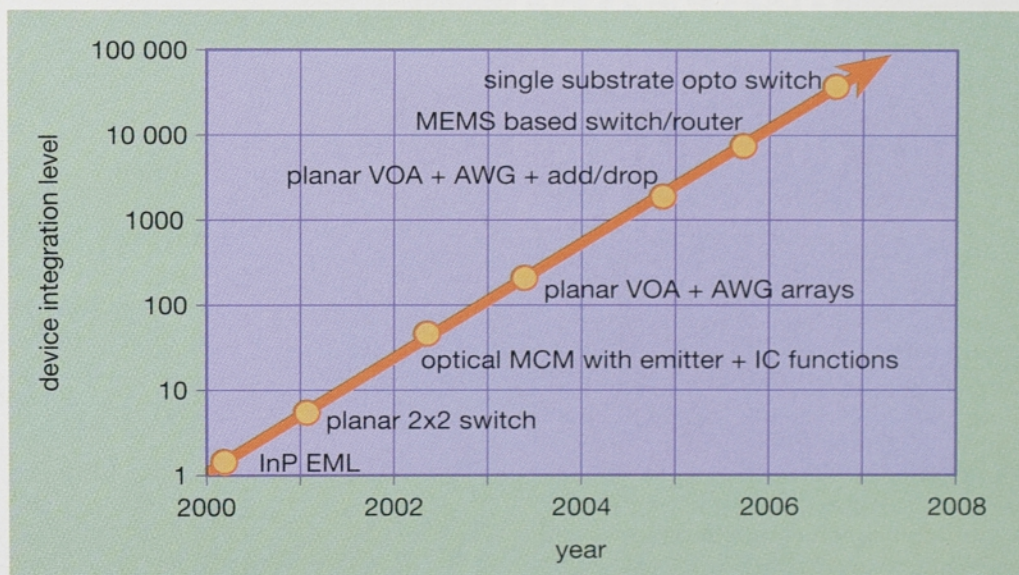


Fig. 1. Possible integration schemes for OEICs. Starting with InP EMLs and progressing to optical multi-chip modules (MCMs). Further integration sees variable optical attenuators (VOAs) integrated with AWGs and eventually single substrate optical switches using over 10 000 devices.

and higher performance coupled with smaller footprints. In addition, if piggy-backing off the IC industry can be achieved, this will be viewed as a bonus. Many silicon foundries and packaging and assembly lines are being viewed as sites to transform optical component manufacturing from a labor-intensive, custom operation into a truly automated manufacturing line. It is in this rapidly maturing environment that OEICs now find themselves.

Integration

The traditional definition of an OEIC implies a monolithic approach with devices lattice matched to a substrate. This method of OEIC fabrication gives lower packaging costs and reduced parasitic inductance and capacitance when compared to the hybrid approach, where individually optimized devices are mixed and matched. Examples of monolithically

integrated devices include PIN photo-detectors integrated with amplifiers, and electroabsorption modulated lasers (EMLs). Here, a DFB laser and voltage controlled optical modulator are integrated on the same chip. This method of modulation allows continuous operation of the laser, minimizing chirp.

Monolithic integration represents a significant challenge when trying to optimize different devices grown in a single epitaxial growth run. Compromises between material choice, high quality epitaxy, and device performance have to be made. One approach to further integration has been to use selective area epitaxy. Here, one of a number of masking techniques can be used to allow deposition of device layers on specified areas of the substrate or upon previously grown device layers.

Different devices may require different material systems to achieve optimal performance. It is here that monolithic

integration stumbles, as lattice mismatching between different materials makes growing high quality crystalline layers difficult. Researchers have been busy trying to overcome this problem using a variety of techniques including wafer bonding (already firmly established in silicon microelectronics and MEMS), and the virtual substrate approach. Here, monolithically integrating III-V based devices with silicon microelectronics is one of the goals.

As suppliers gear up for the implementation of OC-746 40 Gbit/s applications, a number of material systems are being considered for the new generation of devices that are required. InP is being seen by some as the material of choice for these high-speed devices. InP-based lasers and detectors are already established. If other devices are to be implemented in InP then monolithic integration seems a logical step.

Many so-called integrated devices are actually hybrid components, with a number of discrete devices linked together on a single substrate. Examples of the hybrid approach include flip chip lasers mounted onto silicon platforms, opto devices mounted to glass platforms for display applications, waveguide structures with lasers/detectors, MEMS with driver electronics and emitters/detectors, and a variety of tunable lasers. The inherent flexibility of the hybrid approach should lead to a rapid rate of integration, as illustrated in figure 1, which predicts on average a doubling of the integration level every six months. It is anticipated that the growth rate will not be constant, but will show a series of steps and plateaus as new hybrid integration approaches are implemented and brought into production. Early indications are that the level of integration is actually ahead of the curve with examples such as silicon planar optical add-drop multiplexers (OADMs) using arrayed waveguides. These structures have device counts in the 100–200 range for today's 40 channel versions.

DWDM drives greater integration

The major application that is driving this need for integration is the deployment of DWDM systems. These systems are currently moving into the 160 and 320 channel regime, each channel requiring amplifiers, detectors and lasers (although a tunable laser could serve multiple channels). The cost of such sys-

	2000	2005	2010
trunk network			
TDM, single I	40 Gbit/s	100 Gbit/s	400 Gbit/s
TDM + DWDM	1.6 Tbit/s	10 Tbit/s	
interoffice network	2.5–10 Gbit/s	40 Gbit/s	100 Gbit/s
residential access	ADSL (≤ 8 Mbit/s downstream) & cable modems, 155 Mbit/s FTTH	155/622 Mbit/s–2.5 Gbit/s	10 Gbit/s
business access			
TDM w/o WDM	2.5–10 Gbit/s	40 Gbit/s	
• LAN	10 Gbe (~2001)	40 Gbit/s	
• LAN backbone (WDM)	100 Gbit/s	1 Tbit/s	
• wireless LAN	0 Mbit/s	155 Mbit/s	

Fig. 2. The anticipated increase in transmission speeds as DWDM technologies migrate from telecom to datacom applications. This is part of the OIDA roadmap published in 1999.

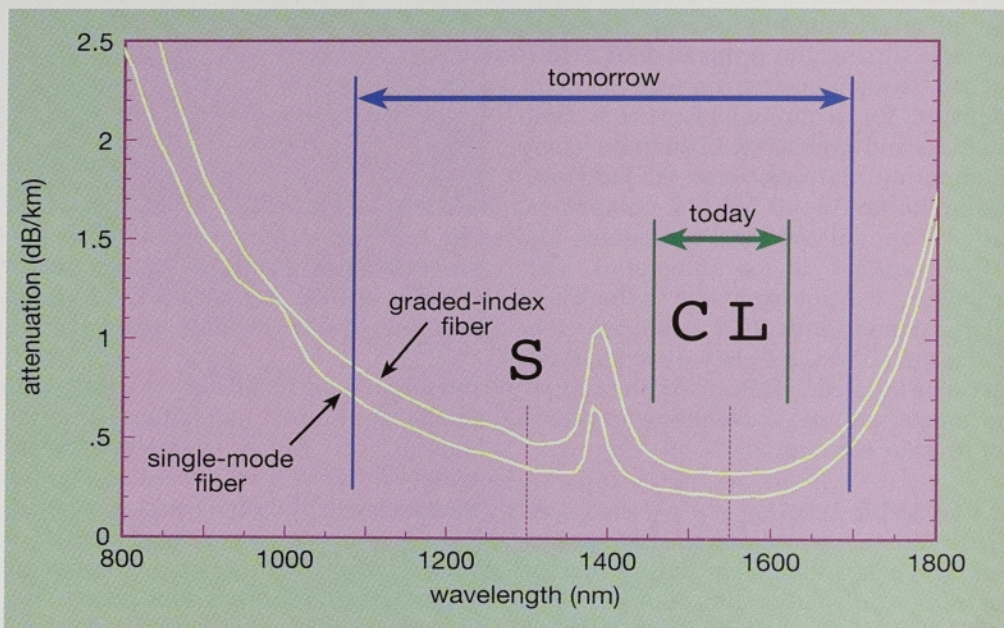


Fig. 3. Wavelength dependence of signal attenuation in fiber. Currently operating over 1530 to 1610 nm, within three years fiber systems should be operating over S, C and L bands from 1100 to 1700 nm. With 50 GHz channel spacing a single fiber will carry 1500 channels.

tems can be greatly reduced by increasing the level of integration, thereby increasing functionality while at the same time reducing footprint and packaging needs. Figure 1 illustrates the various levels of anticipated integration, starting currently with just a few devices, such as lasers, drivers and waveguides, to single substrate optical switch systems anticipated by

2007, using in excess of 10 000 devices.

Life-cycles

In addition to specific applications, it is useful to examine how a technology's life-cycle impacts its deployment. Typically, a newly developed OEIC technology will first see insertion into telecom systems. These can typically afford the

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latest technology since volume requirements are low and margins are high. After telecom systems have tested out the new technology, it becomes inserted into metro telecom/datacom systems, where the margins are still high, but volumes begin to increase. Lastly, the technology is inserted into datacom applications, characterized by cost reduction and very large volumes.

The evolution of OEICs from a costly, low-volume technology to high volume lower cost products, has come about through the explosive growth in single fiber capacity in recent years and the multi-wavelength technologies that have been adopted. The anticipated increase in system transmission speeds as DWDM-type technologies migrate from telecom to datacom applications is illustrated in the table shown in figure 2, which is part of the OIDA roadmap assembled in 1999. Most of these numbers are on track to meet the 2005 goals, with the possible exception of the increase in residential speeds from 155 to 2500 Mbit/s.

Multiplexing pushes up the speed

The great enabler that has pushed both transmission speed and bandwidth has been the ability to pass multiple singles of differing wavelengths through individual fibers. This trend is not expected to diminish in the coming years, but to accelerate. Currently operating over C and L bands from approximately 1530 to 1610 nm, it is anticipated that within the next three years, fiber systems will be able to operate over S, C and L bands, encompassing a wavelength range of 600 nm from roughly 1100 to 1700 nm. With channel spacing of 50 GHz, this would allow a single fiber to carry 1500 channels, roughly 20 times more than is currently possible (figure 3).

The challenges for manufacturing

The technical challenges of developing laser sources capable of operating from 1100 to 1700 nm are daunting. An even bigger challenge is the ability to manufacture such systems today, given a manufacturing infrastructure that is characterized by a low level of automation, yields that are often as low as 10%, a process that does not lend itself to scaling to high volumes, and one that is extremely labor-intensive. This manufacturing bottleneck has been identified, and by applying silicon-processing

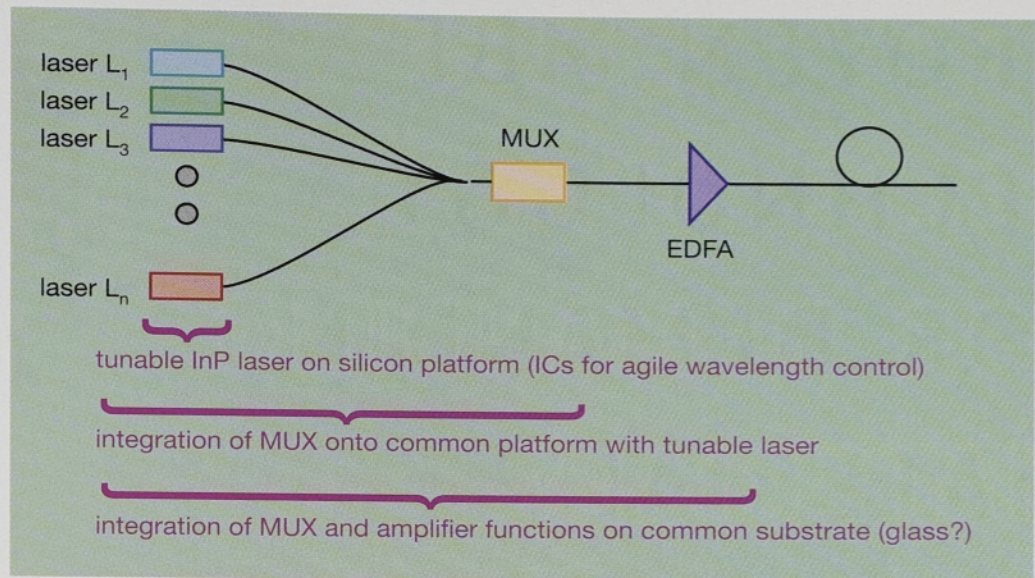


Fig. 4. The evolution to higher levels of integration. A system of multiple lasers of single wavelength followed by MUX and EDFA eventually becomes a tunable laser, MUX and EDFA integrated on a common substrate.

techniques, higher levels of integration are being achieved. The implementation of arrayed waveguide grating (AWG) multiplexers using planar optical sub-assemblies on silicon wafers is a good example of this. This micro-optic form of OEIC has the potential for high-volume manufacturing.

Other approaches to decreasing costs and improving yield are to implement

Many Si foundries and packaging and assembly lines are seen as sites to transform optical component manufacturing from a labor-intensive, custom operation into a truly automated procedure.

AWG multiplexers in InP. The higher refractive index allows a great reduction in device size and monolithic integration with electronics, although there can be high coupling losses to the fiber. Some of these issues can be overcome with a hybrid integration approach by fabricating devices on silicon oxy-nitride. This evolution towards higher levels of integration is illustrated in figure 4. A system of multiple lasers of different wavelengths, followed by a MUX and erbium doped fiber amplifier (EDFA), is superseded by a tunable laser on a silicon platform providing the wavelength control ICs. Further integration follows with the MUX on the same platform as the tunable laser. Eventually, the EDFA is integrated

with the MUX and laser functions on a common glass substrate.

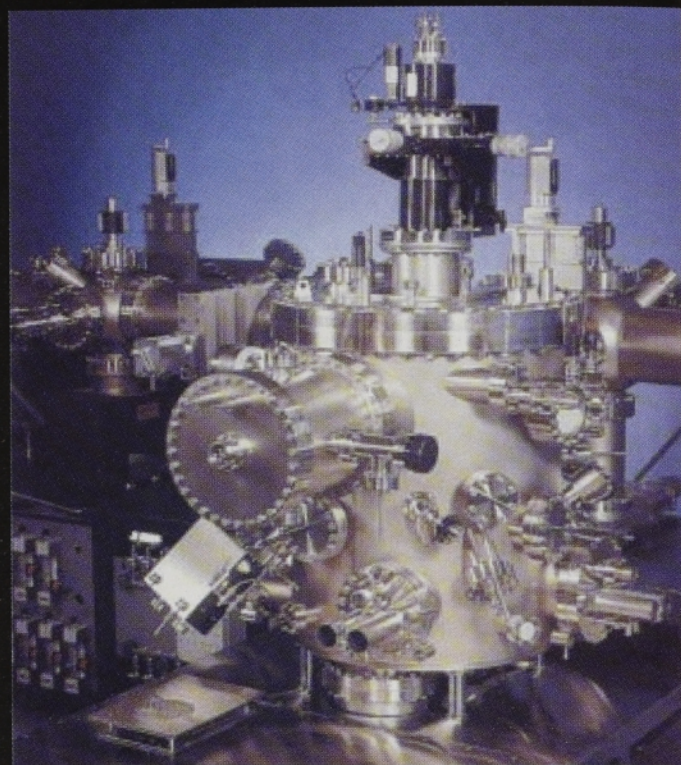
Conclusions

Expertise developed by the semiconductor industry over the last 30 years will help to overcome many of the hurdles that OEICs will face in the near future. This is especially true in making the transition from small volume, labor-intensive production to high volumes where higher yields, greater repeatability, better tolerances and smaller devices will be critical. Further improvements will be obtained when these manufacturing enhancements are coupled with the use of silicon or silicon-like platforms in a hybrid integration approach. In addition, the design, foundry, and packaging aspects will be just as critical as any other aspect of the manufacturing process, including the need for the development of improved device simulation and CAD tools. Adopting the big fab mentality of running large numbers of devices, and using existing silicon packaging lines to assemble OEICs, will enable advantage to be taken of the development and know-how that silicon manufacturers have already brought to bear on the high-volume packaging problem.

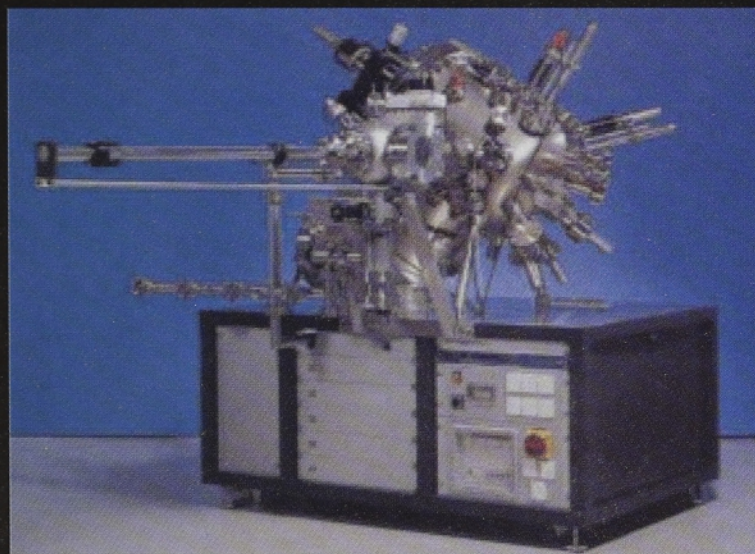
Michael Lebby is the CEO of Ignis Optics, San Jose, California. Web: www.ignisoptics.com. This article is based on a presentation at the 2001 Key Conference, held 5–6 March in Key West, Florida.

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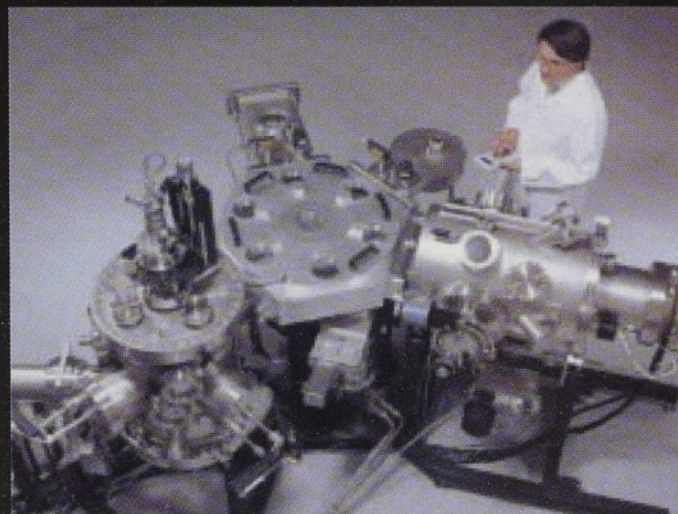
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Fabrication challenges for enabling metropolitan WDM network technologies

*Issues relating to the fabrication of echelle grating demultiplexers based on indium phosphide – a building-block for next generation integrated optical components – are described by **Bedwyr Humphreys** and **Emil Koteles** of MetroPhotonics Inc.*

The Internet's future depends on migrating the large bandwidth that is present in optical backbones of telecommunications networks around the world to homes and businesses. Long haul WDM components, the savior of the backbone, are just too expensive for metropolitan markets.

The key enabler is cost. Recent advances in monolithically integrated (de)multiplexers (planar waveguide etched grating devices) and a novel, elegant technique for flattening DWDM channel spectra without increasing crosstalk promise a cost-effective solution. Inexpensive WDM components, made possible by photolithographic processing techniques and increased manufacturing tolerances, will help unleash the full potential of the Internet to all.

Until recently, WDM signal processing (generation, detection, multiplexing, demultiplexing, etc) has been accomplished using discrete optical components. These perform well but their fabrication is labor intensive and so they are expensive to manufacture. It is universally believed that the next generation of optical components will be based on integration technology. The planar waveguide is the technology of choice for monolithic photonic integrated circuits (PICs) since such circuits can be easily fabricated using standard semiconductor photolithographic processing techniques.

Two-dimensional (planar) optical waveguides can be fabricated using a variety of materials, although glass and semiconductors are the most common. By increasing the refractive index slightly (for example through the use of ridges – see figure 1), light can be directed, at will, in the plane (Koteles).

Some two decades ago, planar waveguides were first proposed for demulti-

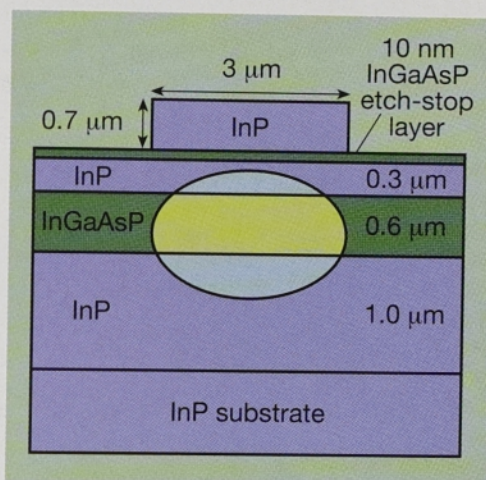


Fig. 1. Typical layer structure of an InP-based single mode planar waveguide. The refractive index of the InGaAsP core layer ($\lambda_g = 1.0 \mu\text{m}$) is slightly larger than that of the InP cladding layers, and the core region under the InP ridge has a higher index than that on either side, thus confining the light.

plexing (and multiplexing) WDM wavelengths. The first “spectrometer-on-a-chip” was based on echelle grating technology, itself over a hundred years old. Figure 2 schematically illustrates a typical etched grating demultiplexer (DEMUX) based on InP waveguides. Light from a singlemode fiber is coupled into the edge of the chip at the input waveguide. The light follows the guide to its end, where it begins to expand in the 2-D plane until it reaches the grating, which is etched through the waveguide. The grating reflects and disperses the light and focuses it onto an arc located near the input waveguide. There, a series of output waveguides collects the dispersed light and transports it to the edge of the chip, where it is either detected or collected by other optical fibers. The fabrication of the grating required a deep

vertical etch with smooth sidewalls, but unfortunately such capability was not available at the time. For these reasons, Meint Smit of Delft University in the Netherlands and others (Smit) developed an alternative technology, the phasor or arrayed waveguide (AWG) DEMUX. This device solved these issues but had other drawbacks (see sidebar “Echelle grating and AWG demultiplexers”).

Fabrication challenges

Deep vertical etching of semiconductor material has come a long way in recent years with much attention being paid to materials such as InP and GaAs. In particular, many studies looked at the possibility of using dry etching for on-chip facet fabrication in long-wavelength InP-based devices. Early studies used reactive ion etching (RIE) to achieve the anisotropy required, and although successful in principle, many of the processes could not be implemented for manufacturing due to very low etch rates and excessive damage. The development of the inductively coupled plasma (ICP) source for use in semiconductor processing proved to be a turning point, providing higher etch rates, improved anisotropy and the potential for lower damage processing.

Many of the factors considered for the fabrication of etched facets also apply to the fabrication of echelle gratings. These factors are primarily confined to photolithography and etching, with key requirements on certain process parameters.

Photolithography requirements

Correct selection of photolithography tools can mean the difference between success and failure, hence a thorough understanding and analysis of key device parameters and how they may be affected by the photolithography process is essential.

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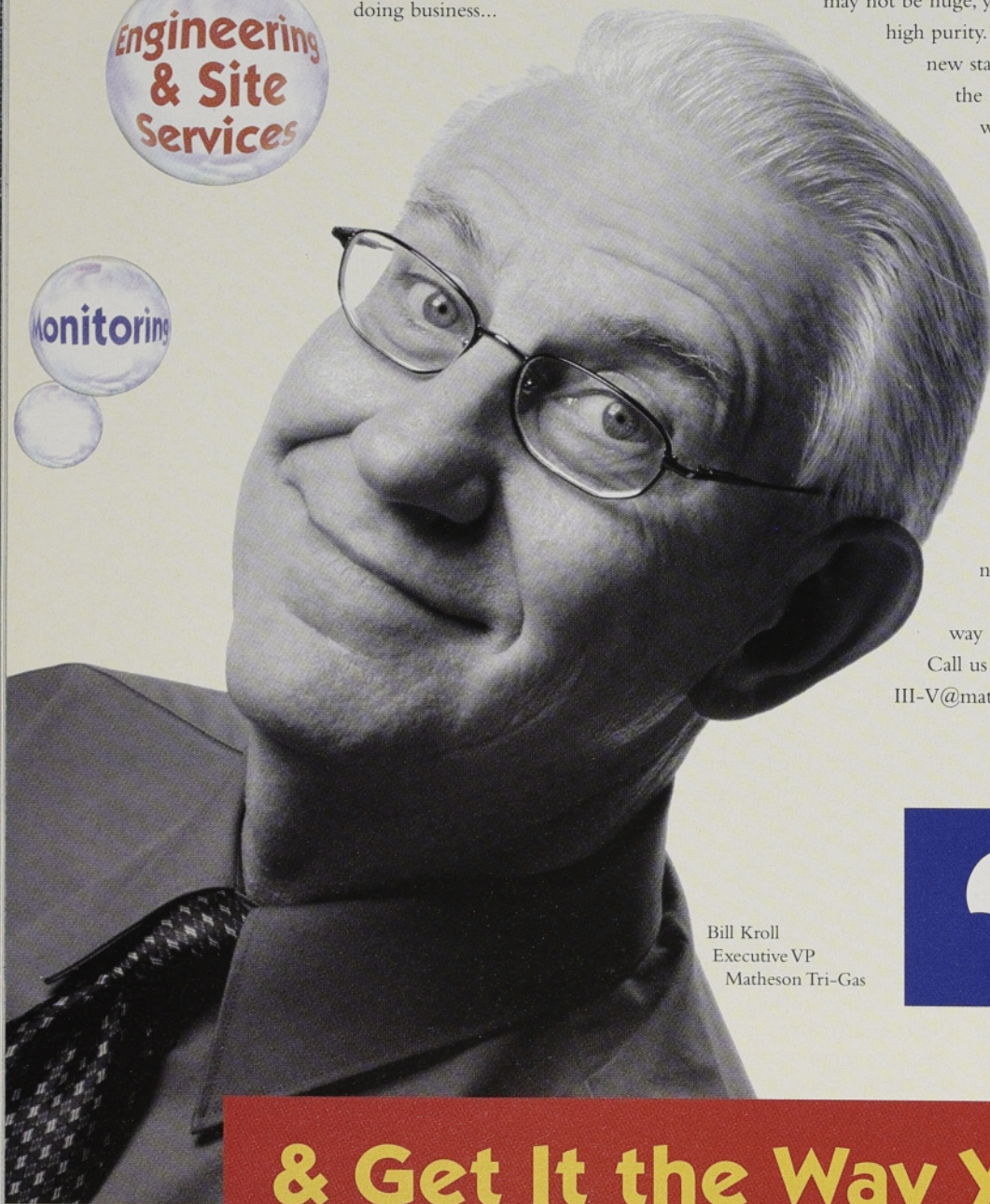
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Photomask fabrication There are a number of choices to be made regarding the type of photomask to be used, e.g. binary, phase shifted, laser write, in addition to the choice between 1:1 or 5:1 pattern transfer. The photomask fabrication method employed and the choice of materials determines the accuracy of the pattern on the mask or reticle as well as the quality, e.g. feature resolution (rounding errors) and stitching errors. Rounding errors result from the finite step size of the mask machine, whereas stitching errors occur when small write fields are "stitched" together to form a large element, e.g. the array of waveguides in the AWG.

Rounding errors The impact of rounding errors on device performance is to produce a more or less constant noise background (non-adjacent crosstalk) that decreases as rounding errors are reduced. In addition to photomask rounding errors, rounding at sharp feature edges can occur during pattern transfer due to nonlinear distortions caused by optical diffraction and resist process effects. Causes include reticle pattern fidelity (as discussed), optical proximity effects, and loading effects during resist and etch processing.

Stitching errors When translated onto the device, stitching errors on the photomask produce mode structure on the sides of the main channel spectra that die away in intensity as a function of distance. These "ghosts" can be eliminated by using only one field (no stitching) or by increasing the field size. It is possible for an etched grating DEMUX in InP to be written in a single field since the grating size is comparable to the largest field size (~1 mm) in state-of-the-art e-beam writers.

In addition to photomask considerations, the more typical manufacturing elements to consider include photoresist thickness and uniformity, and exposure dose reproducibility and uniformity, all of which need careful control using statistical process control (SPC) techniques. For example, photoresist thickness and uniformity can drift out of specification if environmental controls for temperature and humidity fluctuate beyond a few degrees.

Dry etch requirements

One of the major requirements for the fabrication of echelle gratings is a vertical etch profile. Typically, the tolerance on the profile angle for achieving a working device with acceptable losses is less than $\pm 0.5^\circ$. Achieving this specification de-

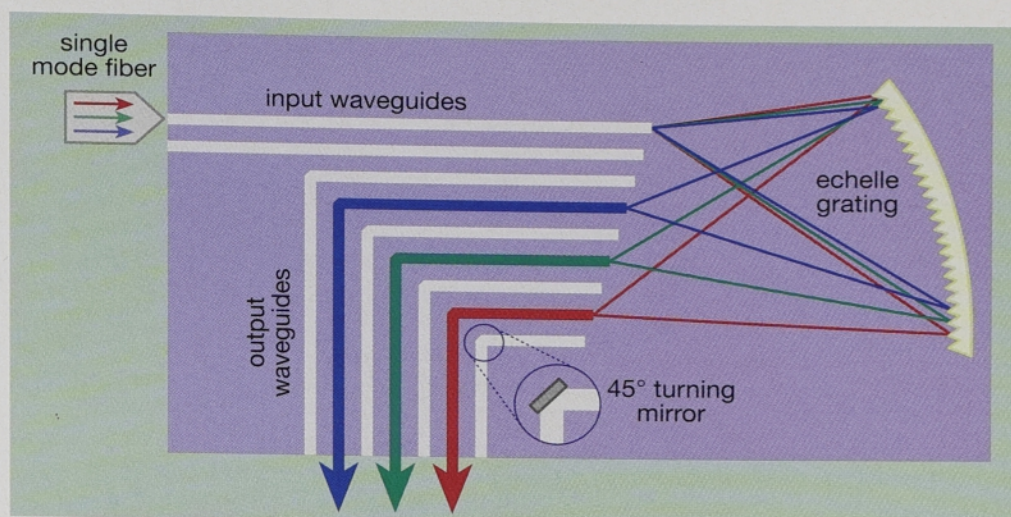


Fig. 2. Schematic diagram of an echelle grating planar waveguide (de)multiplexer.

Echelle grating and AWG demultiplexers

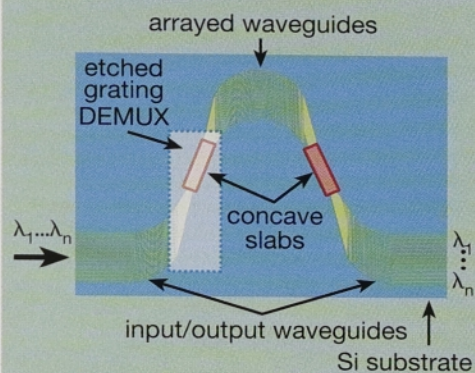


Fig. 3. Schematic diagram illustrating the relative sizes of etched grating and AWG planar waveguide DEMUXes.

The echelle grating and the arrayed waveguide demultiplexer both work on a similar physical principle. The facets of the grating and the ends of the waveguides act as a series of coherent light sources. By precisely adjusting the phase shift from each source relative to all the others, an interferometric pattern is set up which results in light of different wavelengths being focused at different spatial locations on an output arc.

The phase shift in the case of the

echelle grating is simply determined by the relative position of each facet with respect to the others. In the case of the AWG, the phase shift is accomplished by adjusting the length of each waveguide with respect to the others.

The major differences between the two devices lie in size and phase shift accuracy. An array of waveguides is generally much larger than a grating (usually a factor of 4 or 5 for similar performance – see figure 3). This affects not only the number of chips per wafer, but also yield, as non-uniformities across the chip become more critical the larger it is. Furthermore, as the channel spacing decreases, necessitating a significant increase in the number of waveguides required to increase resolution, total component size increases dramatically. Echelle gratings require an increase in the number of facets, which is easier to accommodate without resorting to significant size increases.

As discussed in the main text, phase error accuracy is easier to control in etched grating DEMUXes since only facet positions affect it; in AWGs, additional phase errors can be generated in the waveguide array itself.

depends on a number of parameters, both lithography- and etch-related. These include the following.

Vertical etch-mask profile A sloped etch-mask profile is more likely to result in a sloped feature etch, especially when the mask selectivity is low (see figure 4).

High mask selectivity The greater the selectivity between the mask and the etch layer, the greater the likelihood of a vertical etch profile regardless of the mask profile. Infinite selectivity processes are almost impossible to develop, hence a combination of vertical profile and high

Materials for planar waveguides

Glass waveguides are typically formed by growing thin layers of glass (SiO_2) of various compositions on silicon substrates. This is a complex process requiring precise control over all aspects of the layers. Uniformity and reproducibility of the waveguide refractive index are important issues. Since the layers are grown at elevated temperatures and the temperature coefficient of expansion of silicon and SiO_2 differ significantly, room temperature strain is also an important issue. That being said, a number of companies have developed the technology for fabricating glass waveguides and AWG DEMUXes based on them. The important advantages of

glass waveguides is their stability, low propagation loss, and low coupling loss. However, since they are dielectrics, it is difficult to envision their monolithic integration with active devices such as optical amplifiers, photodetectors, etc.

Semiconductor waveguides are grown by MBE, MOCVD, CBE etc – the same techniques used to fabricate active optoelectronic devices such as lasers, SOAs and photodetectors. Therefore, quality semiconductor waveguides can be obtained in quantity from the same manufacturers that supply the active WDM component industry. Semiconductor waveguides typically have a somewhat larger propagation loss than glass waveguides, although this is

offset by the smaller device size since the refractive index is more than double that of glass. Waveguide uniformity, reproducibility, and stability are equal to or better than glass waveguides, and they are commercially available. Furthermore, novel waveguide designs can match glass waveguide coupling losses while increasing wafer yields.

Finally, using semiconductor waveguides it is possible to monolithically integrate active elements such as photodetectors with passive planar waveguide DEMUXes, thereby achieving true photonic integrated circuits. It will also be possible to integrate optical amplifiers with passive DEMUXes, thereby producing truly lossless DEMUXes.

selectivity is the optimum practical solution (see figure 4).

Low mask damage Minimal damage to the mask edge is required to prevent loss of mask integrity at the mask/semiconductor interface. Low mask damage also reduces the likelihood of vertical striations being transferred from the mask edge into the etched feature. Facet striations in all optical devices should be kept to a minimum.

High anisotropy Zero undercutting of the mask maintains precise feature pattern transfer into the etched layer. The etched profile should remain vertical throughout with no bowing of the profile.

High etch rate Echelle gratings or etched facets usually require a relatively deep etch, thus a high etch rate is desirable to maintain a reasonable wafer throughput.

Hardware configuration

Having defined the process requirements and characteristics, the next step is to determine the hardware configuration best suited to achieve the requirements. The types of system currently on offer for plasma etching include parallel plate RIE, magnetically enhanced RIE (MERIE), MORI ($m=0$ resonant induction) and ICP. The suitability to the task can be determined by assessment of the critical operational parameters and how these in turn affect the defined process requirements and characteristics. The critical operational parameters in plasma etching are process pressure, ion energy, ion density and process chemistry.

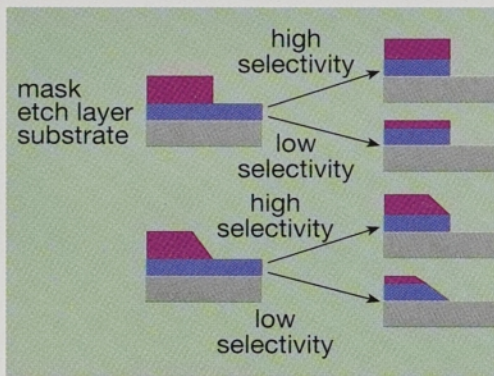


Fig. 4. Schematic emphasizing how the combination of mask profile and process selectivity contribute to the final etched profile.

Low pressure processing (<10 mT) This is accepted as a method for improving profile control, particularly for deep, high aspect ratio features. In plasma terms, low pressure increases the mean free paths of the plasma species thus reducing ion/neutral scattering in the sheath, which in turn promotes improved directionality of ion trajectory. Additionally, lower pressure processes increase the volatility of etch by-products, thus promoting a “cleaner” residue-free etch surface after etching. In general, low pressure processing is desirable for deep vertical etching (Coburn and Winters).

Ion energy This is commonly referred to as DC Bias in conventional parallel plate RIE. The ion energy determines the physical etching component for the process, which in turn determines the physical/sputtering damage occurring at the wafer

surface to both mask and etch layer. Generally, for vertical feature etching, the mask material is chosen so as to be inert (or as resistant as possible) to the process chemistry. However, the physical component of the etch can still result in a high sputter etch rate for the mask, which can lead to mask sidewall damage, causing vertical striations in the etched profile.

High ion energy also creates mask edge faceting caused by the increase in sputter etching for angled facets related to the angular dependency of sputter etch for the mask material. Mask faceting results in a loss of profile control as well as a roughening of the etch near the mask edge. In addition to mask damage, high ion energy can also lead to lattice damage by collision cascade and preferential sputtering in the etching layer. However, one of the benefits of high ion energy is the potential for higher etch rates through ion-induced chemical reaction (i.e. chemical reactants desorb on the wafer surface, but do not react until additional energy is provided). In general though, a lower ion energy figure is desirable to maintain high mask integrity for deep vertical etching.

Ion density The ion density in the plasma in effect determines the chemical etch component of the plasma through ion/neutral and electron/neutral collisions. A high chemical etch component (compared to the physical etch component) can lead to reduced etch damage, and, with careful selection of process pressure, can result in very high rate etching.

The disadvantage of a high chemical

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etch component is the increase in the isotropic nature of the etch, which is highly undesirable for deep vertical etching. It is therefore important to maintain a high ion density (to maintain a high reactive neutral density), but to ensure that the reaction mechanism at the wafer is induced by low-energy ions. This has the effect of promoting high rate, but also high anisotropy, so long as the ions arriving at the wafer surface do so perpendicular to the plane.

Furthermore, the ion density at the wafer surface is an important value since it determines etch rate and damage. It is more desirable to have a high ion density at the wafer surface to promote higher etch rates, but the ion energy should be low to restrict physical damage. In summary, a high ion density in the plasma and at the wafer surface is desirable to maintain higher etch rates for acceptable throughput whilst minimizing physical damage.

Chemistry The choice of chemistry determines the etch rate, the uniformity, the verticality and the level of damage. The basic approach is to determine what gas or gases, under plasma excitation, will react with the solid to be etched (the wafer) to form a volatile by-product, i.e. another gas. A reaction that takes place spontaneously at the surface, without the need for ion excitation, is similar to a wet etch – under these circumstances, etching proceeds in all directions resulting in an isotropic etch. To improve anisotropy a second gas can be added to provide sidewall passivation. Usually this occurs through polymerization, which forms on all surfaces of the wafer but is removed from the horizontal areas by ion bombardment. The polymer therefore continues to form on the vertical features, thus providing sidewall protection from the isotropic etch chemistry.

Similar to this method is to choose a gas chemistry which does not react spontaneously with the wafer but will do so under ion bombardment, i.e. ion-induced reactions. This type of reaction needs additional energy to take place, which is supplied by the incident ions. So long as the incident ions arrive perpendicular to the surface, the resultant etch proceeds vertically.

In addition to the four primary parameters, process temperature is also an important factor to consider as higher temperatures increase the volatility of the etch by-products. This can mean higher

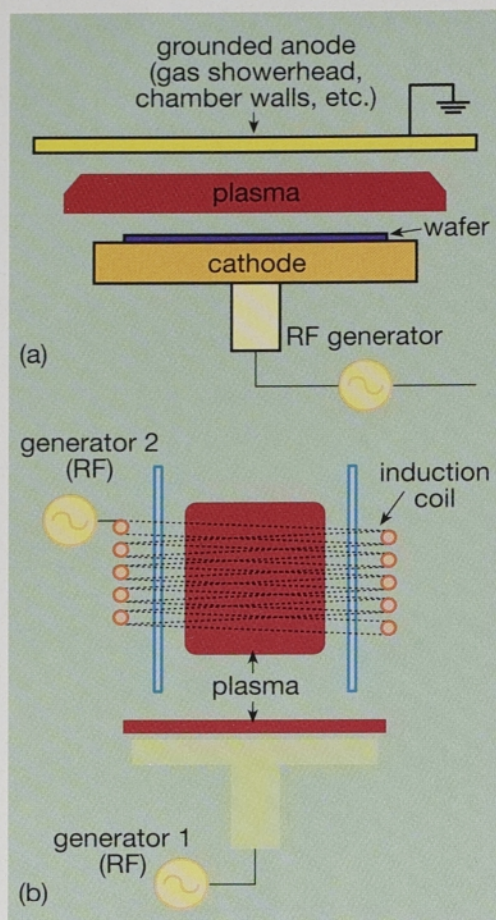


Fig. 5. Schematic of (a) a conventional parallel plate RIE system, and (b) an ICP system.

etch rates, but at the expense of greater lateral etching. Therefore, an understanding of the effect of temperature on the process, and how this can be compensated for, is essential for fabricating deep vertical features.

In summary, the hardware configuration required must be capable of providing a low pressure, low ion energy and high ion density plasma.

Hardware technology

Parallel plate RIE In a typical parallel plate RIE configuration (figure 5a), a single RF generator is connected via a matching unit to the lower electrode (wafer table). When the area of the RF-driven electrode (cathode) is smaller than the area of the grounded surfaces forming the anode (such as the gas showerhead and chamber walls), a self-bias is formed on the cathode due to the greater mobility of the electrons compared to the mobility of the ions in the plasma. Ion density and ion energy are directly related, since an increase in RF power leads to an increase in the ion density, which in turn results in

an increase in the self-bias.

The pressure response for the parallel plate RIE is also a limiting factor due to decreasing ion densities at decreasing pressure. The increased mean free path at lower pressure results in a lower number of plasma-generating collisions, leading to an increasing dominance of the plasma loss mechanisms. The increased mean free path at low pressures also results in a higher self-bias due to a reduction in energy dissipating collisions (Van Roosmalen *et al.*). Therefore, under the required low pressure operating regime, a parallel plate RIE reactor will generate a low ion density and a high ion energy plasma – the opposite in fact to the ideal characteristics required for deep vertical etching.

ICP Compared to conventional RIE the ICP, one of the many high-density plasma systems currently available to the semiconductor industry, has the advantage that two RF generators are used as opposed to one (figure 5b). One generator (Gen 1) is connected directly to the lower electrode as in the RIE case, while the second (Gen 2) is connected to the induction coil. Gen 1 creates a conventional RIE plasma at the electrode surface resulting in a self-bias, whereas Gen 2 creates a remote plasma, independent of Gen 1, in the region above the wafer. Simply put, the ion energy (controlled by Gen 1) becomes independent of the ion density (controlled by Gen 2).

High-density plasma systems typically provide a plasma ion density of 10^{11} – 10^{12} cm⁻³. Such systems, including the ICP, rely on resonant energy transfer and some degree of plasma self-confinement (a time-varying axial magnetic field induces an azimuthal electric field, thus confining the plasma current) resulting in a high-density plasma even at low process pressures. Additionally, higher ion densities at the wafer surface decrease the thickness of the plasma sheath, further reducing ion/neutral scattering, a feature desirable for deep vertical etching.

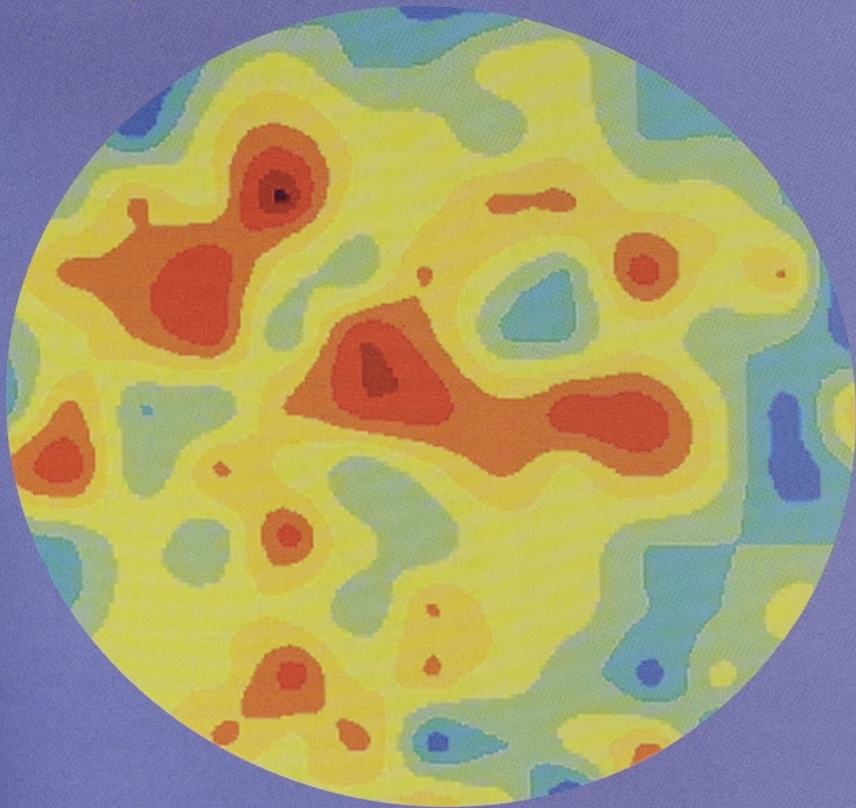
Therefore, unlike the conventional RIE system, the ICP operating regime provides the opportunity for low pressure with high ion density at low controllable ion energy – ideal for deep vertical etching. Some recent results achieved using ICP for echelle grating devices fabrication are shown in figure 6.

Manufacturing and SPC

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remaining part involves linking all the processes together in a sequence to form a manufacturing line. Processes that work well in isolation may begin to drift when repeated a number of times, or may simply be too sensitive to external factors to be of any use in a production environment.

The goal in developing processes for manufacturing is to maximize the operating window for the process so that small fluctuations, e.g. in gas flow or pressure control, are tolerated and have little or no effect on the process result. It is therefore important to determine the sensitivity of the process to its various parameters and to monitor those on a regular basis.

This leads to the use of SPC to monitor both process and equipment behavior. The most commonly used SPC charts are the X bar (mean) and R (range) charts, which record respectively the mean value and the range value for a particular process. For example, process etch depth across a wafer may be monitored at five points on the wafer. The mean value of those five points is recorded on the X bar chart, whilst the difference between the maximum and the minimum points is recorded on the range chart. An equipment-related check would be the day-to-day stability of mass flow controllers (an important factor in ensuring reproducible process results), where daily checks on the partial pressure response and gas calibration factor can be carried out and plotted on an SPC chart.

When a process is in statistical control, the only variation seen in the process is due to random causes (natural variation), for which there is no assignable cause. Therefore, if the variation is deemed too great, then the only way to tighten the distribution is by making a process change, e.g. widening the process window. This is often called a "management team solvable problem".

If, on the other hand, the control chart indicates that the process is out of statistical control, it means that an assignable cause is present and it can be found and corrected, e.g. the etch depth is too deep due to endpoint system failure. This is often called a "floor solvable problem".

The upper and lower control limits (UCL and LCL) for the chart are determined during chart set-up, where a number of points from an initial sample (e.g. 20) are recorded on the chart. The control limits are then determined using statistically derived equations, where the sample

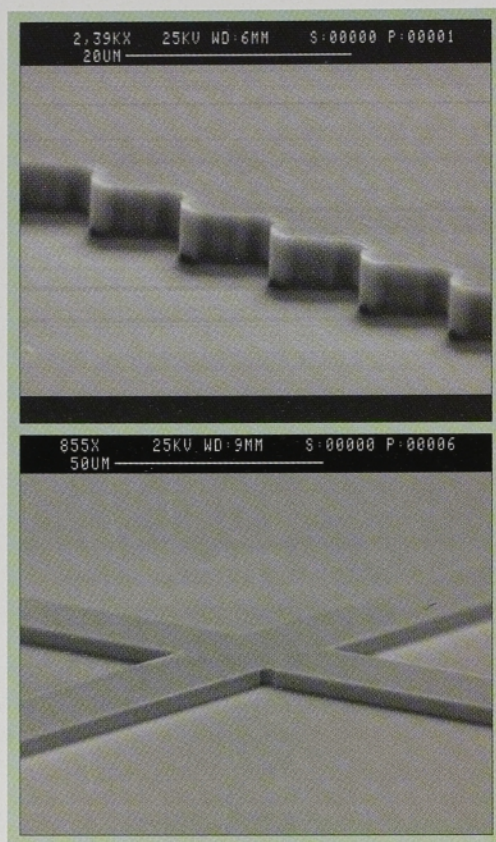


Fig. 6. Vertical echelle grating facet structure, etched to ~6 µm deep using an ICP etch process (top). Waveguide feature in InP (bottom).

size, the mean and the range are all taken into account to give the final answer. It is important at this point to compare the measured variation (i.e. the spread) of the process, with the pre-defined limit set by device performance criteria. For example, the process variation for critical dimension control is ± 50 nm, whereas the acceptable device performance criterion is ± 30 nm. In this example, the required specification is tighter than the achievable specification and therefore a certain percentage of fabricated devices will be outside the acceptable criterion. At this point, improvements in the process are sought in order to tighten the process variation to bring them within the defined specification. The predefined limits are referred to as the upper and lower specification limits (USL and LSL) or tolerance limits.

Process capability (C_p or C_{pk}) is a measure of the match between the control limits and the specification limits and is reported as a ratio. C_p simply compares the specification limits with the control limits, whereas the C_{pk} value compares the limits, but also takes into account the

deviation of the process from the target mean. The C_{pk} is therefore the more meaningful measure of capability.

If the control limits are wider than the specification limits, then the value is less than 1, i.e. some items will fail. If the control limits are less than the specification limits, then the value is greater than 1, while if the limits are equal, the value is 1. Most companies aim to maximize the capability figure and often insist on a C_{pk} of greater than 1.33. The aim then is to maintain a process of continuous improvement to make further increases to the C_{pk} value (Dietrich and Schulze).

By using SPC techniques, problem areas within the manufacturing line can be easily identified and improvements made. All of which contributes to increasing process yield, a major factor in determining device cost and hence the acceptance of such devices for optical networking.

Summary

The fabrication of devices based on echelle grating for WDM applications poses a number of technological and manufacturing problems. Using present day fabrication technology designed specifically for compound semiconductor applications, MetroPhotonics has overcome and solved a number of technology barriers, especially those related to the fabrication of deep vertical facets. From a manufacturing perspective, implementation of established silicon IC industry techniques, such as SPC, provides the means for control of manufacturability which is now necessary for products from the emerging arena of compound semiconductor device manufacturing.

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Bedwyr Humphreys is director of device fabrication and Emil S Koteles is a founder and chief technology officer of MetroPhotonics Inc, Ottawa, Canada.

Surface emitters revolutionize photonics

New approaches to the design and manufacture of surface emitting lasers will help fiber to further penetrate all areas of the network. Malcolm Thompson and Aram Mooradian of Novalux explain how.

Recent years have seen a massive proliferation in fiber infrastructure, starting with a few high bandwidth, long distance, submarine-based systems, and eventually reaching down to enterprise and even residential fiber applications which represent a potentially huge fiber market. For each one of these applications, the available channel bandwidth is growing at a phenomenal rate, as illustrated in figure 1, with all applications seeing growth of 1–2 orders of magnitude in the last decade. This growth rate is expected to continue for the next decade.

Lasers lift the barriers

It is often assumed that it is the core of fiber infrastructure – the physical fiber lines – that are the limiting factor to future growth. To examine this hypothesis, the fiber environment in the vicinity of the Novalux headquarters building in Sunnyvale, California was investigated. Nine different fibers had been laid within 100 yards of the building.

That so many fiber lines lie so closely together demonstrates that fiber is not the rate limiter to further fiber penetration. The true limiter lies in the component cost of connecting to the fiber. A typical optical add/drop multiplexer (OADM) might cost \$100 000. The need for low-cost lasers, a basic building block of all optical systems including the OADM, is critical to further penetration.

Lasers are used in several components in the system, including erbium-doped fiber amplifiers (EDFAs), which need to be replaced, especially in the dense metro environment, by lower cost amplifiers. It would also be best to incorporate lasers that are directly modulated, chirpless and tunable into today's transmission systems. Tunability not only reduces the laser count in DWDM systems (where currently up to 160 different wavelengths are

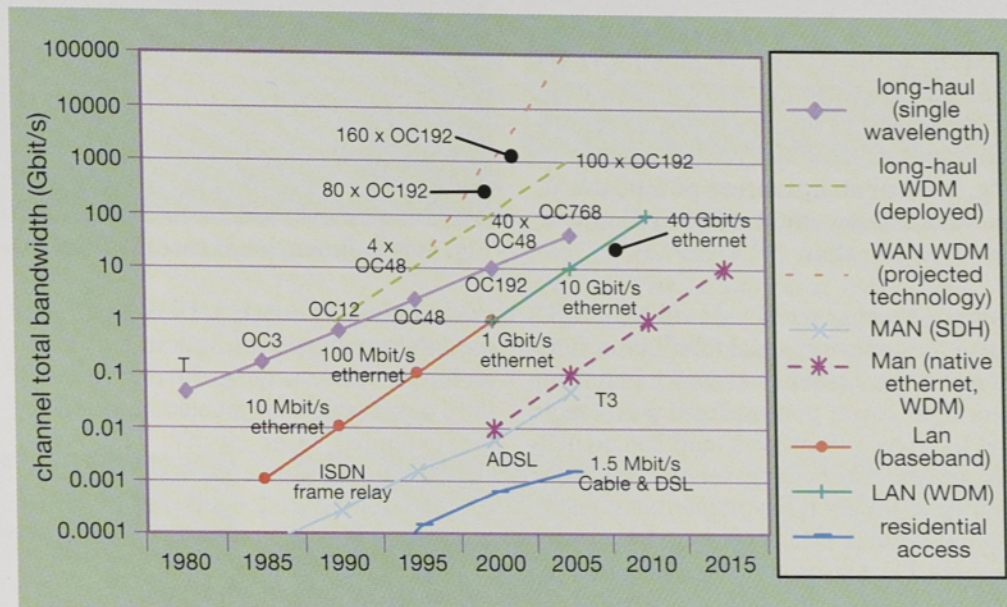


Fig. 1. Past and predicted future growth of channel bandwidth from residential access to long distance submarine-based systems.

required), but would also radically reduce the number of spare transmitters needed to maintain system reliability. A single tunable laser can act as a back-up for a multitude of different wavelengths.

The opportunities in this area are huge. In the period 2000–2004, total networking expenditures are expected to grow from \$10.5 to \$47.5 billion, with the components segment growing from \$4.5 to \$24 billion, according to RHK, a market researcher in telecom components.

In addition, the infrastructure needed to support and utilize fiber networks is growing at an explosive rate, but the continued growth of all of these sectors relies on a decrease in the cost of components. This cost reduction will be led by those components that are designed for automation and high-volume manufacturing.

Currently the photonics manufacturing industry is in its infancy. This typically means an industry focussed on product research, brute force approaches to solving problems, homegrown equipment, a

lack of sophisticated high-volume infrastructure, and low revenue per employee. In many ways the photonics industry is where the silicon industry was 20–30 years ago. The lessons learned by the silicon industry, and even more importantly the attitude of silicon manufacturers, must be applied to the photonics industry. Part of this attitude is the establishment of highly manufacturable, baseline products. These would be based on standard design rules and standard process modules, and would utilize the vast amounts of data generated in the manufacturing process to control and maintain product specifications. In this environment manufacturing times for a given product will be radically shortened, and this will act as a vehicle for increasing yields and outputs.

NECSELs

At the core of Novalux's approach to manufacturing a wide range of optical components is the Novalux extended cavity surface emitting laser (NECSEL) plat-

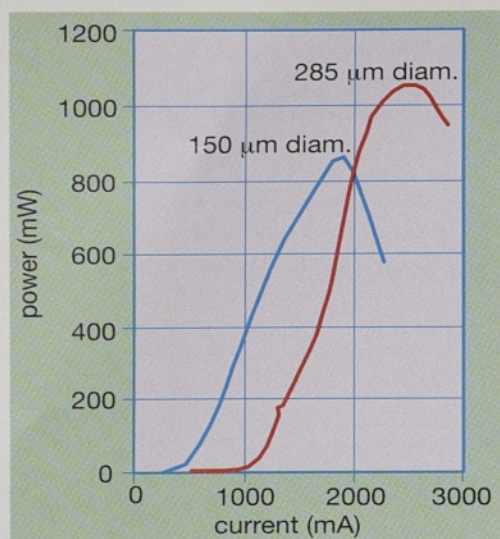


Fig. 2. At peak operating power, the current density in the 150 μm diameter device is less than 10^4 A/cm^2 .

form. The characteristics of NECSELs make these devices ideal for all laser functions in the optical network, including very high power pumps, fixed wavelength and tunable transmitters, and fast switching architectures. In essence, this is the first high-power laser platform amenable to high-volume manufacturing because of its surface-emitting characteristic and thus lower costs for telecom components.

NECSEL technology

Key to high performance optical communication networks are high power EDFA pumps. These are typically edge-emitting 980 nm lasers (as opposed to surface emitting lasers). The limitations of these lasers are the damage to the optical facet that can occur at high power levels, as well as the need for external gratings for wavelength stabilization. Other laser sources include surface emitters that are capable of very high powers from large apertures, but which experience current crowding and operate in a multimodal fashion, which is not appropriate for a conventional EDFA. NECSEL technology solves these problems with an electrically pumped GaInAs surface-emitting laser in which both the optical modes and the wavelength are controlled by an extended cavity. These lasers are capable of producing extremely high power levels of more than 1 W cw in multimode operation and more than 500 mW cw in a single TEM_{00} mode.

NECSELs use a three-mirror coupled cavity design (see *Compound Semicon-*

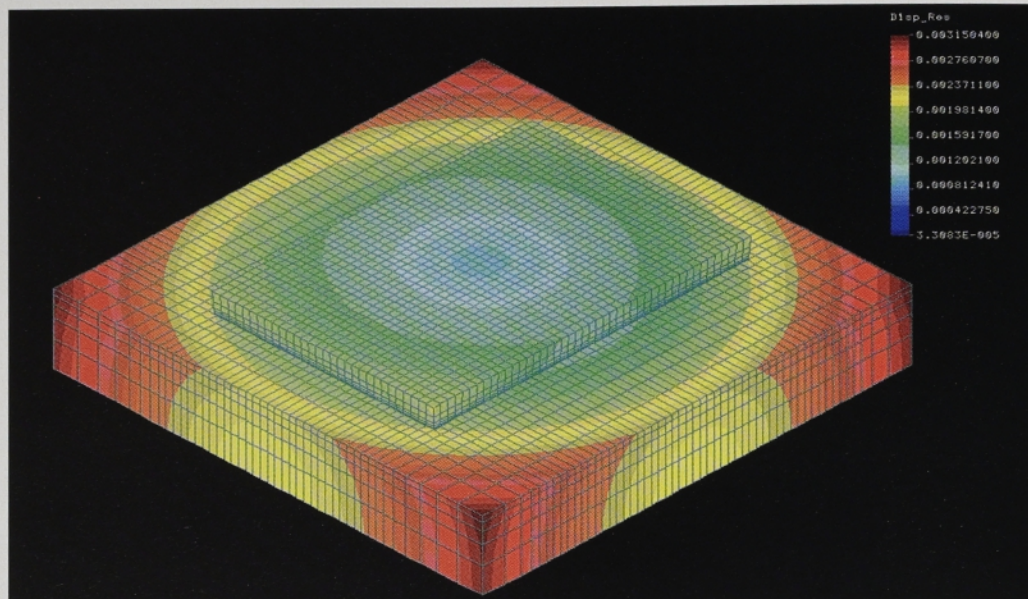


Fig. 3. A 3-dimensional model of the stress field of a NECSEL on a heat sink.

ductor May 2001, p51). DBR layers are used to form the p-type bottom mirror and an intermediate n-type mirror, while the third output mirror is located at the end of the extended laser cavity. The active region of the laser consists of GaInAs strain-compensated 8 nm-wide MQWs grown by MOCVD on n-type GaAs substrates. Current is injected through a circular p-aperture defined by a Si_3N_4 layer, while the n-contact has an anti-reflection coated circular aperture to allow the beam through to the external mirror. The n-aperture is larger than the p-aperture to avoid clipping of the beam inside the cavity.

High performance was achieved by greatly reducing carrier crowding effects in the gain region for efficient power extraction in a fundamental or low-order spatial mode. At the same time, both the substrate optical absorption and the electrical resistance are kept low. The GaAs substrate thickness ranged from 50 to 350 μm , depending on the device design.

High-power performance

Large area devices are used to reduce laser power densities and therefore eliminate potential catastrophic damage effects. Devices with 150 μm diameters operating in a multi-mode regime delivered cw output power of 850 mW at a current of 2000 mA, therefore operating at a current density of less than 10^4 A/cm^2 (see figure 2). The large areas of these devices result in a low output beam divergence of about 3 mrad at full angle half maximum. As a result, fiber coupling effi-

ciencies of about 90% with powers of 420 mW cw in single-mode fiber have been achieved. When operating in the TEM_{00} mode at up to 500 mW, the laser wavelength is stabilized near 980 nm by the short cavity Fabry-Perot, with a linewidth of less than 0.1 nm and shifted with temperature at a rate of only 0.07 nm/ $^\circ\text{C}$. Accelerated lifetime testing has shown that with over 3000 hours of continuous operation at 110 $^\circ\text{C}$ junction temperature and 50% of threshold to rollover, these lasers exhibit reliability characteristics similar to those demonstrated for low power VCSELs.

Manufacturing for high yields

At Novalux, modeling and simulation are an integral part of the manufacturing process. A device modeling cycle that gives information on optical, thermal, mechanical and electrical properties is used to test any given design (see figure 3). A design is modeled in various configurations until the desired properties are realized.

Devices are fabricated in a high volume, cassette-to-cassette wafer processing facility running both 4 inch GaAs and 3 inch InP wafers. Continuous in-line monitoring and testing is critical to maintaining high yields. Laser testing is done at the wafer level and as a function of variable burn-in, allowing the identification of known-good-die that are then picked and passed along to a fully automated packaging and assembly step. Relatively loose alignment tolerances are possible in the fiber to laser mounting due to the use of

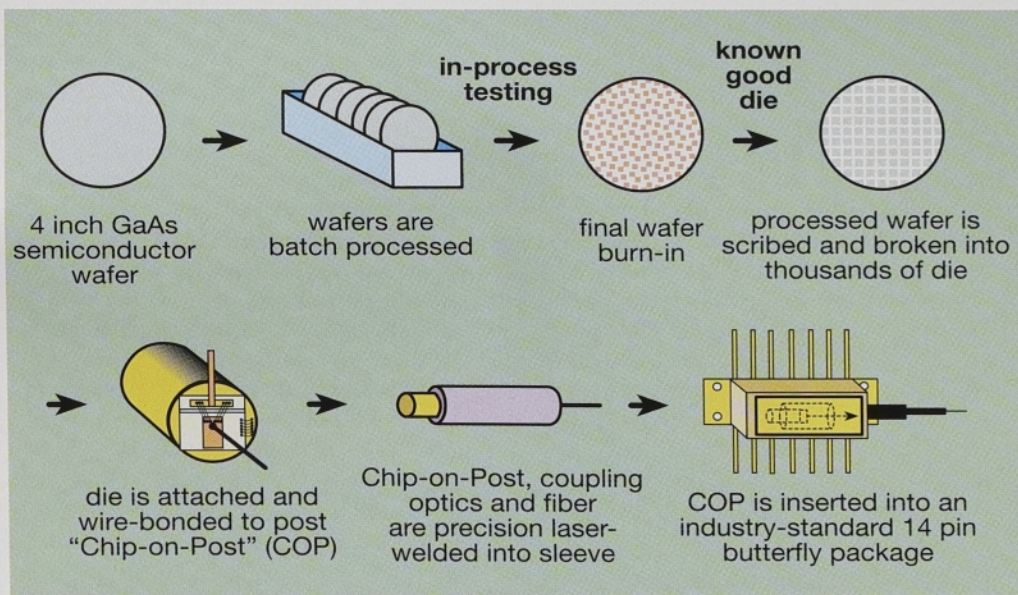


Fig. 4. The highly automated and monitored NECSEL manufacturing process.

circular TEM₀₀ beams. The manufacturing sequence is illustrated in figure 4. With this highly automated and monitored process, cycle times are greatly reduced,

with laser testing occurring only six days after the GaAs substrates enter the processing line. This rapid cycle time allows very fast device optimization times.

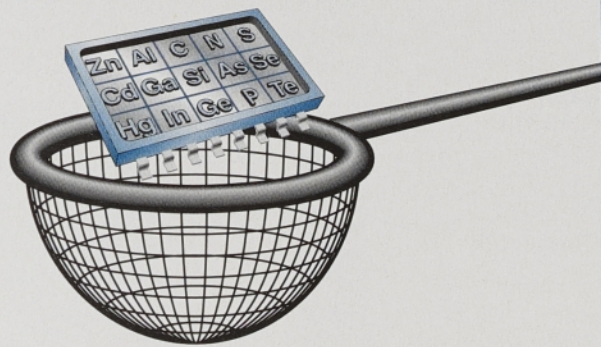
The future for fiber

Using NECSELs as the underlying platform technology opens the way for fiber infrastructure to penetrate every part of the network, not just the long haul and short reach areas. Initial products that Novalux will implement based on this platform will broadly be divided into two families: pumps and transmitters. On the pump side, the 980 nm single and multimode pumps described above, will be followed by 14xx nm pumps. On the transmitter side, a fixed-frequency transmitter will be introduced, followed by a demonstration of very fast tunability, enabling some very advanced switching architectures.

Malcolm Thompson is the CEO and Aram Mooradian is the founder and chief technology officer with Novalux Inc, Sunnyvale, California. This article is based on a presentation at the 2001 Key Conference, which was held 5-6 March in Key West, Florida.

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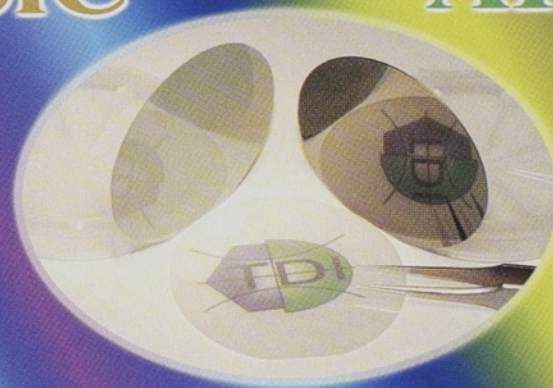


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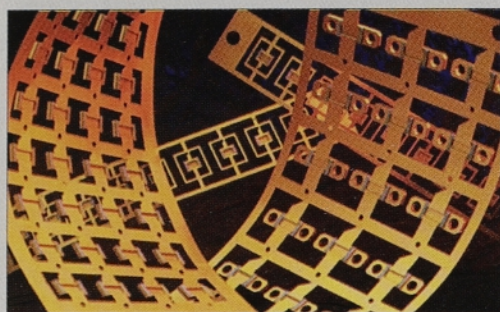


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Power packages in array formats

Zentrix Technologies (Newburyport, MA) has introduced plastic-free high-power RF and microwave packages in array formats. Based on a metal-ceramic design for high-power high-bandwidth operation, the company's packages are designed to enhance the performance and reliability of a wide range of Si,



GaAs and SiC power devices.

A variety of standard and custom packages with power ratings from 10 to 250 W are available in low-cost multi-up array formats, and are priced as low as 2 cents per W. Zentrix says the arrays can be configured to allow assembly and DC and high power testing to be completed on all devices in the array prior to device separation.

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Blvd, Tucson, AZ 85706, USA
Tel. +1 520 295 9302
Fax +1 520 573 9077
E-mail lvalenzu@zentrix.com

SSEC sealers handle 1 mm packages

The new 2300 family of package sealers from Solid State Equipment Corporation is designed for packaged devices as small as 1 mm². The parallel seam process operates at lower temperatures and with less heat penetration than traditional furnace-based sealing techniques, says the company.

Members of the 2300 series include the PSS, a manually-loaded parallel seam sealer that allows weld or solder sealing in linear or rotary mode, while

the PSS/DLL automates the lid placement process. Batch automation is also facilitated using the Cassette Automation model, which loads complete trays or cassettes of packages.

The 2300 Full Automation model incorporates both digital lid loading and cassette automation, where as many as 1000 packages can be sealed in an hour.

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Tel. +1 215 328 0700
Fax +1 215 328 9410
E-mail t.kolodziejski@ssecusa.com

Palomar automates RF assembly

Palomar Technologies' new RFA cell fully automates the precision assembly of RF power amplifier components. With a placement accuracy of $\pm 10\text{--}12\text{ }\mu\text{m}$, the system is designed for void free assemblies using eutectic die attach methods.

Known as HotRail, Palomar's assembly cell increases the throughput by preheating components on a feed conveyor system using mesas or HotRails. A clamping mechanism holds the headers in place at the eutectic temperature to achieve precise placement of die for subsequent wire bonding with consistent wire loop profiles.

Contact Bruce Hueners, Palomar Technologies, 2230 Oak Ridge Way, Vista, CA 92083, USA
Tel. +1 760 931 3600
Fax +1 760 931 5191

Vitronics' ovens meet soldering demands

The advent of lead-free solders has widened the soldering processing window – reducing damage to the PCB and its components. Reflow soldering ovens from Vitronics Soltec are designed to complement lead-free soldering by incorporating relatively small heat zones and creating a flat heat concentration profile in the peak zone. This keeps the

temperature below the damage threshold, while at the same time remaining above the liquidus temperature of the soldering alloy.

In addition, lead-free solders require accurate control of the time spent above the liquidus temperature. Too short a time results in improper wetting, whereas too long will result in intermetallic layers and microstructure coarsening. Vitronics' ovens offer controlled cooling as well as a special flux flow control management for collection of exhaust vapors.

Contact Eddy Nijhof, Vitronics Soltec North America, 2 Marin Way, Stratham, NH 03885, USA
Tel. +1 603 772 7778
Fax +1 603 772 7776
E-mail enijhof@us.vitronics-soltec.com

IN USA reduces ozone to safe levels

The reactivity and oxidative power of ozone has resulted in a wide variety of industrial applications such as semiconductor wafer manufacturing and ultra-pure water treatment. However, excess ozone generated in these applications can reach concentrations of 20% by weight (120 000 ppmv). To counter this dangerous build-up, IN USA



has introduced the O3-CAT range of ozone catalysis systems to decompose the highly reactive molecule to oxygen at safer levels (i.e. below 0.1 ppmv).

The O3-CAT system uses chemical adsorption at the solid surface of a catalyst bed, which decomposes ozone in an exothermic reaction to form oxygen. The O3-CAT design takes into account the temperature, flow and humidity levels of the sample.

Contact IN USA, 87 Crescent Road, Needham, MA 02494, USA

Tel. +1 800 798 4029

Fax +1 781 444 9229

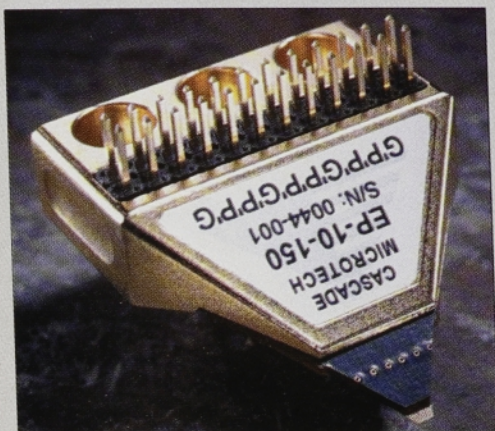
Web www.inusacorp.com

Prober eyes challenging circuits

Cascade Microtech has unveiled a probe designed to provide a number of simultaneous connections to a wafer. The Eye-Pass system also employs power bypassing to provide low-impedance and resonance-free power connections over a wide frequency range.

Among the other benefits are on-wafer evaluation of digital circuits, oscillation-free testing of wide-bandwidth analog circuits and compatibility with the company's Air Coplanar probes, which allows functional testing at speed for known-good-die.

Flexibility is also built-in with up to



12 contacts per probe head. Available contact types include ground, logic, standard and Eye-Pass power supply, power supply sense and AC signal.

Contact Ellen Payne, Cascade Microtech, 2430 NW 206th Avenue,

Beaverton, OR 97006, USA

Tel. +1 503 601 1181

Fax +1 503 601 1002

E-mail ellen_payne@cmicro.com

RSoft pack simulates optical links

RSoft has upgraded its LinkSIM optical link modeling and simulation software package. LinkSIM aids in the design and analysis of optical telecommunication and broadband fiber-optic links for telecommunications, datacom, WDM and TDM systems, in addition to optical LANs, parallel optical and free space optical interconnects.

The new version 3.0 calculates the effects of the latest laser sources, in addition to treating non-linear effects experienced in fiber during Raman amplification. The significantly expanded program now includes a single-mode, non-linear fiber model with intra-pulse Raman scattering, frequency-dependent loss, non-linearity and Raman gain profiles, and nonlinear interactions between noise and signal fields. A new bi-directional Raman amplifier model also handles Raleigh back-scattering and spontaneous emission.

The addition of VCSELs to a datacom system can also be modeled, including such parameters as spatial hole burning, lateral carrier diffusion, thermally dependent gain and thermal carrier leakage. At the receiver end of the link, an enhanced treatment of signal-spontaneous and spontaneous-spontaneous ASE beat noise has been added, as has an improved treatment of polarization in CW signals.

Contact Andrea Papa, RSoft Inc, 200 Executive Boulevard, Ossining, NY 10562, USA

Tel. +1 914 734 2665

Fax +1 914 736 9823

E-mail andrea@rsoftinc.com

Feeding pick and place systems

The SMarT Feed system from Cambridge Automatic is designed to separate, feed and present loose surface-mount components to the vacuum pickup head of most placement machines. The company's system is designed to cut



prepackaging costs associated with tape and reel, and also enables the placement of feed pins or sockets in paste, which eliminates the need for selective soldering in some applications.

Contact George Burnell, Cambridge Automatic, 3 Huron Drive, Natick, MA 01760, USA

Tel. +1 508 653 9002

Fax +1 508 651 3687

Aeronex GPS reaches purity standards

Aeronex's new Infinity Gas Purification System (GPS) features a continuous supply of pure gas at sub-ppb contaminant levels, and is designed to meet the standards required for high purity gas used in the fabrication of blue, green and white LEDs. The Infinity GPS purifies ammonia, hydrogen and inert gases of contaminants such as H₂O, O₂, CO, CO₂ and hydrocarbons from process gases and liquid bulk sources.

Designed with two purifier beds in parallel, a continuous supply of purified gas is guaranteed without interruption for replacement of a saturated or spent purifier bed. The inorganic media operates at room temperature and handles high flows at very low pressure, a requirement for MOCVD production equipment. The system allows each vessel to be purified while the other is in service.

Contact Jeff Spiegelman, Aeronex, 6975 Flanders Drive, San Diego, CA 92121, USA

Tel. +1 858 452 0124

Fax +1 858 452 0229

E-mail info@aeronex.com

9–11 July
CS-MAX – Compound Semiconductor Manufacturing Expo
 Boston, MA, US
 Web: www.cs-max.com

8–12 July
NFOEC (National Fiber Optic Engineers Conference)
 Baltimore, MD, US
 Web: www.nfoec.com

16–19 July
CLEO/Pacific Rim 2001
 Co-located with **InterOpto 2001**
 Chiba, Japan
 Web: www.bcasj.or.jp/cpr2001

16–20 July
Fourth International Conference on Nitride Semiconductors (ICNS-4)
 Denver, CO, US
 Web: www.mrs.org/meetings/icns-4

16–20 July
International Conference on

Defects in Semiconductors
 Giessen, Germany
 Web: www.uni-giessen.de/icds21/icds.htm

29 July – 3 August
Solid-State Lighting and Displays
 (part of SPIE's International Symposium on Optical Science and Technology)
 San Diego, CA, US
 Web: spie.org/conferences/calls/01/am/30

30 July – 1 August
IEEE/LEOS Summer Topical Meetings
 Copper Mountain, Colorado, US
 Web: www.ieee.org/organizations/society/leos/LEOSCONF/SUM/sumtop01.htm

30 July – 4 August
13th International Conference on Crystal Growth
 Kyoto, Japan
 Co-located with the **11th International Conference on Vapor**

Growth & Epitaxy
 Web: iccg.gakushuin.ac.jp

12–16 August
13th American Conference on Crystal Growth & Epitaxy (ACCGE-13)
 Burlington, VT, US
 Web: www.crystalgrowth.org/conferences/acgge13

16–19 August
Opto Taiwan 2001
 Taipei, Taiwan
 Web: www.pida.org.tw/show

9–14 September
International Conference on II-VI Compounds
 Bremen, Germany
 Web: www.ii-vi2001.uni-bremen.de

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Vitesse execs feel your pain

CEO Tomasetta takes a pay cut and speculates about life on the other side of the business cycle at the CIBC Conference. Marie Meyer reports.

Sick and tired of seeing corporate fat cats take home huge paychecks while the value of your investment in their company shrinks? Then Vitesse may be the company you are looking for. Speaking at the 2001 CIBC World Markets "Communications Food Chain" conference in New York City on June 10, Vitesse CEO Lou Tomasetta said that his company's belt-tightening program includes a 10–25% salary reduction for all senior management. Vitesse also shed more than 10% of its workforce, with most of the losses coming from the manufacturing area.

Revenues for Vitesse in the June quarter will be down compared to the \$121 million reported for the March quarter (which was down from the \$165 million reported for the December 2000 quarter). The communications components market is in a tailspin, and Vitesse is being dragged down like many others. But rather than dwell on that fact, Tomasetta offered some interesting observations about recovery.

"For Vitesse, for this quarter and the next few quarters, new product introductions are essential, because that's basically how we get out of this inventory correction – by introducing new products for slots that have no built-up inventory," he said. "We've been through these cycles before, and after the correction is done, the product mix is very different from the product mix that the company or industry had six months before the correction occurred."

Tomasetta went on to say that he believes that Vitesse has positioned itself as well as possible for the next cycle, "however painful it is to survive the current cycle".

Part of that positioning strategy is the recent acquisition of Versatile Optical Networks, a supplier of OC-48 (2.5 Gbit/s) and OC-192 (10 Gbit/s) transponders and optical switches (see page 16). "Substantial revenue shipments" are expected by the end of the year, although the

Company	Symbol	Closing price June 15	52 week low–high	Market cap*	P/E ratio**
GaAs IC companies					
Alpha Industries	AHAA	21.60	13.0625–64.5000	938.0M	28.67
Anadigics	ANAD	16.50	10.5000–44.0000	496.8M	69.63
Celeritek	CLTK	11.95	9.8125–53.3750	142.6M	N/A
Conexant	CNXT	7.59	6.9000–60.8125	1.875B	N/A
Endwave	ENWV	1.28	1.6100–20.6250	43.7M	N/A
RF Microdevices	RFMD	20.07	8.7500–55.6250	3.274B	111.25
Standford Microdevices	SMDI	9.41	4.2188–60.2500	275.1M	335
TriQuint	TQNT	14.25	10.2500–66.6250	1.147B	17.74
Vitesse	VTSS	17.42	15.1250–95.1875	3.194B	86.27
Opto companies					
Agilent	A	30.00	25.0000–80.9375	13.712B	19.11
Agere	AGRA	5.19	4.1000–9.5000	8.486B	N/A
Alcatel Optronics	ALAO	12.89	13.4500–71.7500	212.7M	11.84
Coherent	COHR	32.89	25.0000–93.5000	910.1M	11.81
Cree	CREE	23.10	12.2100–87.5000	1.679B	55.63
JDS Uniphase	JDSU	10.60	10.8100–140.5000	13.952B	N/A
Uniroyal Technology	UTCI	8.15	5.2500–18.8750	213.0M	N/A
Semiconductor materials & equipment companies					
ATMI	ATMI	27.35	14.3750–50.5000	827.4M	19
AXT	AXTI	21.59	13.2500–47.1875	479.1M	17.75
Emcore	EMKR	21.60	19.8750–62.5000	744.3M	N/A
Kopin	KOPN	8.99	4.0000–45.6250	583.7M	N/A
Tegal	TGAL	2.97	1.3125–8.0000	37.3M	62.80
Trikon	TRKN	10.55	7.1250–28.5625	125.5M	5.37
European shares (currency data in Euros)					
Aixtron	AIX	41.00	30.05–86.34	2.65B	82
Bede	BED	3.29	1.87–3.46	95.9M	N/A
Filtronic	FTC	2.97	2.20–7.99	218.4M	N/A
IQE	IQE	2.48	2.44–4.44	412.5M	115
Picogiga	PICO NM	8.19	7.70–36.50	52.9M	N/A
Riber	RIBER	8.40	8.10–38.50	162M	N/A

*Market capitalization = # shares × current share price.

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

acquisition is expected to have a negligible impact on the balance sheet until the end of 2002.

More CMOS and InP in the future
CMOS now accounts for about 24% of

Vitesse's revenue, and Tomasetta predicted that it would grow to 50–60% over the next few years, as the company continues to expand into the switch market. He used a railroad analogy to illustrate the choice of technology issues in this area.

Bede PLC operating results

	3 months ended March 31 2001 (£ thousands)	3 months ended March 31 2000 (£ thousands)	12 months ended December 31 2000 (£ thousands)
Turnover	1157	450	4868
Cost of sales	550	231	2514
Gross profit	607	219	2354
Operating loss/profit	(259)	(316)	64
Loss on ordinary activities	(101)	(388)	(127)

Of the three basic types of switches, only the cross-point switches are very high-speed devices, requiring GaAs (or SiGe). In Tomasetta's analogy, these switches function like a connection between two sections of a railroad track. The second type, time slot interchange SONET switches, typically run at 155 Mbit/s, and can therefore be done in CMOS. Their function can be compared to changing cars on a train. And, finally, at the edge of the network, are the highly complex, intelligent packaged switches, also done in CMOS. These, Tomasetta said, can be compared to moving the freight around inside a boxcar. He also noted that the opportunities provided by the switch market will allow Vitesse to expand the size of the markets they address from just under \$5B today to more than \$13B in 2005.

InP will also play a role in Vitesse's future (see page 7) and it is becoming a major component of the company's proprietary technology portfolio (in contrast, the CMOS fabrication is outsourced). Tomasetta identified two advantages of this strategy. The first is access to new markets in the optical components area, such as integrated receivers, transmitters, transceivers and transponders. "Optics have moved from the essential core of the network five years ago out to the edges of the network today, and relatively soon will be in the short reach access equipment as well," he said. "This will enable us, particularly after the Versatile acquisition, to come to market with incredibly cost-effective, high-performance solutions, that will exploit our ability to integrate all of the optical components that one needs." He offered, as an example, the receive side of a transponder, where Vitesse would be able to supply the PIN detector, the transimpedance amplifier, plus the clock and data recovery chip and demultiplexer. "Today these components, at OC-192, probably cost \$600 to \$1200," Tomasetta said. "We believe we can manufacture these components, particularly when we

integrate them, for probably less than \$40 or \$50. Put that into our own module, and we can capture almost all of the margin and be at a tremendous cost advantage relative to any of our competitors."

The second advantage that Vitesse sees in InP is the ability to supply higher speed physical layer parts, such as multiplexers and demultiplexers, and laser drivers. He said that Vitesse plans to use InP for 40 Gbit/s circuits in the near future and 80 and 100 Gbit/s circuits in the future, contrasting its future prospects to those of SiGe, "which really doesn't have an expansion path beyond 40 Gbit/s". Vitesse is interested in 80–100 Gbit/s circuits for Ethernet applications, perhaps within the next two or three years.

Alcatel Optronics issues warning

Earlier in this issue we discussed the wave of bad news that has broken over the North American telecom equipment companies (see page 4). Not surprisingly, the impact is being felt in Europe as well.

In early June Alcatel Optronics warned that its 2001 outlook was in need of revising. "Given Alcatel Optronics' high exposure to the submarine market and the increased lack of visibility and potential delays in large projects, as well as inventory build-ups and forecasts being continuously pushed out in the US, we feel it necessary to revise our outlook," said CEO Jean-Christophe Giroux. "Given the current market conditions, we now foresee a 20–25% top line growth for the full year 2001 with the operating margin coming in at 15%. For the [June] quarter we foresee sales down sequentially in the high single-digit range with a 15% operating margin."

At the end of April, Alcatel Optronics predicted a 50% sales growth and an operating margin of 20% this year.

SLI: is this the end at last?

In early June, executives at Semiconductor Laser International (SLI) announced that the company was exploring the

possibility of a bankruptcy filing in the face of rising credit obligations. The company's primary lender precipitated the crisis by demanding immediate payment on \$1.7 million. SLI indicated that it may sue the bank for "unreasonably" withholding consent for one or more of SLI's bail-out proposals.

SLI stock, which is now traded on the over-the-counter markets, has fallen from its high of \$10.50 in May 1996 to around 5 cents. In its five-year history the company has never generated any significant revenues, has never had a profitable quarter, and has generated a cumulative loss of more than \$20 million.

The company has failed to make any filings with the SEC since December. SLI and its CEO, Geoffrey Burnham, are currently the subject of an SEC investigation for possible violations of federal securities laws.

Bede sales up 157%

On June 14, X-ray equipment maker Bede announced that sales grew 157% in the March quarter, reaching £1.16 million (\$1.63 million). The company recorded a loss of £100 000 (\$141 000) for the quarter, compared with a loss of £390 000 (\$550 000) for the same period last year.

The revenue figure was slightly below the record levels achieved in the final quarter of 2000, but Bede's chairman Norman Price explained that "this is consistent with seasonal variations historically and in line with expectations given the lag between receiving the float [IPO] proceeds and applying these funds to increasing sales output to meet current demand."

Bede's order book grew to £2.64 million (\$3.72 million) at the end of March, an 82% improvement from the previous year, but up only 5% over the December quarter. Sales into the US market account for 45% of the total, and have grown by more than 180% in the past year.

Bede raised £17 million (\$24 million) in its flotation on the London Stock Exchange in November. Part of the proceeds are being used to build a new 27 000 sq. ft facility in County Durham that will be completed in the final quarter of 2001. The company believes that additional manufacturing capacity is needed to keep up with rising demand; while output has tripled to 12 X-ray machines per quarter, its average delivery time has doubled to 16 weeks.

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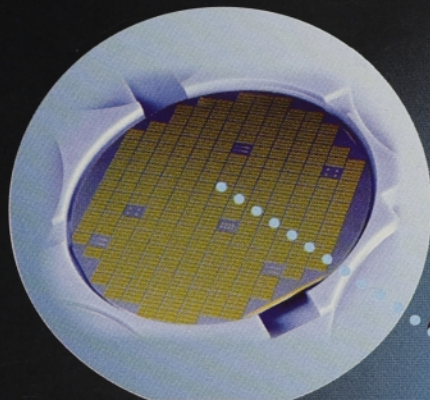
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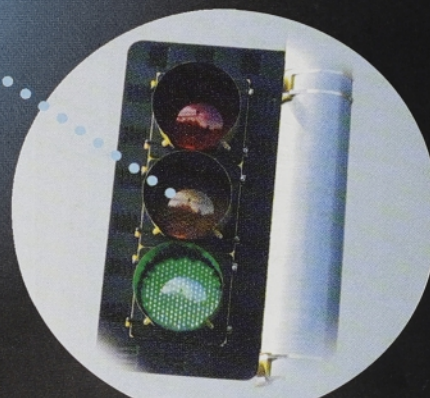
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