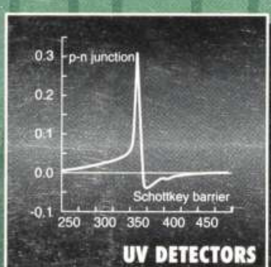
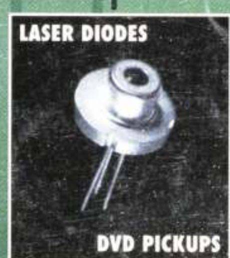
COMPOUND SEMICONDUCTOR

May/June 1996

Volume 2 Number 3

OPTOELECTRONICS





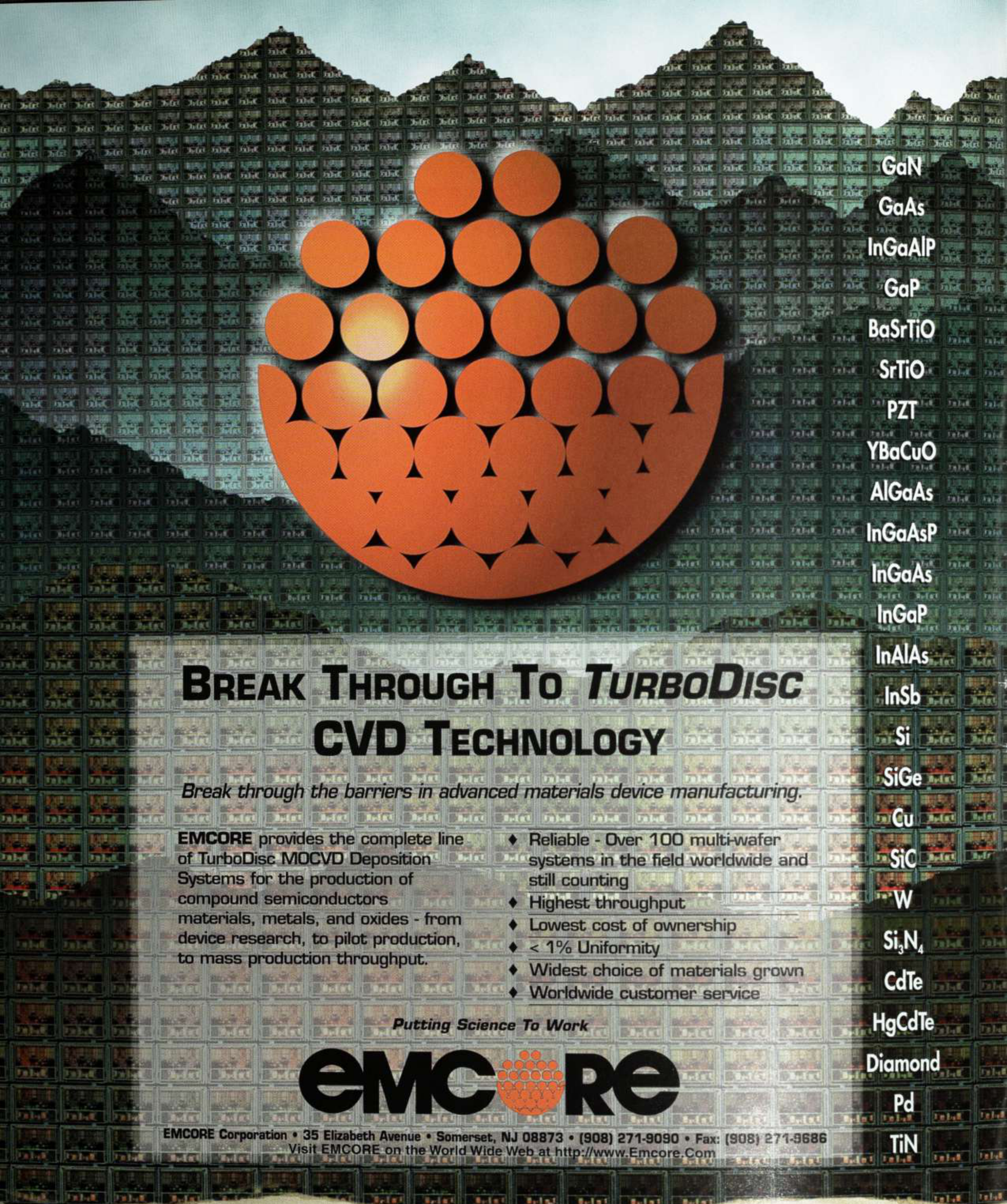
ALSO IN THIS ISSUE:

GaAs

- Mitsubishi debuts fully integrated GaAs RF front end
- German GaAs
- SOI: potential competition in RF?

Other Features

- Nitride News
- Can America compete in the global optoelectronics market?
- And much more...



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MAY/JUNE 1996 VOLUME 2 NUMBER 3

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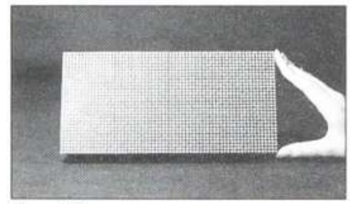
COVER STORY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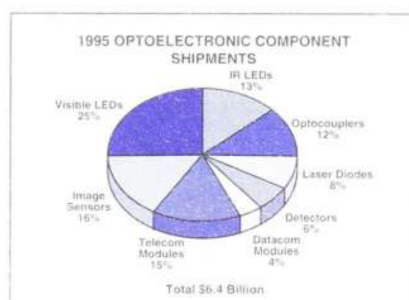
DEPARTMENTS



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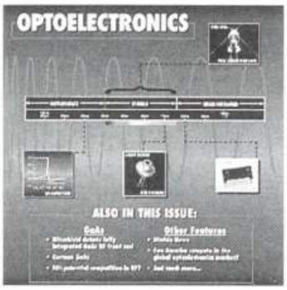

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FROM THE EDITOR

New In This Issue

Please allow me to draw your attention to a new feature which we are introducing in this issue - the "Forum" section, which begins on page 41. We are pleased to be able to introduce this addition to our magazine with two interesting and informative contributions: "A Different Blue Laser", a report from Hewlett-Packard about a GaAs VCSEL which emits blue light through second harmonic generation; and "The Cooled IR Detector Market Heats Up", a report from Richard Miles of Hughes Research Laboratories on the rivals for pre-eminence in the IR detector field.

The "Forum" section is intended to allow our readers to offer their observations about timely topics in the compound semiconductor industry, and/or to provide an overview of interesting new work. We believe that quality contributions from our readers can greatly enhance the usefulness of our magazine, and that this new feature is an important part of our attempt to fulfill our mission statement of "providing a focal point for the global compound semiconductor industry". Therefore, we hope that all of you will consider writing a contribution about your area of expertise. The basic instructions are given below. If you have any questions, please let us know. We hope to hear from you soon.

Marie Meyer

Invitation to Contribute to *Compound Semiconductor*

The mission statement for our magazine is "to provide a focal point for the global compound semiconductor industry". To help achieve that goal we are instituting a new feature, to be called the *Compound Semiconductor* Forum. It is designed to allow our readers to share their unique viewpoints or specialized knowledge about compound semiconductor science and technology by analyzing, summarizing or explaining recent work or developments. We are soliciting contributions from qualified individuals who wish to make a contribution to the general understanding of compound semiconductor technology or the industry which is based upon it.

Instructions

1) Almost any compound semiconductor-related topic is acceptable, provided that it is not too narrowly focused. Our primary selection criteria will be the article's level of interest or usefulness to our readers.

2) We will be particularly interested in certain topics by the dates given below, but we would welcome other items as well:

GaAs ICs	August 1
Nitride Technology	October 1
Epitaxial Growth	December 1

3) Remember that you are writing for a magazine, not a technical journal. The familiar structure used in technical papers - abstract, introduction, experimental detail, etc. - does not apply here. Instead, you should focus on a lively discussion of the chosen topic. Space is limited, so please pay attention to the Technical Specifications given at right, especially regarding word counts.

3) Whenever appropriate, the author should review/describe not only his/her own recent work but also significant reports from other leading workers in the field. The reader will benefit from receiving a more complete picture.

4) When in doubt, contact us - we'll be happy to provide help along the way.

Technical Specifications

1) Maximum word count = 1100.

2) Provide a succinct and descriptive title, and try to incorporate at least two sub-headings in the main body of the text. Provide the author's name and brief discussion of affiliation and background - not more than 25 words.

3) One figure is desirable. Up to two are acceptable. Subtract 200 words from the maximum word count for each figure used. Include a descriptive caption for each figure.

4) Due to space constraints, we cannot accommodate more than 3 bibliographic references.

5) FAX or mail the completed manuscript to us. Please: no email submissions. Include the figures and captions, and an exact word count. We will notify you of acceptance or rejection, or suggest appropriate revisions, as soon as possible.

Address contributions or questions to:

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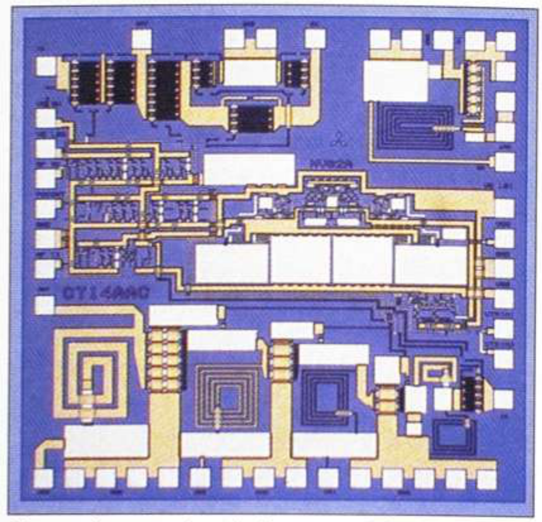
Mitsubishi Introduces a Single Chip GaAs RF Front End

The Personal Handy-phone System is becoming the proving ground for the highest levels of GaAs RF integration seen to-date



Photomicropragh of the new 1.9 GHz GaAs transceiver recently announced by Mitsubishi for use in PHS handsets.

ROBERT A. METZGER

Most wireless phone manufacturers build the RF front end of the handset from discrete components, meaning that the transmit/receive switch, low-noise amplifier (LNA), power amplifier and up/down converters are individual devices or, in some cases, small scale MMICs. Designers say they like this approach because it offers more design flexibility though the ability to mix different technologies and device types (i.e. both GaAs and Si, as well as Si bipolar and GaAs MESFETs and HBTs). And as long as the wireless market remains as fragmented as it currently is, with a large number of competing standards, it may be an economically advantageous approach as well, because it is difficult for the GaAs IC manufacturers to recover the development costs for more sophisticated RF chips unless they can sell large numbers of them.

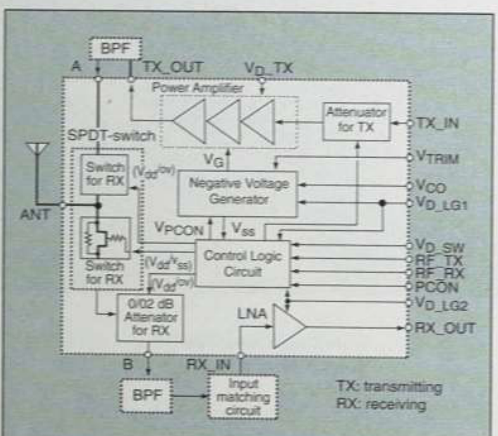


Figure One: Circuit diagram of the GaAs RFIC.

The Japanese Personal Handy-Phone System (PHS) has the potential to change all that, because it creates a high volume market for (relatively) high frequency RF transcievers, and it places a premium on size and weight. The PHS is a TDMA-based digital wireless standard operating at 1.9 GHz that is intended to fill the gap between short range cordless phones and more conventional cellular phones. PHS handsets need only relatively modest output power (10-80 mW) and are intended for stationary or walking use, primarily in dense metropolitan areas. PHS was launched in mid 1995, and it currently has ~1.5 million subscribers. There have been reports of dissapointing sales of PHS phones in the first months of 1996, but the major phone manufactures have recently adopted the familiar American marketing strategy of subsidizing phone saless in order to increase subscription sales. As a result, sales of PHS handsets have jumped from ~50,000 to ~300,000 per month, and the number of subscribers is expected to reach ~4 million by the first quarter of 1997.

Mitsubishi Electric Corporation [Hyogo, Japan] recently introduced a three chip set targeted for the PHS market. The chip set includes a GaAs IC which is a complete RF front-end, containing the LNA, power amplifier and transmit/receive switch. See Figure One. The chip set also includes an Intermediate Frequency Processing BiCMOS LSI which contains up/down converters and phase modulation circuitry; and a Baseband Processing CMOS LSI which containing voice coding circuitry. Used with a microcontroller, the three chips provide all the main functions required in a PHS handset, reducing by half the number of chips typically required. The chips set also reduces the board size by 30%, and reduces standby power requirements to 230 μA, thereby extending standby time. Mitsubishi will use the chips in its own phones and make them available to other manufacturers as well. Mitsubishi has already demonstrated a very small PHS handset using this chip set. When folded, the phone measures 8 x 5 x 1 cm^3, and it weighs less than 100 g.

Integrated GaAs & SAGFETs

The Mitsubishi approach to GaAs RF integration in the PHS chip set represents one of the largest levels of RF complexity in any wireless phone. As described by Kazuya Yamamoto of Mitsubishi, the GaAs transceiver consists of both analog and digital circuitry. The analog portion of the chip contains the power amplifier (PA), a SPDT switch (SW), two attenuators (ATTs) for transmitting and receiving modes, and a low noise amplifier (LNA). The digital circuitry contains logic circuitry to control other circuits, as well as a negative voltage generator (NVG), which thereby enables single power supply operation. The control logic can select transmitting, receiving, or standby modes. The NVG operates only during communication - thereby cutting down on power consumption. To reduce chip size, Mitsubishi has adopted a simple SW which consists of two FETs connected in series for transmitting, and a single FET for receiving. Operating with a single 3.4 V power supply, the chip requires 171 mA while transmitting, 6.1 mA while receiving, and 4.4 mA in the standby mode. The entire chip measures 2.5 x 2.5 mm^2.

Unlike most GaAs device manufacturers which rely on MESFET technology, Mitsubishi has chosen to use a self-aligned gate FET (SAGFET) approach. According to Nobuyuki Kasai of Mitsubishi, "the recessed gate MESFET provides higher breakdown voltage, so these types of FETs are widely used for high power applications. However, the recessed gate FETs have poor uniformity of DC/RF performances due to the low controllability of the recess etching process - hence from the practical viewpoint of manufacturing, recessed gate FETs are a disadvantage." Therefore, Mitsubishi has gone to a planar SAGFET process, where DC/RF uniformity is obtained by way of ion implantation, and no recess etching is required. A buried p-layer (BP) lightly doped drain (LDD) SAGFET structure is used in the implementation of the transceiver chip. A WSi/W double-layer gate structure is used to reduce gate resistance. By placing the gate closer to the source than to the drain, and using a SiO sidewalls on the edge of the gate, which are used as masks during ion implantation in order to separate the heavily doped regions away from the gate edge, gate to drain breakdown voltages as high as 20 V were obtained. Using 1.0 µm gate-length and 1.2 mm gate-width devices, a maximum output power of 24.7 dBm, corresponding to 240 mW/mm and a PAE of 54% was obtained for 1.9 GHz operation. This power density is the highest value ever reported for SAGFETs at this frequency.

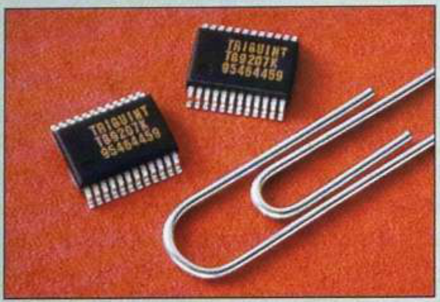
Competition

The new Mitsubishi chip set will challenge another product using highly integrated GaAs circuits. PCSI, a "fabless" semiconductor manufacturer based in San Diego, CA, has been supplying PHS chip sets for more than a year. The four-chip PCSI set includes CMOS and BiCMOS baseband chips, as well as two MESFET-based GaAs RF circuits fabricated by TriQuint Semiconductor. (See *CS* 1(2), pg. 39). The first GaAs chip contains a power amplifier, LNA and transmit/receive switch - a chip very similar to the Mitsubishi transceiver. In addition, the PCSI chipset includes another GaAs IC which contains all up/down converter functions required for PHS. (Mitsubishi chose to implement this function in its BiCMOS baseband chip.) According to John Meyer, Vice President and General Manager of PCSI's Semiconductor Group, "we have now sold 2,000,000 PHS chip sets to Japan, and we supply 50-60% of the PHS market". A second version of the chip set, in which all the baseband functions currently done in 3 different silicon chips will be combined into one large baseband chip, is planned for later this year.

Mitsubishi will begin shipping its chip set by mid 1996, and the company plans to be producing 300,000 sets per month by the end of the year. PCSI has demonstrated that integrated GaAs RF transceivers can not only successfully compete in the marketplace, but can actually dominate. Mitsubishi's aggressive production estimates demonstrates that they plan to recreate that experience for itself.

For more information about integrated GaAs RFICs, see next page.

2.4 GHz RF Front End from TriQuint



TriQuint Semiconductor has introduced a 2.4 - 2.5 GHz amplifier/switch for use in RF front end transmit/receive designs. It is optimized for use in general Industrial, Scientific, and Medical (ISM) band spread-spectrum wireless communications, including wireless LANs, portable data terminals, and remote monitoring systems. The new circuit provides a very high level of integration, as it integrates a transmit/receive switch with a low-noise amplifier (LNA) in the receive path and a 100 mW transmit amplifier suitable for modulation schemes that require linear operation. Transmit or receive is controlled by a complimentary CMOS-logic compatible T/R control pin in which only one mode is active. Power-down is an extension of the T/R control logic. Each RF port is matched to 50 ohms, eliminating external matching circuitry. It operates from a single 5-V power supply, is housed in a 24-pin SSOP package, and is available from stock at a unit price of $4.95 in order quantities of 100,000.

New ICs from Anadigics, Vitesse, NEC, Motorolla

Anadigics has announced two new GaAs products. The first is a **single supply power amplifier MMIC** for use with the GSM cellular telephone standard. This is the first product developed by Anadigics to serve this standard, and the company claims that it offers the highest power level so far for GSM. Typical efficiency for the three stage amplifier is 50% at 35 dBm power out. Anadigics has also introduced a new GaAs **high sensitivity transimpedance amplifier for use in SONET OC-3 (SDH-STM 1) optical** receiver chains and other applications including ATM, FDDI and Ethernet Fiber LAN networks at 155 Mb/s or less. The significant feature of the new circuit is its excellent sensitivity (typ. -42 dBM, depending on photodetector performance). Other features include single +5 volt power supply, automatic gain control, and 0dBm optical overload. The company claims that "this device performs at levels nearly ten times better than silicon and is significantly better than any other GaAs solution currently on the market. It is expected to be an enabling technology for fiber optic networks generally, and especially for telecom applications, because it will significantly increase the range per link and thus reduce the number of repeaters needed."

Vitesse Semiconductor has released a new **SONET/SDH compatible 4-bit MUX/DEMUX for telecom and ATM applications at OC-12 data rates**. The new IC offers on-chip high speed clock generation at 622 MHz from a 155 MHz reference clock. An integrated PLL provides a fully monolithic clock multiplier unit, eliminating the need for external components for 622 MHz clock generation. The new circuit also meets critical SONET jitter generation specifications and has a typical power dissipation of 1.1 watts. It is currently in production with 1000 piece pricing at $82.

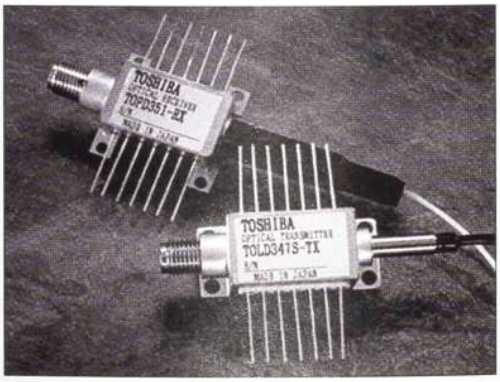
Several new products have been added to **NEC's growing line of GaAs products**. Two new medium power (4-10 W) GaAs FETs are now available for use as output stages or a drivers for high power devices in UHF to 3 GHz transmitter applications. The 4 W model provides 45% PAE, the 10 W model provides 40% PAE. Housed in ceramic packages, the new FETs are priced at 490-$150. Two new plastic-package GaAs MESFETs are also available. The NE76118 is designed for LNA applications in the 1-4 GHz range; the NE 25118 is a dual-gate device that is designed to be used as a mixer, AGC amplifier, or LNA. By shorting the second gate to the source, the NE 25118 can deliver up to 20 dB of power gain at 900 MHz, with a noise figure of 1.1 Db Prices start at $0.50. Also new is a pair of single pole, double throw (SPDT) switches for WLAN, PCS and 900 MHz digital cordless and cellular phone applications. Prices begin at $1.00.

Also available is a new **GaAs SPDT antenna switch from Motorola** which can be used as a transmit and receive or antenna diversity switch operating on a single positive supply in the 100 MHz to 2.0 GHz frequency range.

Optoelectronics

SDL has announced the introduction **of a 30 mW distributed feedback (DFB) laser for fiber optic transmission systems operating in the 1550 nm wavelength range**. This is the highest power that is commercially available at this wavelength from a DFB laser. This is the first new product to be jointly developed by SDL and its recently acquired subsidiary, SDL Optics. The DFB laser chip was developed and is manufactured by SDL; the single mode fiber optic packaging is performed by SDL Optics.

Toshiba America Electronic Components, Inc. has announced that **five new transmitters and four receivers** have been added to Toshiba's line-up of communication laser diodes. The new transmitters operate at bit rates from 622 Mbit/s to 10 Gbit/s. The receiver modules operate at bit rates from 622 Mbit/s to 50 Gbit/s. The high-end, 10 Gbit/s transmitter module has a built-in automatic optical power and temperature control function. The 5 Gbit/s receiver module includes a HEMT front-end amplifier and an InGaAs photodiode. Prices for the transmitter modules range from $340 to $11,197. Toshiba has also announced **a new 650 nm laser diode design specifically for the DVD format**. The new device is the first commercialized self-pulsating laser diode for this application.



New communication laser diodes from Toshiba America Electronic Components include a 10Gbps optical transmitter and 5Gbps optical receiver.

Research Review

The following is a sampling of recent papers in the compound semiconductor field, compiled by the staff of Compound Semiconductor from a variety of international journals.

Optoelectronic Devices

Low Dark Current GaInAs/AlInAs MSM Photodetectors

GaInAs/AlInAs MSM photodetectors are potentially important components for optoelectronic receivers due to their high speed performance, large signal to noise ratio and integrability with FETs. A past limitation to the performance of these devices has been the sizable dark current resulting from the moderately low Schottky barrier of the structure. Two different approaches for lowering the dark current have recently reported similar results. The first approach placed the electrode tips and contact pads on top of an insulating layer of silicon nitride. The second approach used thin CdS layers deposited by a chemical bath to passivate the detector surface. In both studies, dark current was reduced by more than an order of magnitude from that of a standard GaInAs/AlInAs MSM detector. The resulting dark current densities, ~0.4 pA / μm^2 in both studies, are the lowest reported dark current densities in GaInAs/AlInAs MSM photodetectors. See "Low dark current, long wavelength metal-semiconductor-metal photodetectors", W.A. Wohlmuth, et al. Electron Lett. 32(3) 249 [1 February 1996] (work performed at University of Illinois, Urbana, IL] and "Cadmium Sulfide Surface Stabilization for InP-based Optoelectronic Devices", K. Vaccaro, et al. J. Electron. Mats. 25(4), 603 [1996] (work performed at USAF Rome Laboratory, Hanscom Air Force Base, MA).

Progress in Mid-IR Diode Lasers

Mid-IR lasers have important potential applications in areas such as atmospheric pollution measurement, medical diagnostics and automotive engine exhaust diagnostics. Significant advances have been recently reported in both lead salt and III-V diode lasers. A continuous wave (cw) operating temperature as high as 223 K was achieved in a separate confinement buried heterostructure PbTe diode laser. This represents the highest cw operating temperature for any type of mid-IR diode laser. The laser was grown by MBE on a PbTe substrate. The epitaxial structure consisted of a PbTe active layer with PbEuSeTe cladding layers. And although MBE is usually employed for the growth of mid-IR diode lasers, encouraging MOCVD results were recently obtained in InAsSb lasers operating at 3.5 µm wavelengths. This device employed InPSb cladding layers, rather than the AlAsSb clads usually employed in MBE devices. In pulsed operation at 135 K, the lasers displayed characteristic temperatures of 33 K, equaling the highest value reported for MBE-grown devices. See "Low threshold PbEuSeTe/PbTe separate confinement buried heterostructure diode lasers", Z. Feit, et al. Appl Phys. Lett. 68(5), 738 [5 February 1996] (work performed at Laser Photonics, Andover, MA] and "Pseudomorphic InAsSb multiple quantum well injection laser emitting at 3.5 µm ", S.R. Kurtz, et al. Appl. Phys. Lett. 68(10), 1332 [4 March 1996] (work performed at Sandia National Laboratories, Albuquerque, NM).

Self-Pulsing VCSEL's at Ultralow Operating Currents

Self-pulsing in oxide-confined small area (<4 μm^2) VCSEL's has been reported at dc currents as low as 470 nA. Lasing is indicated by linearly polarized emission, narrow linewidths and coherent near and far field patterns. The authors state that an electronic nonlinearity allows the injection of relatively high peak currents over short times, resulting in low average currents. At average currents near 10 µA, sub-microsecond light pulses are emitted with oscillation frequencies of 4 kHz. As the drive current increases, the oscillation frequency increases until continuous wave operation is reached at 500 µA. This effect may complicate the measurement of lasing thresholds in small area VCSEL's. Work performed at Sandia National Laboratories [Albuquerque, NM]. See "Self-pulsing oxide-confined vertical-cavity lasers with ultralow operating current", K.D. Choquett, et al. Electron. Lett. 32(5), 459 [29 February 1996].

Optical Bistability in Wafer Fused Vertical Cavity at 1.55 µm Wavelength

Low power optical bistability was reported in a hybrid semiconductor structure. The device consisted of two epitaxial structures grown by MOCVD on different substrates that were combined by wafer fusion. An InP/GaInAsP double heterostructure was grown on an etch stop layer on InP and fused on top of a GaAs/AlAs reflector stack grown on GaAs. The fusing was carried out by pressing the two structures together and heating to 630°C for 30 minutes in a hydrogen atmosphere. After the fusion, the etalon was completed by depositing 3 pairs of SiO_x - Si reflector stack. The device showed a switching contrast greater than 8 : 1 in the reflective mode and a bistability threshold power less than 1 mW. A steady state memory is observed with continuous wave input. The switching time of the device is in the nanosecond range. Work performed at France Telecom CNET [Bagneux, France]. See "Submilliwatt Optical Bistability in Wafer Fused Vertical Cavity at 1.55 µm Wavelength", F. Jeanes, et al. IEEE Photon. Tech. Lett. 8(4), 539 [April, 1996].

Very High Efficiency and Reliability Red LEDs

LEDs are already the dominant compound semiconductor device (see page 24). How much further can LED technology go, and to what extent can it challenge the role of the incandescent light bulb? There is already an entire spectrum (red, orange, yellow, green and blue) of devices that have been reported which have luminous efficiencies superior to unfiltered incandescent bulbs. In addition, since the light generating electron-hole recombination event in the LED is not an inherently destructive process (in contrast to a burning incandescent filament) the reliability of LEDs may greatly exceed that of incandescent sources.

Most of the recent news stories involving LEDs focus on advancements in blue and green emitters fabricated from the GaN material system. (For example, see page 22 in this issue.) However, researchers at Hewlett-Packard's Optoelectronics Division [San Jose, CA] are continuing to further the development of the already mature technology for red LEDs. They recently reported the use of wafer bonding to produce record efficiency red AlGaInP LED's. The LED's possess external quantum efficiencies of 24% at 636 nm, 23% wallplug efficiencies, and 36 lm/W luminous efficiencies. The devices emit 9.3 mW at 20 mA and 2V. In comparison, the best AlGaAs red LED's have 18% external quantum efficiency at 650 nm and the highest efficiency red AlGaInP vertical cavity surface emitting lasers have 10% wall plug efficiencies at 676 nm. Projected lifetimes of these AlGaInP LED's exceed 100,000 hours.

The devices were constructed by starting with an AlGaInP double heterostructure grown by MOCVD on a GaAs substrate. A 45 micron thick VPE-grown GaP cap is added to facilitate current spreading and light extraction. The absorbing GaAs substrate is removed by selective etching. Finally, a transparent GaP substrate is added to the structure by wafer bonding at elevated temperature under uniaxial pressure. After patterned ohmic contacts are applied, the wafers are diced into 5 mm LED's.

See "Highly-reliable and efficient semiconductor wafer-bonded AlGaInP/GaP light emitting diodes", F.A. Kish et al. Electron. Lett. 32(2), 132 [18 January 1996].

Compound Semiconductor Materials

Graded $GaAs_{1-x}P_x$ Bases in GaInP Emitter HBTs

GaInP emitters for GaAs HBTs benefit from a high etch selectivity between GaInP and GaAs and therefore permit the implementation of high-yield HBT processes. The exclusion of aluminum from the epitaxial layers has also been related to reliability improvements in GaInP/GaAs HBTs when compared to conventional AlGaAs/GaAs HBTs. Researchers from the Furukawa Electric Co. (Yokohama, Japan) have further improved the performance of GaInP emitter HBT technology by incorporating a carbon-doped, tensile-strained $GaAs_{1-x}P_x$ graded base in lieu of the usual uniform GaAs base. The structures were grown by low-pressure MOCVD with the TMGa, AsH_3, and PH_3 precursors for the GaAsP alloy. Hole concentrations above 10^{19} cm^{-3} could be achieved in both GaAs and $GaAs_{1-x}P_x$ by using the methyl group of the TMGa precursor as the carbon doping source; the actual hole concentration was easily controlled by the V/III ratio. Transistor characteristics revealed a common-emitter current gain of 85 at a collector current density of 30 kA/cm^2 for a base with the phosphorus content graded from 0 to 5%, resulting in an aiding built-in field of 10kV/cm. The built-in field in the graded $GaAs_{1-x}P_x$ base devices resulted in a current gain enhancement factor of nearly 2 compared to similar devices with a uniform GaAs base. The GaAsP graded base devices showed a significantly reduced size dependence in comparison to uniform GaAs base devices. Common-emitter I-V characteristics featured a collector offset voltage of less than 0.15 V. See "Graded-GaAsP Bases in Heterojunction Bipolar Transistors with InGaP Emitters," M. Ohkubo, et al., Microwave and Optical Technol. Lett., 11(3), 150 [20 February1996].

Diamond/GaAs Heterojunctions by Wafer Bonding

Differences in lattice constants and in thermal expansion coefficients make it difficult to form high-quality heterojunctions between widely different semiconductors with conventional growth techniques such as MOCVD or MBE. The formation of pn junctions is key to the development of diamond-based electronic devices such as bipolar transistors or junction field-effect transistors, but unfortunately, n-type impurity doping of diamond films has so far proven difficult to achieve. Researchers from Osaka University (Osaka, Japan) have made use of direct wafer bonding to form pn junctions between n-type GaAs films (Se -doped, 10^{18} cm^{-3}) and CVD boron-doped p-type diamond epitaxial layers grown on (100) diamond substrates. The room temperature I-V characteristics for the n-GaAs / p-diamond direct bond junction displayed rectifying behavior between -5V and +5V, suggesting that a pn heterojunction can indeed be formed through direct bonding. An analysis of the band lineup for the GaAs/diamond heterojunction system suggests that the hole current dominates transport in the forward bias regime. A measurement of the photovoltaic effect confirmed that the direct bonded GaAs/diamond structures indeed function as pn junctions. See "p-Diamond/n-GaAs Junctions Formed by Direct Bonding," T. Sugino et al., Electron. Lett. 32(1), 71-72 [4 January 1996].

Highly Conductive P-Type ZnTe:As Grown by MOCVD

Zinc telluride is a highly conductive wide gap II-VI compound that is a promising candidate for the implementation of low-resistance contact layer in ZnSe blue-green light emitters. MBE has been used to produce highly conductive nitrogen doped ZnTe layers, MOCVD has so far been limited to doping levels of 10^{18} cm^{-3}. Researchers from the Toshiba Research Laboratories (Kawasaki, Japan) have successfully grown highly conductive p-type ZnTe layers by atmospheric pressure MOCVD using DMZn and diisopropyltelluride (DiPTe) as the group II and group VI precursors. The acceptor impurity source was chosen to be trimethylarsine (TMAs), because it contains no As-H bonds in its structure (Arsenic behaves as a shallow acceptor in ZnTe when it substitutes into Te lattice sites). A smooth epitaxial surface morphology was obtained at 400°C when a low VI/II flux ratio. Hall effect measurements revealed a maximum hole concentration of 1.3×10^{19} cm^{-3} for a VI/II ratio of 2, which is the highest reported carrier concentration for MOCVD-grown p-type ZnTe. See "Highly Conductive P-Type ZnTe:As Grownby Atmospheric Metalorganic Chemical Vapor Deposition Using Trimethylarsine," A. Kamata et al., Jpn. J. Appl. Phys, 35(2), L87-L89 [15 January 1996].

GaInP Ordering and V/III Ratio in MOCVD Growth

The $Ga_{0.5}In_{0.5}P$ alloy has been found to be useful for the fabrication of light emitting diodes, injection lasers, heterojunction bipolar transistors and heterostructure field-effect transistors. MOCVD grown GaInP tends to order with the In and Ga atoms segregated into alternating {111} planes. The ordering can significantly reduce the energy gap, and affect device performance. The degree of order has been found to be affected by the growth temperature, by the growth rate, and by the phosphorus flow rate. Researchers from the University of Utah (Salt Lake City, Utah) have performed *in-situ* surface photoabsorption (SPA) to measure the concentration of [$\bar{1}$10]-oriented P dimers characteristic of the (2 x 4) reconstruction on (001) -oriented GaAs substrates as a function of the input partial pressure of the TBP phosphorus precursor. For a growth temperature of 670°C, the P-dimer concentration increases systematically with TBP pressure as it is increased from 10 to 200 Pa. At low TBP flow rates (or V/III ratio), the Cu-Pt ordering disappears presumably because of the disappearance of the (2x 4) reconstruction because of the absence of P-dimers; the degree of ordering is clearly enhanced at higher V/III ratios. Photoluminescence data show that the 20K PL peak energy shifts from ~1.968 eV down to ~1.912 eV as the V/III ratio is increased from 8 to 160. For a V/III ratio of 40, the PL peak energy was found to be equal to ~1.952 eV for a growth temperature of 670°C, and ~1.888 eV for a growth temperature of 620°C. See "Surface photoabsorption study of the effect of V/III ratio on ordering in GaInP," H. Murata et al., Appl. Phys. Lett, 68(13), 1796 [25 March, 1996].

In-Plane Schottky Gate Quantum Wire Transistors

Quantum-based devices have been the focus of much interest for future high-speed electronics applications. Quantum wire transistors are pursued with the intent to implement near ballistic (scattering-free) quasi-one-dimensional gate-controlled electron waveguides. Truly ballistic transport in 1D waveguides results in a quantization of conductance in steps of $2e^2/h$. One approach commonly used to implement quantum wires is to use the fringing fields in a split Schottky gate to selectively pinch-off a 2DEG while defining a 1D electron waveguide channel. In this configuration, the split-gate sits on the sample surface while the 2DEG is located below the surface: the non-planar geometry smoothes out the split-gate confining potential, and decreases the subband spacing between in the 1D electron waveguide. Unfortunately, it turns out that the quantized conductance associated with ballistic transport can only be observed below temperatures T such that $\Delta E > 3kT$.

Researchers from Hokkaido University (Sapporo, Japan) have implemented $Al_{0.3}Ga_{0.7}As/GaAs$ quantum wire transistors with in-plane Schottky gate electrodes: the in-plane gate (IPG) features a much more favorable electrostatic aspect ratio which should in principle lead to ballistic transport at much higher temperatures due to the stronger electron confinement. The IPG quantum wire structures were implemented by electron beam lithography and wet chemical etching of the $Al_{0.3}Ga_{0.7}As/GaAs$ quantum well structure. The platinum IPG electrodes were deposited in-situ by a masked electrochemical plating process following an anodic dissolution of the sample surface. This process results in oxide-free and damage-free Schottky contacts on GaAs.

The IPG quantum wire transistor drain characteristics display a complete pinch-off and good drain current saturation with no kinks or hysteresis. The IPG QWW transistors can be modeled by assuming the IPG does not alter the QW electron sheet density and only affects the quantum wire width. This model is experimentally supported by a linear dependence of the drain saturation current upon the gate voltage. Magneto-resistance measurements also confirmed that the sheet density is independent of the gate voltage near pinch-off: this indicates the IPG changes the channel width without changing the electron density. The experimental drain current data indicated an electron velocity close to the Fermi velocity of electrons in the 2DEG, suggesting nearly ballistic electron transport through the electron waveguide. Low-temperature measurements near pinch-off revealed conductance quantization in steps (up to n=3) very close to $2e^2/h$ for the relatively long wire lengths of 1.6=µm . The first conductance quantization plateau persisted up to a temperature of 40K, and is very encouraging for the possible realization of quantum devices at higher operating temperatures.

See "Transport Characterization of Schottky In-Plane Quantum Wire Transistors Realized by In-Situ Electrochemical Process," H. Okada et al., Jpn. J. Appl. Phys., 34(1), No. 12B, 6971 [December, 1995].

Circle 152 on Reader Service Card

Electronic Circuits and Devices

Ka-Band InP/InGaAs/InP HBT Power

Millimeterwave operation is seeing more and more demand in a wide range of applications, including phased array radars, satellite communications, smart munitions, collision avoidance systems, indoor LANs and radiometry. What all these systems share in common is the need for millimeterwave power sources. For the first time, Ka-band (30 GHz) power performance on InP/InGaAs/InP DHBTs is reported. Using MOMBE grown DHBTs, with 800 nm InP collectors and a 28.8 nm InGaAs/InP superlattice grading layer between base and collector, DHBTs with f_t of 69 GHz, f_{max} of 166 GHz, and a BV_{CEO} greater than 8 V were fabricated. These DHBTs exhibited an output power density of 1.91 W/mm with an associated gain of 5.3 dB and a PAE of 35.5% at 30 GHz operation in the common-emitter configuration. Work performed at Texas Instruments [Dallas, TX]. See "Ka-Band Power Performance of InP/InGaAs/InP Double Heterojunction Bipolar Transistors," H.F. Chau et al, IEEE Microwave and Guided Wave Lett., 6(3), 129 [March 1996].

4H-SiC Schottky Rectifiers

SiC is a promising material for devices requiring high-power, high-frequency, and high-temperature operations owing to its unique electrical and thermal properties of high breakdown field, high electron saturation drift velocity, and high thermal conductivity. The 4H-SiC polytype exhibits both a large bandgap (3.3 eV), and the highest electron mobility among αSiC, making it ideally suited to high-voltage electronic devices. Ti/4H-SiC Schottky rectifiers with edge termination formed by B^+ implantation were fabricated. Compared with a Schottky structure without edge-termination, where high electric fields are generated, the reverse-blocking characteristics of the edge-terminated devices were significantly improved, showing breakdown voltages up to 1700 V - twice that of the structure without edge-termination. In high temperature operation, blocking voltages of over 1100 V were obtained at 150°C operation. Work performed at Kyoto University [Kyoto, Japan]. See "Excellent Reverse Blocking Characteristics of High-Voltage 4H-SiC Schottky Rectifiers with Boron-Implanted Edge Termination," A. Itoh et al, IEEE Electron. Device Lett., 17(3), 139 [March 1996].

SiGe P-type MODFETs

While the large increase of the electron mobility achieved due to Si/SiGe heterostructure formation has lead to the fabrication of high performance Si/SiGe n-type FETs, p-type devices are lagging behind in performance partly due to much lower hole mobility. High speed p-type modulation-doped field-effect transistors (MODFETs) grown by UHV-CVD and with $Si_{(1-x)}Ge_x$ channels where x ranges from 0.7 to 0.55, have been fabricated on relaxed $Si_{0.7}Ge_{0.3}$ buffers. Utilizing both 0.7 µm and 1.0 µm gate-lengths, the MODFETs exhibited f_t values of 9.5 GHz and 5.3 GHz, respectively. At room temperature, the p-type MODFETs exhibited a 2-D hole-gas mobility of 700 cm^2/Vs, a hole sheet density of $3.5x10^{12}$ cm^{-2}, and maximum extrinsic transconductance was 105 mS/mm. Work performed at the University of Illinois [Urbana-Champaign, IL] and IBM [Yorktown Heights, NY]. See "High Speed P-Type SiGe Modulation-Doped Field-Effect Transistors," M. Arafa et al, IEEE Electron. Device Lett., 17(3), 124 [March 1996].

Sb-based RITs for Logic Circuits

A promising application for the InAs/GaSb/AlSb heterostructure system is low voltage operation devices utilizing resonant interband tunneling (RIT) diodes where the peak current of these devices (mid-10^4 A/cm^2) is attained at voltages on the order of 100 mV. For the first time, integrated RIT and Schottky diode structures using the InAs/GaSb/AlSb system are demonstrated. Grown by MBE, the RIT diode structure consists of a 5.4 nm GaSb quantum well sandwiched between symmetric 1.1 nm AlSb barriers, 12 nm undoped InAs spacer layers, and 30 nm InAs (n^-) spacer layers. Using n-type InAs/AlSb superlattices for the semiconducting side of the Schottky barriers provides the means for tailoring the barrier height for a given circuit architecture. A complete logic family has been demonstrated, including AND, OR, XOR and INV functions, suitable for 10 GHz operation. Work performed at the Hughes Research Laboratories [Malibu, CA], Mayo Foundation [Rochester, MN] and University of Notre Dame [South Bend, IN]. See "InAs/AlSb/GaSb Resonant Interband Tunneling Diodes and Au-on-InAs/AlSb-Superlattice Schottky Diodes for Logic Circuits," D.H. Chow et al, IEEE Electron Device Lett., 17(2), 69 [February 1996].

90% PAE GaInP/GaAs HBT at L-Band

High power added efficiency (PAE) power sources are critical elements for a wide range of applications, including mobile communications and T/R modules for active array radars. A very high 90% PAE with an output power of 200 mW and a power gain of 18 dB was achieved at 1.8 GHz operation with a 240 $µm^2$ GaInP/GaAs HBT. Class C operation combined with suitable harmonic termination was chosen for the transistor's mode of operation, where the dissipated power is low under both small signal and large signal conditions, making this suitable for the design of high power and high efficiency narrow band microwave amplifiers. Work performed University of Limoges [Limoges, France] and Thomson-CSF [Orsay, France]. See " A 90% Power-Added Efficiency GaInP/GaAs HBT for L-Band Radar and Mobile Communication Systems," A. Mallet et al, IEEE Microwave and Guided Wave Lett., 6(3), 132 [March 1996].

Low-Cost Plastic Packaged PHEMTs for DBS

Satellite direct broadcasting receiver systems have been experiencing a worldwide increase in demand - driving the direct broadcast satellite (DBS) market for low-cost, extremely low-noise amplifiers. Currently, the cost of ceramic packaging is still a dominant factor in the price of a receiver. Therefore, the production of low-noise and high-gain devices in low-cost plastic packaging would be very desirable for the DBS market.

Researchers at Hewlett Packard [Santa Clara, CA] report on the fabrication of 0.2 µm gate length pseudomorphic AlGaAs/InGaAs/GaAs HEMTs in low cost SC-70 plastic packages for DBS applications at 12 GHz operation. Grown by MBE on 3 inch GaAs substrates, these HEMTs use a combination of optical and electron-beam lithography to define 0.2 µm T-gates, along with both wet and reactive ion etching to define the gate recess. The 0.2 x 200 $µm^2$ PHEMTs have typical maximum transconductances, g_{max}, of 390-430 mS/mm at a drain-to-source voltage of 1.5 V, reverse drain-to-gate breakdown voltages, BV_{gd}, of 4 to 6 V, and an f_t of 72 GHz. These devices were stress tested at three different channel temperatures, T_{ch}, of 200, 220 and 240°C, and reliability failure tests gave a mean time to failure (MTTF) of $1.2x10^7$ hours at a T_{ch} of 150°C - more than sufficient for commercial applications.

Noise measurements made on wafer under conditions of V_{ds} = 1.5 V and I_{ds} = 10 mA, result in typical noise figures of 0.42 to 0.47 dB with typical associated gains of 12.6 -13.5 dB at 12 GHz. The devices were packaged in both ceramic and plastic packages and measured at the same frequency, giving typical noise figures of 0.45-0.52 dB and 1.0-1.2 dB with typical associated gains of 12.1-13.0 and 9.5 -9.9 dB, for ceramic and plastic packaged devices, respectively. Although the devices in plastic packaging experienced a greater degradation in both noise figure and associated gain than the devices in ceramic packaging, they can still be used for the second and third stages of a front-end receiver, where the lower cost of the plastic package makes this an attractive alternative to a higher-performance ceramic packaged PHEMTs.

See "Pseudomorphic AlGaAs/InGaAs/GaAs HEMTs in Low-Cost Plastic Packaging for DBS Application," T. Hwang et al, Electron. Lett., 32(2), 141 [18 January, 1996].

Optoelectronic Technology in the U.S. and Japan

Also in this issue:

Evaluating the relative competitiveness of the world's two largest optoelectronics industries

MARIE MEYER

Equipment based on optoelectronics technology plays an increasingly significant role in the global economy. Some commentators, grasping for a metaphor, have taken to saying that "optoelectronics will be to the 21st century what electronics was to the 20th century". While that may be a bit of an overstatement, it is still obvious that optoelectronics-based telecommunications, data-storage and sensing technologies will have great impact throughout the foreseeable future. As a result, optoelectronic technology offers new wealth-creation opportunities for component and system manufacturers. The history of electronics suggests that fierce competition for technological leadership and manufacturing prowess lie ahead for the optoelectronics industry. Today's policy makers are, therefore, well advised to consider the steps which should be taken now to help their local/national/regional economy to reap the benefit of helping to build the optoelectronics infrastructure.

Unfortunately for the U.S. manufacturing base, recent history also shows steady erosion of its once-dominant position. With that in mind, the Japanese Technology Evaluation Center (JTEC) has released a report evaluating the competitiveness of the U.S. optoelectronics industry in comparison with its counterpart in Japan. (See box, page 14.) To prepare the report JTEC convened a panel of seven experts (Table One) to study the relevant literature and conduct site visits at 42 relevant facilities in the U.S. and Japan. The investigations focused on five topical areas that the panel considered to be most economically strategic to both Japan and the United States, namely:

1) Optoelectronic systems, with emphasis on telecommunications, LANs, and optical interconnections;
2) Optical storage technology;
3) Waveguide devices and optoelectronic packaging technology;
4) Photonic devices and materials; and
5) Optical sensor technology, including specialty fibers.

A summary of the major findings in these five areas is given in Table Two, along with analysis of two "interdisciplinary" technologies (consumer optoelectronics and custom optoelectronics[1]), as well as the panel's assessment of the effectiveness of the overall environment surrounding the optoelectronics efforts in the two countries. As is reflected in the table, the panel concludes that Japan clearly leads in consumer optoelectronics and data storage, Japan and the U.S. are both competitive in the areas of communications and networks, and the U.S. leads in custom optoelectronics. Panel chairman Stephen Forrest notes that there are always exceptions to the rule: for example, although the panel concluded that Japanese companies lead in consumer optoelectronics, U.S. manufacturer Hewlett-Packard is undoubtedly the worldwide leader in the production of LEDs for that same market. Nevertheless, these "big picture" generalizations help to illustrate the dominant position of Japanese manufacturers in the global optoelectronic equipment market.

JTEC Panelist	Report Contribution
Stephen R. Forrest (Panel Chair) Princeton University	Methodology & Summary
Larry A. Coldren University of California, Santa Barbara	Emerging Device Technology
Sadik C. Esener University of California, Santa Diego	Optical Storage Technology
Donald B. Keck Optoelectronics Research, Corning, Inc.	Optical Sensors and Specialty Fibers
Frederick J. Leonberger Uniphase Telecommunications Products	Guided Wave Devices and Photonic Packaging Technology
Gary R. Saxonhouse University of Michigan, Dept. of Economics	Optoelectronics in Japan: some Economic Considerations
Paul W. Shumate Bellcore	Telecommunications, Cable Television, and Data Link Systems

Table One: JTEC Panelists contributing to the report.

Shedding Light on the Numbers

The fact that Japanese companies have the lead in the consumer optoelectronics field (which is dominated by CD players, both audio and CD-ROM) is not surprising to anyone who has surveyed the brand names in the local electronics store recently. Nevertheless, the report

[1] *"Interdisciplinary" in the sense that they combine two or more of the five fields listed above.*

does highlight some surprising statistics. For example, the Japanese optoelectronics industry is more than six times larger than its American counterpart ($40 billion/year for Japan vs. $6 billion/year for the U.S.). Also, analysts attribute ~50% of the current market for optoelectronic-enabled equipment to consumer optoelectronics, and another 40% to optical data storage (meaning high density, large scale bulk storage, as opposed to CD-ROM). As is shown in Table Two, the JTEC Panel attributes leadership in both areas to Japanese manufacturers; therefore, they conclude, "Japan dominates 90% of the world's optoelectronics markets, and can be expected to continue its dominance for a number of years." Panelist Gary Saxonhouse, a professor of economics at the University of Michigan, describes the global market share held by Japanese optoelectronics firms as "substantially in excess of 50%", as a result of explosive growth over the past dozen years, during which time the Japanese optoelectronics industry grew at an average annual rate of 23.7%. He notes that such a rapid rate of growth is unlikely to continue in the future; and in the years since 1989, growth has slowed to an average annual rate of 11.6%. Nevertheless, this rate is still faster than the American industry's average annual growth rate of 9.9% over the same period.

And why do these numbers matter? Saxonhouse sums up the point neatly. The global market for optoelectronic enabled equipment is forecasted to reach $400 billion by 2013[2]. This implies a 9.5% average annual growth rate, which is about what the industry has experienced over the past few years. However, sustained over a twenty year period, that rate implies that the industry will grow by a factor of six. And, most importantly, given the slow rate of growth of gross domestic product expected for both Japan and the U.S. over the next two decades (usually estimated to be ~2%), it appears that optoelectronics will be an ever increasingly important part of both economies than it is today.

The Problem with American Industry

The panel concludes that, but for the exception of Hewlett-Packard, American manufacturers will concede the consumer field to their Japanese counterparts. This is symptomatic of the existence of a strong, long-term commitment to large-scale, low-cost manufacturing in Japan that is not equaled in the U.S. The report launches the familiar criticism of

[2] *Including, in order of size in 2013: Display-enabled equipment such as TV's and computers (monitors, laptops); optical communications; optical storage (computer data, audio and video); and printing/reprographics.*

Key Technologies	Research & Development Leader	Research & Development Trend	Manufacturing Leader	Manufacturing Trend
Transmission Systems	Japan	no change	even	no change
high capacity networks	even	no change	even	no change
high capacity interconnects	Japan	Japan gaining	even	no change
Optical Storage	Japan	no change	Japan	Japan gaining
Optical Sensors	U.S.	no change	even	no change
Emerging Device Technology	even	no change	Japan	Japan gaining
Waveguide Devices	even	Japan gaining	U.S.	Japan gaining
Packaging	Japan	Japan gaining	Japan	Japan gaining
Interdisciplinary Topics				
Consumer Optoelectronics	Japan	Japan gaining	Japan	Japan gaining
Custom Optoelectronics	U.S.	no change	U.S.	no change
General Environment				
Infrastructure	even	Japan gaining	Japan	no change
Gov't/Industry Support	U.S.	no change	U.S.	no change
Gov't/University Support	U.S.	Japan gaining	NA	NA
Univ./Industry Interaction	even	no change	U.S.	no change

***Table Two:** Summary of the JTEC Panel's findings regarding the comparative strengths of the U.S. and Japanese optoelectronics industries. The panel's overall assessment is that Japan clearly leads in consumer optoelectronics, Japan and the U.S. are both competitive in the areas of communications and networks, and the U.S. holds a clear lead in custom optoelectronics.*

American business practices when it says "Management in large U.S. publicly-owned companies is reluctant to take significant, long-term, and potentially costly risks in new technology ventures, because they must produce short-term profits for shareholders." As a result, it is common for the risk-taking challenge to be shouldered by smaller "spin-off" companies. But in spite of, or perhaps because of, the diversity of the American industry, the panel concludes that the U.S. has maintained a strong industrial base in optical communications, with several companies both large and small that are committed to this strategically important field. However, they caution that due to a significant erosion in market share held by U.S. companies, the U.S. no longer enjoys the fully dominant position in the fiber optic field.

One bright spot for the American industry is custom component manufacturing, meaning products specifically tailored to a customer's specifications, as opposed to a catalog item. Examples include specialized detector arrays or a laser with unique performance characteristics. The report suggests that this is an area which is well suited to the smaller, more entrepreneurial spin-off companies in the U.S. optoelectronics industry. However, the panel notes that there is a fairly low ceiling on the growth potential for many such ventures, perhaps around the $50 million mark. Nevertheless, the panel concludes that American industry could capitalize on this capability to gain a key position in the relatively new field of optical sensors, which is described as having "explosive" growth potential. Another potential opportunity for American industry may lie in the optical storage area. At present the Japanese photonics industry is ahead in both manufacturing and R&D, but the panel reports that "several" opportunities exist for major advances in read/write devices and in storage media technology. Therefore, they conclude, "the United States has several realistic opportunities to gain market success on the basis of rapidly evolving technologies".

And What About Devices?

Most of the planning and policy-making for the future is, of course, centered around system-level issues. But the JTEC panel did include some device experts, including Larry Coldren of the University of California at Santa Barbara. A summary of his assessment of the relative strengths of the U.S. and Japanese efforts in device development is presented in Table Three. He concludes that in most cases the Japanese component technology is ahead of that found in the U.S.. The major exception is WDM (wavelength-division multiplexed) transmission lasers, which have been the subject of several U.S. government-funded research efforts in recent years. But, regardless of who leads in R&D achievements, the Japanese optoelectronics industry is well positioned to commercialize new products because it possess the technology to produce low-cost, robust and manufacturable device packages. To illustrate the importance of this technology the panel notes that finding low-cost packaging solutions can be the key to enormous market growth. For example, the tremendous growth of the CD market was made possible not because of the semiconductor laser itself, but because Japanese researchers solved the problem of positioning the laser, with considerable precision, with respect to the disc. In this example, the cost of the package (~$20) is far greater than the cost of the laser itself (~$1). The report indicates that their lead in packaging technology and low-cost component manufacture is a major advantage enjoyed by the Japanese optoelectronics industry.

Device	Leader	Trend
1. Lasers		
Transmission		
TDM	Japan	Japan gaining
WDM	U.S.	no change
Pump	Japan	Japan gaining
Access	Japan	Japan gaining
Analog	even	Japan gaining
Interconnect		
1.3 micron	Japan	Japan gaining
0.98 - 0.85 micron	even	no change
0.78 - 0.65 micron	Japan	Japan gaining
Visible		
Red	Japan	Japan gaining
Blue	Japan	no change
2. Amplifiers & Switches	Japan	no change
3. Integrated Receivers	Japan	Japan gaining
4. New Materials	even	no change

Table Three: Summary of the JTEC Panel's findings regarding the comparative strengths of U.S. and Japanese optoelectronic device development efforts.

Conclusions

The JTEC panel presents convincing evidence that the Japanese optoelectronics industry enjoys a significantly superior position with respect to its American counterpart. In explaining why, the report states that

> "Optoelectronics is one of the most important technology fields currently being supported by the Japanese government, by Japan's industrial sector, and by Japanese society in general. Indeed, in light of the panel's conversations with Japanese hosts, it appears that **optoelectronics is regarded as a major vehicle to propel Japanese electronic product dominance in the next century**." (emphasis original)

In contrast, the panel concludes that in the United States optoelectronics is not considered to be as crucial. This is attributed in part to the greater diversity of the U.S. economy, which pursues a more heterogeneous array of opportunities. The panel advises that the reduced emphasis on optoelectronics is "a significant long-term problem for the United States as it struggles to maintain its worldwide leadership in electronics technologies in the future".

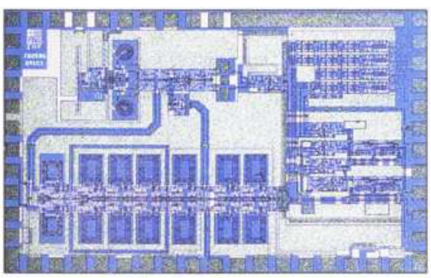
"JTEC Panel Report on Optoelectronics in Japan and the United States", Stephen R. Forrest, et al. PB96-152202. Available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161 USA, TEL [1] 703 487 4650, FAX [1] 703 321 8547. JTEC and its companion world Technology Evaluation Center (WTEC) operate under the International Technology Research Institute (ITRI) at Loyola College (Baltimore, MD) in cooperation with the National Science Foundation (NSF). JTEC/WTEC defines their mission as "to inform U.S. policy makers, strategic planners, and managers of the state of selected technologies in foreign countries in comparison to the United States".

German GaAs

Key members of the German III-V industry wrap up a five-year joint-research program

In mid-March the Fraunhofer Institut Angewandte Festkorperphysik (IAF) in Freiburg, Germany, announced the successful conclusion of a five-year program aimed at developing an infrastructure for III-V technology in Germany. The "III-V Electronics" program included 11 participants from industry and academia (see Table One) and was funded for 150 million DM ($100M), more than half of which was provided by the German Federal government. A total of 23 joint R&D projects were carried out in three major areas.

The first area, high speed ICs, focused on developing devices for applications such as transportation safety (collision avoidance radar, navigational systems, and microwave landing systems), environmental control (through radar systems, millimeter-wave detectors, and traffic guidance) and novel communication services (including short-distance communications at millimeter-wave frequencies, multigigabit per second data transmission in optical networks, satellite communications, and wireless LANs). The specific projects included process development and optimization, fundamentals of ultrahigh frequency circuits, device modeling, circuit design, and simulations and test aiming at the demonstration of ICs for advanced system applications. Highlights of the results achieved in this portion of the program include:



One example of developments from the recently concluded "III-V Electronics" program: A monolithic optoelectronic receiver IC (3.0 x 2.0 mm^2) for data rates up to 10 Gbit/s, fabricated by the Fraunhofer IAF. The MSM-photodetector is located in the upper left corner of the chip, followed by a transimpedance amplifier, clock recovery (lower left), comparator and 1:4 Demux (right). A serial data stream of 10 Gbit/s is parallelized into four channels at 2.5 Gbit/s each.

- A broadband GaAs MESFET power amplifier (4.2 x 4.1 mm^2) for a synthetic aperture radar (SAR) system at 9.5 - 9.7 GHz achieving top values of 5.6W of power output and 33% efficiency. (Siemens AG).

- A multifunctional GaAs MESFET chip (4.3 x 3.0 mm^2) for a microwave landing system at 5.0-5.2 GHz. The chip includes monolithic integration of a power amplifier and two small-signal ICs, the first time this has been achieved in Europe. (Siemens AG).

- A three-stage amplifier (2.6 x 1.7 mm^2) for 80 GHz millimeterwave signals to be used as the center of a short-distance radar sensor for automotive applications. This device was fabricated in InP using HEMT technology with coplanar waveguides. (Daimler-Benz).

- A GaAs variable gain amplifier (2.9 x 1.9 mm^2) for 38 GHz signals, to be used to interlink base stations in mobile communications systems. (Daimler Benz).

- A monolithic optoelectronic receiver IC (3.0 x 2.0 mm^2) for data rates up to 10 Gbit/s. This device exhibits a world-class level of integration, as it includes a MSM-photodetector, transimpedance amplifier, clock recovery, comparator and 1:4 Demux. A serial data stream of 10 Gbit/s is parallelized into four channels at 2.5 Gbit/s each. (Fraunhofer IAF).

Other work done in this area of the project included designs at 60 GHz for short-distance radio (Fraunhofer IAF, Bosch and Alcatel-SEL), and an A/D converter system aiming at 200 megasamples capacity with a resolution of 10 bits (the measure of the accuracy with which an analog signal is digitized) (Fraunhofer IAF and Fraunhofer IIS).

Mesoscopic Devices and Polytectic Technologies

The timing of the IC portion of the program was fortunate, as the market potential for devices such as those described above appears to be quite good. The program also included two areas aimed at more fundamental studies, in hopes of paving the way for the next generation of devices. The participants in the second area of the program cooperated to demonstrate III-V semiconductor structures with the smallest dimensions achievable to-date (referred to as "mesoscopic devices" because their dimensions are between microscopic and macroscopic). The basic physics of quantum effects were explored with quantum dots, wires and wells, and new concepts for the realization of HBTs were also investigated, aiming at applications such as power MMICs.

The third area of the program involved technologies to realize mesoscopic devices (referred to as "polytectic techniques"). Techniques for creating fine vertical and lateral patterning were explored, including *in-situ* techniques to allow disparate epitaxially-based structures such as lasers and HEMTs to be combined on the same chip. Another area of exploration was the fabrication of low dimensional structures without the use of lithography. Examples include using focused ion beams to fabricate transistors, or performing epitaxial growth on novel GaAs surfaces to obtain *in-situ* fabrication of quantum wires or dots.

		Area(s) of Participation		
Company or Research Institute	City	High Speed ICs	Mesoscopic Devices	Polytectic Techniques
Siemens	Munich	x	x	x
Daimler-Benz Research	Ulm	x	x	x
Daimler-Benz Aerospace	Ulm	x		
Bosch Telecom	Backnag	x		
Alcatel-SEL	Pforzheim	x		
Max-Plank-Institute	Stuttgart		x	x
Fraunhofer IAF	Freiburg	x	x	x
Fraunhofer IIS	Erlangen	x		
Walter-Schottky-Institute	Munich		x	x
Henrich-Hertz-Institute	Berlin			x
Paul-Drude-Institute	Berlin			x

Table One: Participants in the recently concluded five-year joint effort on III-V electronics in Germany.

Follow-up Programs

Many of the participants in the III-V Electronics Program will also participate in the follow-up programs dealing with the development and prototyping of low-cost GaAs components, focusing not only on chips but also on packaging. In a joint effort coordinated by Guenter Weimann of the Fraunhofer IAF, nine industrial and three research partners will develop high frequency components based on a variety of III-V MMICs for communications. A follow-up program studying quantum systems in III-V semiconductors has also been launched, under the direction of Klaus von Klitzing of the Max-Plank-Institute.

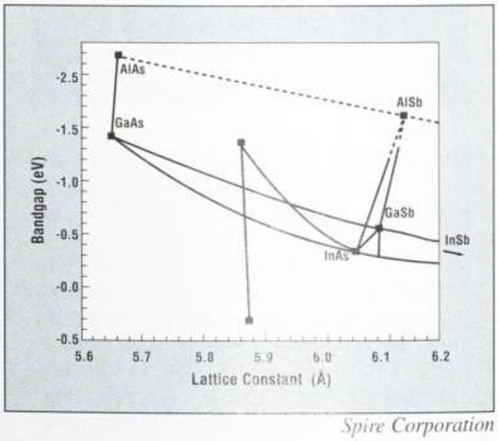
Spire Receives Contracts to Develop InTlP and InTlAs

Spire Corporation [Bedford, MA] has announced the receipt of two contracts to develop a new III-V ternary materials, indium thallium arsenide (InTlAs) and indium thallium phosphide (InTlP). The funds are being provided by NASA's George C. Marshal Space Flight Center. Spire plans to explore whether the new compounds can be grown by MOCVD for potential uses such as near- to mid-IR lasers and detector arrays.

According to Harvey B. Serreze, Senior Scientist for Laser Operations at Spire, the $In_xTl_{(1-x)}P$ compound is interesting because it is lattice-matched or nearly lattice-matched to InP over the range of $0< x <1$, making it analogous to the AlGaAs/GaAs system. In addition, the bandgap, in principle, spans the entire range from 1.35 eV to zero, meaning that emitters which operate from the 1.3 micron range all the way to far infrared are possible. Thus one might be able to monolithically integrate disparate emitters and detectors that currently would be fabricated from the InP, HgCdTe, and GaSb systems. But Serreze is quick to point out that all of this data is, at present, theoretical only.

Serreze will act at the principal investigator on one of the contracts, which is aimed at fabricating an IR emitter. He reports that Phase I of the contract will concentrate on demonstrating that InTlP can be grown by MOCVD, confirming some of its basic properties, and then fabricating a simple emitter, most likely an LED. He notes that one of the drawbacks of this new material is the high toxicity of Tl metal. This issue will be addressed by safety precautions and by using only very small quantities. The test structures will be much like conventional InP-based devices, with the use of InTlP restricted to the active layer only.

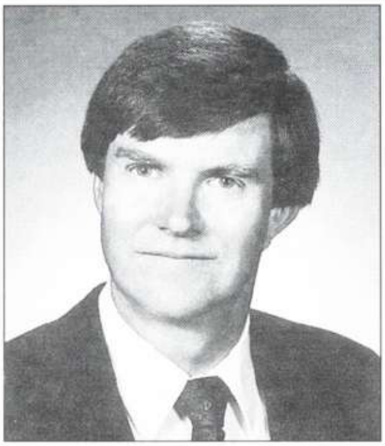
In the second contract, which will be headed by Nasser Karam, Spire plans to demonstrate InTlAs as a candidate for high performance, medium wavelength IR detector arrays. The company believes that InTlAs may offer several advantages over HgCdTe, including higher mechanical strength, the availability of high quality and lower cost substrates, and potentially better compositional uniformity.



Spire Corporation

Diagram showing the theoretical lattice constant and bandgap of the InTlP system.

OSA Awards for Scifres & Kish



Donald R. Scifres of SDL. Inc., recipient of the 1996 Land Medal from the OSA.

The Optical Society of America (OSA) has awarded medals to two leaders in the III-V optoelectronics field.

The 1996 Edwin H. Land medal has been awarded to Donald R. Scifres, president and CEO of SDL, Inc., for "his pioneering scientific and entrepreneurial contributions to the field of high power semiconductor lasers". Scifres received his Ph.D. in Electrical Engineering in 1972 from the University of Illinois. His scientific efforts have led to more than 300 publications and more than 100 issued patents in the semiconductor laser field, addressing topics such as DFB lasers and semiconductor laser arrays for telecommunications and lasers for high power application and a broad range of military, industrial and scientific uses.

Scifres joined Xerox Palo Alto Research Center in 1972 and was given increased responsibility based on his innovation, prolific writings, and organizational abilities. In 1983 he and Xerox, in a joint venture with Spectra Physics, founded Spectra Diode Laboratories as the sole supplier of high power semiconductor lasers. In 1992 the company was reformed as an independent company and renamed SDL after Scifres successfully executed a corporate recapitalization. SDL is now a leading supplier of customized semiconductor-based optoelectronic and laser products.

Among many honors, Scifres is a Fellow of OSA and IEEE. He has received various alumni awards from the University of Illinois and Purdue University, as well as the LEOS award for Engineering Achievement in 1994. In 1992, Scifres served as president of LEOS.

The 1996 Adolph Lomb Medal, which recognizes contributions to the field of optics made before the age of 30, has been awarded to Frederick A. Kish, Jr. of Hewlett-Packard "for pioneering work in solving the problem of replacing the absorbing substrate of red-orange-yellow-green (ROYG) InAlGaP LEDs by wafer bonding and introducing a new high volume family of ultra high brightness ROYG LEDs exceeding in performance conventional sources such as the incandescent and halogen lamp".

Kish began his research career at Amoco Technology Co. working on III-V semiconductor optical waveguides and materials characterization techniques. He later joined the Solid-State Device Laboratory at the University of Illinois, studying compound semiconductor optoelectronic devices under the direction of Prof. Nick Holonyak, Jr. While at the university he researched a variety of semiconductor laser device architectures and compound semiconductor device fabrication techniques, including impurity-induced layer disordering and the native oxidation of Al-bearing III-V compounds. His research led to the discovery that the Al-based native oxide can be employed to define optical waveguides, facilitating the fabrication of high-performance index-guided laser diodes and ring laser diodes.

In 1992, Kish joined the Materials Technology Department of Hewlett-Packard's Optoelectronics Division, working on high-brightness ROYG LEDs. He is currently a R&D project manager in the Materials Technology Department. At Hewlett-Packard he has developed techniques for directly wafer bonding compound semiconductor wafers, resulting in the development of transparent-substrate ROYG AlGaInP LEDs, which are the highest (luminous) performance LEDs, with luminous efficiencies exceeding unfiltered 60W tungsten and 25 W halogen incandescent sources. He was instrumental in directing the development of this technology for release to the commercial marketplace. He is co-author of over 30 publications and seven U.S. patents.

In Our Next Issue

The theme for our next issue is "New Applications for Compound Semiconductors". Coverage will include:

- GaAs power devices
- III-V solar cells
- Wide bandgap materials for microelectronics

We have much more planned as well. If you want to know what the future of the industry holds, you don't want to miss this issue!

Please remember that *Compound Semiconductor* is now available only by paid subscription. If you or your colleagues wish to subscribe, please use the form on page 25.

Thomson, Daimler-Benz Launch GaAs Venture

Thomson-CSF of France and Daimler-Benz of Germany are teaming up to develop, produce and market GaAs ICs. The joint venture will be owned 50% by Thomson, with the remainder held by two Daimler subsidiaries - Daimler-Benz Aerospace (DASA), which will hold 30%, and Temic Telefunken, which will hold 20%. The venture will combine the GaAs activities of Thomson's research laboratories in Orsay and Daimler's Ulm research center. The companies are predicting ~$50 million in sales by the year 2000 for the new venture.

Philips & TriQuint Team Up

In late March Philips Semiconductors signed a wafer-sourcing agreement with TriQuint Semiconductor that will give Philips access to high-volume production capacity for GaAs ICs for RF applications. Under the new agreement Philips will continue to develop and prototype its own GaAs ICs at Philips Microwave in Limeil, France, drawing on the company's 20 years of experience in GaAs IC R&D. Volume production will be carried out at both TriQuint and Philips Microwave in Limeil. TriQuint will produce wafers to Philips' specifications at is plant in Beaverton, OR. Philips will assemble and test the circuits and supply them through its worldwide sales organization. The target markets for the new products that will result from this arrangement include cellular and cordless phones and base stations, WLANs, and high-speed transmission equipment and satellite communications.

Philips is already a major supplier of ICs for wireless applications. This wafer sourcing deal is designed to strengthen its position by ensuring that Philips can offer both silicon and GaAs chips which suit their customer's preferences. "TriQuint is a world leader in GaAs wafer production and we are delighted to be working with them", said Bernard Le Henaff, strategic product marketing officer for telecom ICs at Philips. "Our RF applications specialists will now be able to help customers reap the benefits of GaAs technology as well as silicon"

"We are pleased to have the opportunity to work with a global electronics company of Philips' stature," said Steven Sharp, president and CEO of TriQuint. "We are excited at the prospect of partnering with the technical specialists at Philips, sharing technologies so that, together, we can better address communications applications. This agreement with a world leader in silicon RF technology further validates the viability of GaAs devices for high volume applications". Sharp declined to ascribe a dollar value to the new pact, preferring to characterize it as a "multimillion dollar" deal that is more of a partnering arrangement than a simple foundry agreement.

Philips already owns an equity position in TriQuint's sometimes rival Anadigics, but will not be making any direct investment in TriQuint. Philips reportedly selected TriQuint over Anadigics for this deal because of the degree of similarity between the GaAs processes at TriQuint and Philips Microwave Limeil.

New Business for Anadigics

Anadigics has introduced a new GaAs IC for use in cable distribution amplifiers for 750 MHz cable (CATV) systems. The company also announced that it has received a one year, $1 million order for the new ICs from Scientific-Atlanta, a major manufacturer of CATV equipment. Scientific-Atlanta contributed to the development of the new chip. The product has been undergoing field tests since last fall, and production shipments from Anadigics have already begun.

The new GaAs IC will be used as a line extender and will replace the conventional silicon hybrid circuits composed of discrete components which have been used in the CATV application for over 15 years. It is simultaneously being introduced as a surface mount device compatible with automated manufacturing processes and offering the possibility of extended frequency range operation up to 1.0 GHz.

"We are very excited about our new GaAs IC because it represents a broadening of our product offering to the CATV market. Furthermore, Scientific-Atlanta, the leading supplier of distribution amplifiers, represents a new major customer" commented Ronald Rosenzweig, President and CEO of Anadigics. Mr. Perry Tanner, Vice President and General Manager of Transmission Systems at Scientific-Atlanta, said "GaAs amplifiers will allow us improved product performance with lower installation and operation costs for broadband operators. This development is a major advancement for both the CATV and GaAs industries, as well as an exciting partnership of two dynamic companies." According to Tanner, this is not the first GaAs device which Scientific-Atlanta has used in its products, but it is the first time that GaAs has been applied to broadband RF amplifiers. He explains that the motivation to develop the circuit was "to address many of the new business issues our customers face, including meeting emerging market needs for bandwidth beyond 750 MHz."

New Record for $CuInGaSe_2$

Solarex [Newton, PA] has announced that it has set a new record for efficiency for copper indium gallium diselenide (CIGS) thin films by producing a submodule having 13.0% conversion efficiency. Performance was confirmed by measurement at the National Renewable Energy Laboratory (NREL) under standard illumination conditions on a Solarex CIGS submodule of 40 cm2 having 20 segments. The submodule was fully encapsulated using glass and EVA.

According to a company spokesperson, "this achievement results from improved materials deposition methods, advances in module fabrication processes, and improved module design. The demonstration of high efficiency over significant area, coupled with potential low cost of the this thin film submodule, makes CIGS a leading candidate for future large scale photovoltaic production intended for bulk power generation". Solarex plans to leverage this technology, and its new factory for multijunction amorphous Si (currently under construction), to position themselves as the leader in photovoltaic thin film development. Solarex, which owned by oil giant Amoco, is the largest domestic manufacturer of photovoltaics in the U.S.

New WWW Sites

Web sites continue to proliferate. Here are a few which you might want to visit:

- Emcore, manufacturer of MOCVD systems: *http://www.emcore.com*
- Display Technology Systems, manufacturer of FED testing systems: *http://www.distec.com*
- MarkeTech International, "On-Line Catalog" for materials: *http://www.s1l.com/marketech*
- Balzers-Pfeiffer, supplier of vacuum equipment: *http://www.balzers-pfeiffer.com*

For more vendor news, see page 23.

News from Japan

New Devices

ROHM develops smallest infrared data communications module

ROHM has developed the industry's smallest infrared data communications module that encapsulates an infrared LED, PIN photo diode, and modem circuit in a package. The Rpm-801cb conforms to the IrDA 1.0 standard and draws 6.25ma, 1/6 that required of its predecessor, at 9,600bps. Samples become available in May at a unit price of 2,000 yen ($18.69). ROHM will launch volume production in August at 100,000 units per month, targeting portable information and communications equipment.

Matsushita Electronics develops GaAs power amplifier ICs only 0.2cc in volume

Matsushita Electronics has developed GaAs power amplifier ICs which are only 0.2cc in volume and consume about 10% less power than conventional products. Designed for Japanese digital cellular phones, the UNO134F/UNO134H (800MHz/1.5GHz) models use a multi-layered ceramic substrate, rather than a single-sided resin substrate, and are designed using the company's proprietary 3D IC technology. Matsushita, which will produce the new ICs at its Okayama plant, has begun sampling them at 3,000 yen ($28.04) and will release them in August.

Sharp, Pioneer develop high-output DVD semiconductor laser

Sharp and Pioneer have jointly developed and will sample-ship in June a write-once DVD semiconductor laser. Made of AlGaInP, the 635nm red semiconductor laser generates an average output of 30mW at 30°C in a single horizontal mode, about six times higher than play-only semiconductor lasers, and a peak output of 50mw. The companies have employed molecular beam epitaxy to develop AlGaInP crystal for use in a laser chip. The price is yet to be determined.

In Development

NTT develops ultra-fast optical communications transmitter integrating laser and modulator

NTT has developed an ultra-fast optical communications transmitter which integrates a laser and a modulator on an InP substrate. The laser emits a 1.55-micron infrared beam. Capable of operating at 25GHz, the modulator can alter the optical absorption rate by changing voltage. The transmitter, which makes complicated positioning and the use of a lens unnecessary, can support 20Gbps data transmission, an equivalent of sending five years' worth of newspapers in one second. NTT is confident that the transmitter can be used for 40Gbps transmission, and plans to use it in future trunk-line networks such as one between Tokyo and Osaka.

NEC develops miniature milliwave switching IC

NEC has developed a miniature milliwave switching IC. The IC uses four transistors to carry out the on and off operations and yet features shared electrodes to reduce a switching circuit in size to 1/5 that of a conventional switching IC. The new IC is 0.7 x 0.17mm, about the same size of a single transistor for switching applications. The AlGaAs/GaAs heterojunction device achieves a power transmission of 113.5mW at 40GHz. NEC plans to launch commercial models two years from now.

Matsushita Electric develops next-generation DVD RAM red semiconductor laser

Matsushita Electric has developed a next-generation DVD (digital video disk) RAM red semiconductor laser. An enhanced model of the conventional 680nm CD semiconductor laser, the newly-developed laser provides a wavelength of 650nm and an optical output of 30mw. It uses a GaAs inclined substrate and a strained multi-quantum well structure for the active layer. It starts oscillating at 50ma. Matsushita will hasten to develop mass production technology so that the laser will be incorporated into a DVD RAM drive the company plans to commercialize in the second half of 1997.

Research News

Kanagawa Institute of Technology team succeeds in forming superconductor and compound semiconductor thin films on single substrate

A research team led by Professor Takaragawa at Kanagawa Institute of Technology has succeeded in forming superconductor and compound semiconductor thin films on a single substrate. The team deposited yttrium-based superconductor thin film on a strontium titanate substrate and gallium arsenide thin film over a GaAs substrate. Then, the team removed the GaAs film from the substrate using chemical reaction, bonded it onto the strontium titanate substrate, and made interconnection between the two films to form a circuit. The team successfully connected a magnetic flux flow element on the superconductor film with a diode and an FET on the semiconductor film and confirmed normal operation. The technique is expected to pave the way for the development of new functional elements.

NEC continuously oscillates quantum dot laser at room temperature

NEC has succeeded in continuously oscillating a quantum dot laser at room temperature. Developed using the molecular beam epitaxy method, the semiconductor laser has multiple layers of AlAs and GaAs formed on a GaAs substrate and has between the layers 11 10nm-thick InGaAs layers, thus creating a "quantum dot" structure for enclosing electrons in the multiple layers. The structure functions as a light emitter and amplifier. The 960nm operates at a threshold current of 5-6 microA; conventional semiconductor lasers have a threshold current of over 10 microA.

Sharp develops EL display module that emits white light

Sharp has developed an electroluminescent (EL) display module that emits white light. The newly-developed white-light EL display module uses a two-layer structure in which 1-micron-thick strontium sulfide containing a very small amount of cerium is vacuum-evaporated on an insulation layer, over which 0.5-micron-thick zinc sulfide containing manganese is deposited through evaporation. Sharp has also developed a multi-color EL module able to display red, green, yellow and black colors. The achievement is expected to pave the way for implementation of a full-color EL display based on color filter technology and allow EL displays to be applied to a variety of uses.

Other News

Mitsubishi Chemical to make full-fledged entry into optical component business

Mitsubishi Chemical has announced that it will make a full-fledged entry into the optical component business. The company, which has been working on test fabrication of optical isolators for laser diode modules and optical fibers at its Tsukuba research laboratory, will establish a system for producing thousands of optical isolators per month by next spring. One of the major suppliers of compound semiconductor materials, Mitsubishi is considering entering the optical device market by commercializing laser diodes and LEDs based on such materials. Focusing on growth markets, the company will expand its product line in the information and electronics sectors.

Mitsubishi Electric to mass-produce DVD/CD pickups from fall

Mitsubishi Electric will start in early fall to mass-produce optical pickups that can read both digital video and compact disks. The company will market production to other manufacturers and build it into its own DVD players, to be launched in fall. It has already begun investing in volume production equipment at its Nagaokakyo site in Kyoto Prefecture and will make additional investments as justified by market trends. The price and production level will be set soon.

Compound semiconductor material makers expanding production

Japanese manufacturers of compound semiconductor materials are expanding production. Sumitomo Electric introduced 4-inch GaAs epitaxial wafers in April, while Sumitomo Metal Mining is in the process of expanding GaP production by 20%. DOWA Mining will further invest in subsidiary DOWA Semiconductor to boost GaAs wafer output. Furukawa and Hitachi Cable are producing GaAs wafers at their full capacity. A burgeoning demand for portable phone signal reception/transmission chips and display LEDs has contributed to increased GaAs and GaP shipments, making it plausible that compound semiconductor material makers' fiscal 1995 shipments will show two-digit growth to 40 billion yen ($373.8 mil).

Nitride News

Blue Laser News

1. Another Blue Nitride Laser

A second research group has achieved a GaN diode which lases in pulsed mode at room temperature. Isamu Akasaki and co-workers from Meijo University reported at the International Symposium on Blue Lasers and LEDs (ISBLLD, Chiba, Japan, March 5-7, 1996) that they had successfully fabricated an InGaN/GaN double heterostructure (DH) laser which produced wavelengths as short as 376 nm. A unique feature of the structure was a narrow p-type contact layer created by low energy electron beam irradiation which lower the threshold current voltage to 16V. Prof. Akasaki is one of the pioneers in the nitride research field (see *CS* 1(1), p. 38), whose previous achievements include the first demonstration of activated p-type doping in GaN via post-growth annealing of Mg-doped layers.

2. A GaAs Blue Laser (!)

Another group in Japan has recently reported a blue laser diode which uses neither the GaN material system nor its sometime rival ZnSe. Norihide Yamada and co-workers from Hewlett-Packard Laboratories, Japan, recently fabricated a GaAs/AlGaAs/InGaAs VCSEL grown on (311)B GaAs which uses second harmonic generation to produce short-wavelength emission. The lasing wavelength of the fundamental light is 965 nm, and that of the SH blue light is 482 nm. The VCSEL lases under pulsed operation at room temperature; however, the output is rather weak. The maximum CW output power of the fundamental and the SH light are 1.5 mW and 1.0 nW, respectively, at 135 K. For more information, see page 41.

3. Variations on the Nichia Laser Diode

Shuji Nakamura and co-workers from Nichia Chemical have published three new papers which demonstrate further progress on their breakthrough GaN laser diode. At the Chiba conference Nakamura reported the successful room temperature operation (pulsed mode) of an InGaN MQW structure which required only 7 periods in the MQW stack, compared to 26 in the original Nichia diode. Other recent papers from Nichia have demonstrated the first GaN-based laser with cleaved facets. (*Jpn. J. Appl. Phys.* 35, L217 [15 February 1996]) The original Nichia diode was grown on C-face sapphire and the mirror cavity facets were formed using reactive ion etching. In this more recent work the structure was grown on A-face sapphire and the mirror facet was formed by cleaving along the R-face - a somewhat surprising result, as conventional wisdom holds that sapphire cannot be cleaved. And, in their most recent work, the Nichia team demonstrated the growth of an InGaN MQW laser diode on a spinel ($MgAl_2O_4$) substrate. (*Appl. Phys. Lett.* 68(15), 1 [8 April 1996]) Spinel has a smaller mismatch to GaN than the more commonly used sapphire (9.5% vs. 13%). In addition, it may be more amenable to cleaving. However, in this work polished facets used for the mirror cavity.

A photograph of Nichia's blue laser in action.

Nichia Chemical Mass Produces Green LEDs, Doubles Production

Nichia Chemical has announced that it has successfully launched mass production of the high brightness green LEDs which it announced last year (*CS* 1(3), p.5). The GaN-based devices provide 6 Cd of 525 nm light at 20 mA, which is ~60 times brighter than the best GaP-based yellow-green LEDs. Sample pricing begins at ~¥500/$5 each. Total production of nitride LEDs at Nichia has more than doubled over the past 12 months, and current capacity for producing blue, blue-green and green LEDs is 5 million units/month. Nichia recently phased out all of its InGaN/AlGaN double-heterostructure (DH) LEDs in favor of single quantum well (SQW) devices. This move provides greater color purity, as the blue and green SQW structures have a spectrum width of 20-30 nm, compared to as much as 70 nm for the DH devices.

Fujitsu Announces Plans to Develop Laser with GaN on SiC

Fujitsu Laboratories has announced that it has developed a "blue semiconductor laser production technique", based on the MOVPE growth of GaN on SiC substrates. The company has used the process to fabricate functioning LEDs and plans to employ it in future to develop semiconductor lasers, although that work is said to be in the basic research stage. Fujitsu chose to base their development work on SiC because it is conducive to being cleaved, which should allow the formation of cavity mirrors with superior flatness and verticality.

Electronic Journal for Nitrides

There is no question that nitrides are the hottest research topic in the compound semiconductor industry today. But are they hot enough to support a new journal - one which employs an entirely new format? The Materials Research Society is about to find out, because it has launched the "*MRS Internet Journal of Nitride Semiconductor Research*" (MIJ-NSR). The MRS describes MIJ-NSR as a "paperless journal" (though that seems an oxymoron), meaning that it is produced and distributed exclusively via the Internet. Like a traditional journal, MIJ-NSR is peer-reviewed and archival, but as an electronic journal it can offer several new features. For the MIJ-NSR to be successful it will have to capitalize on these new features to woo authors away from the firmly entrenched hierarchical journals like *Applied Physics Letters* and *Japanese Journal of Applied Physics*.

The most important Internet-enabled feature is the speed at which papers can be "published". New works can be posted almost immediately after they have been accepted by the peer review process. Authors are also allowed to post their manuscripts prior to acceptance - something you won't ever see in *APL!* But the most profound difference is that MIJ-NSR is free to anyone with Internet access, a feature which the journal's founders hope will ensure its survival in an era of shrinking library budgets.. The only source of revenue for MIJ-NSR is charges to the authors, which are currently $275 per article.

The other new features of MIJ-NSR are familiar to anyone who has ever visited a WWW site. They include the ability to post full color figures, or even video and audio clips; links to other relevant sources; a searchable database; interactive discussion forums, and a bulletin board for news items. In fact, at present, the MIJ-NSR looks much more like a "nitrides home page" than a technical journal, as it has only published one paper to-date. Eric Hellman of Bell Labs, who helped to found MIJ-NSR along with Toby Strite of IBM Zurich and Cammy Abernathy of the University of Florida, acknowledges that the MIJ-NSR may be ahead of its time, and that some patience may be required before the idea will catch on with the majority of authors in this field. However, he believes that all archival scientific journals will eventually become primarily electronic, for two reasons: the access will [eventually] be universal and cheaper, and interactivity will allow better validation. Time will tell if he is correct. In the meantime, he encourages everyone to visit the site.

The MRS Internet Journal of Nitride Semiconductor Research is located at http://nsr.mij.mrs.org/

II-VI Inc. Awarded DARPA Contract for CdZnTe

'I Incorporated has announced the award of a $2.3 million research and elopment contract from the Defense Advanced Research Projects Agency of U.S. Department of Defense. The contract aims to improve the manufactur- of CdZnTe substrates used in infrared focal plane arrays and is expected to ompleted in December, 1997

ATMI Partners with MCP Wafer Technology

MI and MCP Wafer Technology have signed a strategic partnership agree- t relating to compound semiconductor materials. Wafer Technology will ribute SiC and GaN substrates in Europe for ATMI's Epitronics subsidiary. ill also assist Epitronics' European distribution of SOI wafers from Nippon el. ATMI will distribute Wafer Technology's products in the Eastern U.S. and ada.

Rhone-Poulenc Steps Up Ga Production

to rising demand, Rhone-Poulenc has announced that it will resume galli- extraction at its Pinjarra site in Western Australia. The company currently es on an extraction facility in Stade, Germany, and a purification plant in ndres, Gard, France. The re-opening of the Pinjarra site has the potential to ease Rhone-Poulenc's annual capacity for raw material by up to 50 metric .

QED Receives Contracts

ntum Epitaxial Designs (QED) was recently awarded three U.S. Small iness Innovation Research (SBIR) contracts to support advanced develop- t of GaAs devices for military and commercial applications. The contracts uded a Phase II award to develop a carbon-doped HBT for power amplifier lications, and two Phase I contracts to further develop the state-of-the-art in ntum well infrared photodetector (QWIP) technology. The first Phase I con- t is for development of a dual band (two color) normal incidence QWIP to rate in the 3-5 and 8-12 micron windows. The second Phase I contract is for elopment of an integrated focal plane array (FPA) to provide a higher per- nance/cost effective sensor, compared to existing HgCdTe technology, by grating a GaAs FPA and a GaAs multiplexer.

Aixtron's Order Book

Aixtron has announced the receipt of several new orders, including the sale of an AIX 200/4 MOCVD system to LG Electronics, Korea, for the growth of AlGaInP laser structures, primarily for use in the electronic home entertainment sector. The company also announced the sale of two reactors to Kopin [Taunton, MA] that are to be used to grow 4" AlGaAs/GaAs and GaInP-based HBT wafers.

Solkatronic Launches "Blue" Ammonia

Solkatronic Chemicals [Fairfield, NJ] has announced that it is introducing what it calls "blue" ammonia (NH_3) in response to demand from the research community to develop a higher purity ammonia for use in GaN growth. The minimum purity is 99.99994%, and Solkatronic guarantees "the lowest levels yet achieved for oxygen-bearing compounds, water, carbon compounds and metals".

Fisons Instruments Sold

Fisons Instruments, which includes the MBE system manufacturer VG Semicon, has been sold to Thermo Instrument Systems, Inc. of Waltham, MA. The sale was first announced more than one year ago, but was delayed due to concerns expressed by the US and UK anti-trust regulatory authorities.

Bede Wins Queen's Award

Bede Scientific has been awarded a 1996 Queen's Award for Technological Achievement for its D3 X-ray diffraction system. This year's award follows Bede's 1991 success in winning Queen's Awards for both Export and Technological Achievement.

EPI Parent Creates New Division

Chorus Corporation, the parent company of the EPI MBE Products Group, has created a new business unit, Display Technology Systems (DTS), for the design, sale and manufacturer of UHV testing equipment for field emitter displays (FEDs) used to construct flat panel displays.

Growth in the Electronics Market Spurs Demand for Optoelectronic Components

The worldwide market for optoelectronic components rose 20% in 1995 to exceed $6.4 billion.

ROBERT V. STEELE
STRATEGIES UNLIMITED

The worldwide market for optoelectronic components based on compound semiconductors (GaAs, GaP and InP) and silicon is growing rapidly as the demand for products and services enabled by these components continues to climb. Optoelectronic component shipments exceeded $6.4 billion in 1995, up over 20% from $5.2 billion in 1994. Semiconductor-based optoelectronic components include visible LED lamps and displays, infrared LED lamps and assemblies (e.g. photointerrupters, IR data links), optocouplers, laser diodes, detectors, datacom and telecom modules, and image sensors (e.g. CCDs). Although the market is heavily weighted toward compound semiconductor devices, silicon-based devices are important as well, including many types of detectors and CCDs.

Although small in relation to the silicon semiconductor component industry ($140 billion in 1995), the optoelectronic component business supports a wide variety of advanced electronic products and communication services The demand for optoelectronic components is being driven by rapidly growing markets for personal computers, office automation equipment, high-speed telecommunications and data communications equipment, and consumer electronics products. For example, growth in the personal computer market is driving the demand for CD-ROM drives and laser printers (laser diodes), modems (optocouplers), and infrared data links (IR LEDs). Increasing communications requirements are demanding more fiber optics for broadband multimedia services in the telecommunications industry, as well as high-speed computer interconnections, including FDDI, Fiber Channel and ATM. Consumer product applications for optoelectronic components include video camcorders, CD players, infrared remote controls, and, coming soon, the digital video disk (DVD).

On the supply side the optoelectronic components industry is highly concentrated, with two-thirds of total worldwide revenues accounted for by the top 10 companies (see Figure One), and nearly 80 percent accounted for by the top 15 companies. The remaining 20 percent of the market is shared by a large number of companies, many of which are small. Nevertheless, these smaller companies play an important role in developing new technologies and in supplying components for specialized applications.

The total supply of optoelectronic components is also highly concentrated geographically. In 1995, 64.7 percent of the worldwide demand for optoelectronic components was supplied by Japanese companies, 22.5 percent was supplied by North American companies, 7.6. percent was supplied by European companies, and 5.2 percent was supplied by companies located in the Asia-Pacific region (mainly Taiwan and Korea). Among these four regions, the fastest growing is Asia-Pacific, which saw an increase in optoelectronic component shipments of over 40 percent from 1994 to 1995.

Strategies Unlimited, a seventeen-year-old market research consultancy located in Mountain View, California, provides market research and strategic planning services for optoelectronics, wireless communications, and photovoltaic systems and components. If you would like to receive more information about their services in the optolelectronics field, ***circle 9 on the Reader Service Card.***

Top 10 Optoelectronic Semiconductor Component Suppliers in 1995

Rank	Company	Country
1	Sharp	Japan
2	Hewlett-Packard	USA
3	Toshiba	Japan
4	Sony	Japan
5	Matsushita	Japan
6	NEC	Japan
7	Rohm	Japan
8	Stanley	Japan
9	Siemens	Germany
10	Lite-On	Taiwan

Figure One: Strategies Unlimited's ranking of the top ten suppliers of III-V-based opetoelectronic components in 1995.

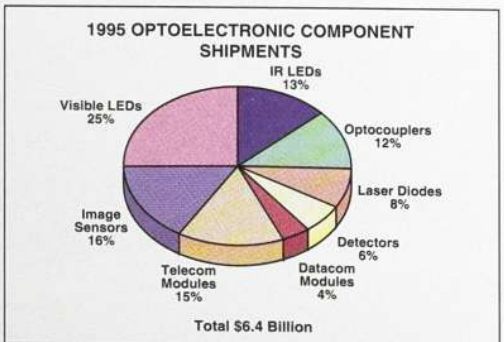


Figure Two: Breakdown of 1995 optoelectronic component shipments by product types. LEDs account for 38% of this $6.4 billion market.

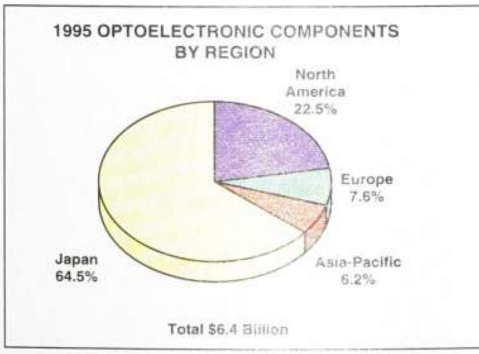


Figure Three: Geographic breakdown of the worldwide supply of optoelectronic componets in 1995.

Ultraviolet Detectors

The same physical properties which make GaN and its related materials suitable as UV emitters also make them suitable for UV detectors

ROBERT A. METZGER

Detection of light in the ultraviolet (wavelength < 400 nm) has a wide range of applications, both commercial and military, particularly in those areas where the UV component of light needs to be analyzed in the presence of large visible or infrared (IR) backgrounds. In the commercial sector these applications include: flame and heat sensors, medical applications (sterilization), UV calibration devices (tanning monitors), plasma diagnostics, and engine monitoring. Military applications include: the detection of missile plumes, missile guidance, detection of biological/chemical agents (key absorption lines are in the UV), secure intersatellite communications (UV will not penetrate Earth's ozone layer), and underwater/submarine communications systems. Most of these applications require a solar blind detector - one which detects only in the UV, but does not sense longer wavelengths. As an example, an in flight missile may have an exhaust plume which extends to distances of up to a mile. When trying to use a seeker missile to shoot down this missile, if the detector in the seeker missile senses a wide spectrum of light, including the visible and the IR, then the missile appears to be almost a mile long due to the exhaust plume, thereby making it nearly impossible to target the actual missile. However, if the detector is only sensing in the UV, it will see the hottest exhaust gases which are just escaping at the base of the missile, and strike it there, thereby destroying the missile. In the same manner, UV detectors can be used to sense the presence of a flame (which has a UV component), rather than just detecting a hot object which may or may not be associated with a flame - an important consideration in fire detection systems.

Alternatives

Traditionally, UV detection has been accomplished by two different devices - the photomultiplier tube (PMT) and the silicon PIN photodiode. A PMT consists of a photocathode material which emits a photoelectron when a photon is absorbed. Photocathode materials such as SbKCs (bailkali) and CsTe can be used which exhibit maximum sensitivity in the range from 400 to 235 nm, respectively, making them well suited to UV applications. Once the photoelectron is emitted it is accelerated by in an electric field (many thousands of volts required) and then run through a photomultiplier, where the signal is amplified, and then the amplified signal collected. The complexities of this detector are that detection and amplification must take place in a vacuum tube, high voltages are required, the tubes are physically large and fragile, often need water cooling, are sensitive to magnetic fields, and can be expensive. These characteristics limit their applications, especially for those requiring small devices consuming small power (key requirements for most military needs). However, the PMT exhibits high gain and low noise, and when using the appropriate photocathode material, can be fairly solar blind. The alternative approach has been to use a Si photodiode. This device offers the advantages inherent in a small, solid state device, requiring only moderate voltages. Disadvantages of this approach include the fact that Si is an indirect bandgap material, so that quantum efficiency is low (conversion of photons into electron-hole pairs), and that the peak sensitivity is around 700 nm, so that external filtering is needed to block out the visible and IR light, this adding both to the expense and volume of the detector assembly. What is needed is a detector which combines the best of both of these devices - the compactness, low voltage operation of the Si photodiode, with the solar blind capabilities of the PMT.

The next generation of UV detectors are those based on wide bandgap semiconductors ($E_g > 3.0$ eV). Unlike Si which has a bandgap of 1.12 eV, and therefore allows the detection of visible and IR light along with UV, those materials with bandgaps > 3.0 eV, can only detect light with wavelengths < 414 nm, thereby making them naturally solar blind. The bandgap of 3.0 eV represents a lower useable limit, while for many applications, especially the military ones, which require wavelengths of 200 - 300 nm, will require bandgaps which correspond to 6.1 - 4.1 eV. The two material systems which are being investigated for this application are those based on SiC ($E_g = 3.0$ - 3.3 eV depending on polytype) and $Al_xGa_{1-x}N$ ($E_g = 3.4$ - 6.2 eV for $0<x<1$).

SiC

Dale Brown and coworkers at Lockheed Martin [Schenectady, NY], Cree Research [Durham, NC], Rensselaer Polytechnic Institute [Troy, NY] and Optronic Laboratories [Orlando, FL] have fabricated 6H-SiC epitaxial based p-n photodiodes for operation over the 200-400 nm range, which exhibit a responsivity of 175 mA/W at 270 nm. S. Sheppard, M. Melloch, and coworkers at Purdue University [West Lafayette, IN] have fabricated buried channel Charge-Couple Device (CCDs) using 6H-SiC, taking advantage of the fact that SiC has a stable oxide which can be used in the CCD structure. Integrating a SiC photodiode with these CCDs would result in UV imaging system. In addition, Boston Electronics Corporation [Brookline, MA] now offers SiC photodiodes grown by Cree. These photodiodes can be used with and without filters, where the filters can block out a large amount of the light from the 300 - 400 nm region. Limitations of this device are due to the indirect bandgap of SiC (and therefore lowered quantum efficiency), and the fact that the 3.0 eV bandgap places it just on the wavelength edge of being useful as a solar-blind detector.

$Al_xGa_{1-x}N$

Anis Husain of DARPA, program manager for several key DARPA sponsored GaN emitter programs, is also initiating GaN-based UV detector programs. Husain says, "we have not exhaustively looked at SiC, but feel that AlGaN is the superior choice for this application, since you can tailor the cutoff wavelength by varying the Al content." This is one of the key advantages that AlxGa1-xN has over SiC - the ability to vary the cutoff wavelength from 360 to 197 nm by varying x (Al content) from 0 to 100%. When this is coupled with high quantum efficiencies due to the material's direct bandgaps, capability to form heterojunctions, low surface recombination rates, and stability in harsh physical and chemical environments, DARPA finds AlGaN the most promising materials system for UV detection. Husain also says, "all the materials issues that we are addressing in our GaN-emitter programs, those of growth, defects and contact layers are the same issues that are faced in the use of GaN and its alloys for UV detectors. What we learn in emitters can be applied to detectors." In addition, he believes that the development of a compact, low power, reliable solid state UV detector will open up a whole range of new applications for UV detectors in the military - both for active guidance systems in missiles, "as well as providing another dimension in the spectrum of early identification."

APA Optics

M. Asif Khan of APA Optics [Blaine, MN] has been actively working on GaN and its related materials for UV detectors since 1980, when at Honeywell. As Khan describes it, "in the beginning, work was greatly hampered by lack of p-type doping in the nitrides. Without p-type doping p-n photovoltaic detectors could not be made, and Schottky-type detectors were also limited, due to the inability at that time to make good rectifying contacts to n-type GaN." Since then the p-type doping problem in GaN has been solved and rapid progress in detectors has been made. Khan and coworkers have recently fabricated AlxGa1-xN photoconductors where the Al content ranged from 5 to 61%. The 61% Al content device exhibited a cutoff wavelength of 240 nm, a record for the moment, but one that researchers are quickly improving upon. Photoresponsivities as high as 300 A/W were obtained for these devices. One of the critical issues that is being addressed is that of defects and the effect that they have on the bandwidth of the photoresponse. As compared to a commercially available silicon photodiode, which can operate at frequencies of 100 kHz, Khan and coworkers find that GaN-based devices can operate only up to 5 kHz, this speed limited by the charge which gets stored at defects in the AlGaN material. Khan says "that even though the GaN shows twice the responsivity of the SiC photodiode, its speed is greatly reduced by defects - this is an issue which is currently under investigation." APA Optics which has been working on the fabrication of GaN-based HFET structures, has utilized the HFET (0.2 mm gate length GaN/AlGaN structures which exhibit fmax of 70 GHz and ft of 20 GHz) as a photodetector, which has exhibited responsivities as high as 3000 A/W for wavelengths from 200 to 365 nm. These large responsivities are caused by the photoinduced shift of the HFET's threshold voltage by the trapped light-generated holes. In terms of applications and markets for GaN-based photodetectors, Khan says "at the moment, 30-40 different customers are evaluating our photovoltaic and photoconductive detectors for a wide range of activities - we believe that detector applications will be a very good market for GaN-based devices."

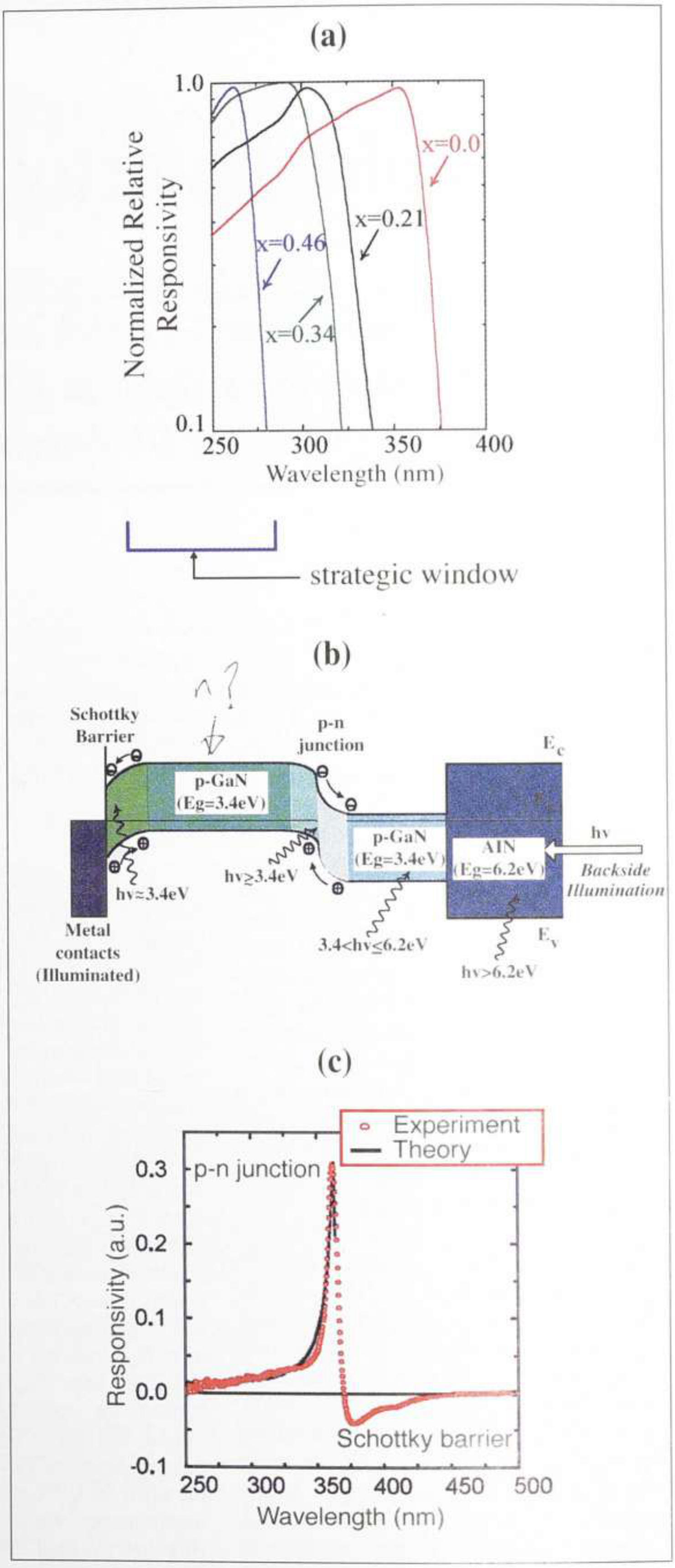


Figure 1. (a) Normalized responsivity for $Al_xGa_{1-x}N$ photoconductor for Al content varying from 0.0 to 0.46. (b) Band diagram of GaN-based self-filtering detector. (c) Responsivity of self-filtering detector. Courtesy of Northwestern University.

Northwestern University

Like the APA Optics effort, researchers at Northwestern University's Center for Quantum Devices, lead by Manijeh Razeghi, are actively pursing the development of AlGaN for photoconductive and photovoltaic UV detectors. Figure 1 (a) illustrates the ability of altering the cutoff frequency of $Al_xGa_{1-x}As$ by changing the Al content, where a cutoff frequency of 260 nm was obtained for an Al content of 46%. An interesting device which the Northwestern University group is pursuing, is that of the self filtering detector which gives a very sharp spectral responsivity. See Figure 1(b) for the energy band diagram of this detector in which the n-GaN layer is 0.5 mm thick and the p-GaN layer is 2.0 mm thick. Utilizing backside illumination through the AlN buffer layer, all light with energy above 6.2 eV is absorbed by the AlN, while permitting lower energy light to pass through. Photons with energy between 3.4 eV (GaN bandgap) and 6.2 eV (AlN bandgap) get absorbed in the n-GaN layer. Because GaN has a very high absorption coefficient (105 cm^{-1}) the photons entering this region all get absorbed within the first 0.1 mm. The diffusion length of minority carriers in GaN is much less than the thickness of the n-GaN region, so the minority carriers recombine before reaching the p-n junction depletion region, and as a result produce no photocurrent. It is only for light which has an energy very close to that of the bandgap of GaN (3.4 eV - wavelength 360 nm) that can penetrate deeper into the device and reach the depletion region to form electron-hole pairs (light of lower energy than the GaN bandgap simply passes through the device) which in turn contribute to the photocurrent. Therefore, the responsivity of this detector is essentially tuned to the bandgap of the GaN. This effect is illustrated in Figure 1(c), showing the strong photoresponse at 360 nm. By adding Al to the GaN in this detector, it should be possible to shift this self-filtering detector response to shorter wavelengths.

In the future, all these UV photodetectors (PMT, Si, SiC, AlGaN) will be available, each exhibiting their own particular strengths and weaknesses. However, for applications requiring small volumes, low powers, and the ability to tune cutoff frequencies, AlGaN based-detectors offer clear cut advantages, which may well make AlGaN the material of choice for future UV detectors.

Full Color LED Displays

For manufacturers of red, green and blue LEDs, there are millions of reasons to love this application

MARIE MEYER

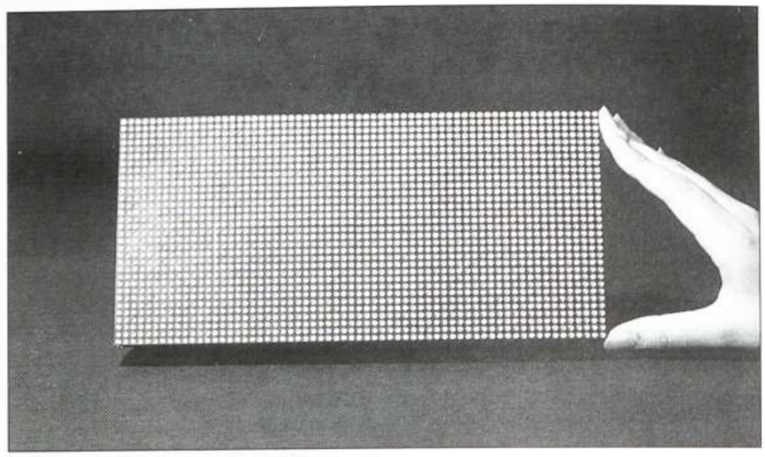
Full color LED-based displays are going to be big - both literally and figuratively. The market is immature, but any medium that can provide a more attention-grabbing method of delivering advertising and entertainment seems guaranteed to succeed. And a handful of recently-released products provide evidence for how the hundreds of millions of red, green and blue (RGB) LEDs that application requires will be packaged and sold.

Integration, of a Sort

There are basically two ways to construct the RGB pixels. The first is to use discrete LEDs. An example of that method, as executed by Toshiba, is shown in Figure One. The RGB pixel is formed using one red, one blue, and two green LEDs, each in its own conventional domed package. (Why use two green LEDs? More on that later...) The second way is to package the individual red, green and blue chips together as one integrated lamp. Sharp's implementation of that method is shown in Figure Two. (A third method, a "single-chip" RGB LED constructed using red AlGaAs and green and blue ZnSe emitters grown on a single GaAs substrate is sometimes discussed, but it is still restricted to the research-only realm for now.)

Both of the illustrated methods have their own strengths and weaknesses. The pixel made from discrete LEDs is best suited for outdoor applications, because it allows the use of a lens to focus the output. This has the effect of decreasing the viewing angle (to a cone ~40°), but at the same time it sufficiently improves the intensity so that the display can be used even in sunlight. And given that outdoor displays are usually meant to be viewed from a relatively long distance, the loss of viewing angle is not considered a fatal flaw. On the other hand, the integrated lamp approach is more suited for indoor applications. Here the viewing angle is more important than intensity, since the display won't be competing with sunlight. Sharp specifies 60° for the example shown in Figure Two, and Siemens offers a surface mount RGB integrated lamp with a maximum viewing angle of 120°. Total resolution is also more important for indoor applications, and the smaller size of the integrated pixel allows ~33% more chips to be packed into the display.

One of the most interesting things about the integrated lamp is the fact that it is, in reality, not very integrated at all. For starters, there is the fact that the RGB chips are individually processed (using three different materials systems) and then bonded together. Moreover, each of the chips has quite different performance characteristics. For example,



Coming soon to a billboard near you: four of Toshiba's full color display modules, built using red, green and blue LEDs.

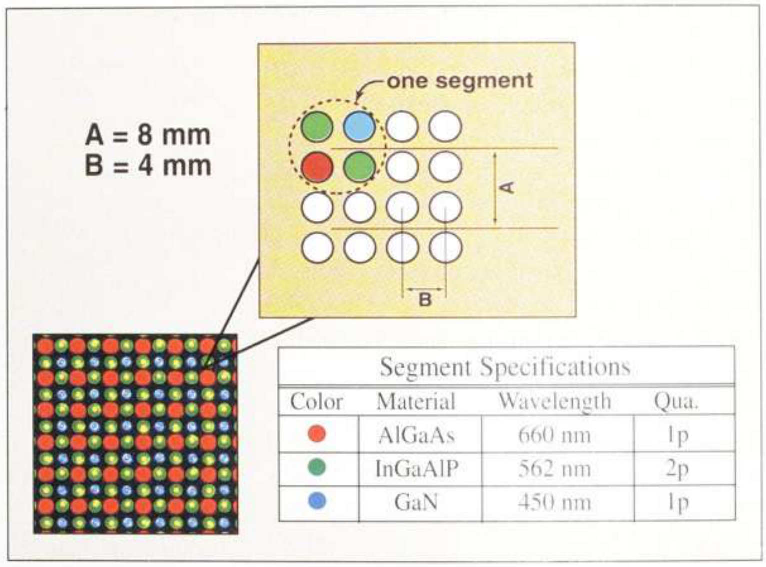


Figure One: Lower left: photo of Toshiba's full color display; upper right: schematic of LED placement.

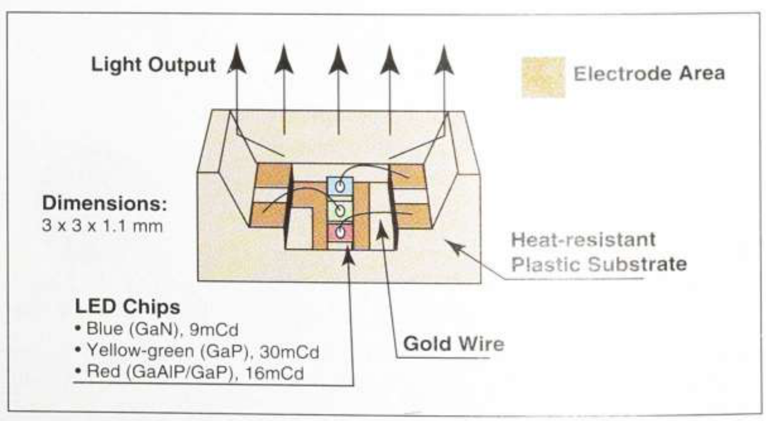


Figure Two: Schematic of Sharp Corporation's full-color LED integrated lamp which combines red, yellow-green and blue LED chips into a single package.

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to produce white light in the Siemens integrated lamp, you must supply the red chip with 2 mA, the green chip with 10 mA, and the blue chip with 50 mA. It is therefore necessary to supply a separate drive circuit for each of the chips. For now, the superior resolution and viewing angle provided by the integrated lamp are enough to compensate for the more complex biasing requirements. But, according to Jonathan Wafer, Senior Product Marketing Engineer for Siemens in Cupertino, CA, the future will require RGB LEDs which provide more closely matched output as well as roughly similar forward voltages, to simplify circuitry.

From Chips to Pixels to Modules

LED pixels are brighter than CRT pixels, and they allow a greater range of colors to be created than is possible with a monitor or projection screen. LED manufacturers calculate that the size of the palette is 16.77 million colors. However, the electronics which are required to execute that range of options are not insignificant, especially when full motion video is involved. Although this application is still at an early stage of its development, it is already apparent that the preferred marketing strategy will be to package the discrete devices or the integrated lamps into a "module" that includes built-in drive circuitry. The photo at the top of the preceding page shows four of Toshiba's modules, which are sample priced at ~$4,500 each. Similar types of products are also available from a growing number of companies, and they typically include an array of 16 x 32 pixels[1], and are often described as "flat enough and light enough to hang on the wall". The LED manufacturer may offer the module directly, or it may work through a strategic ally. For example, like Toshiba, Sharp offers its solution as a module. Siemens has an alliance with Cree regarding Cree's SiC/GaN technology (see *CS* 2(1), p.14), under which Siemens and Cree work together to create the individual chips that go into the Siemens integrated lamp, and the lamps are then offered in a module by Real Color Displays (RCD), a wholly owned subsidiary of Cree.[2] The module offered by RCD, consisting of a 16 x 32 matrix of 5.5 mm pixels, is just 1 cm thick and weighs only 8 oz/225g. RCD is currently demonstrating a 10 foot/3 meter (diagonal) "video wall" built from these modules which, in completely finished form, is only 3"/7.5 cm thick. And Nichia Chemical, the undisputed leader in high brightness blue and green LEDs, is also offering modularized products based on discrete LEDs. For outdoor applications it offers an "LED cluster lamp" measuring 22 mm per side, consisting of two blue, three green, and three red LEDs. For indoor applications it offers a 128 mm square module.

The typical customer for the modules is a company that specializes in marketing and manufacturing signs. The modules are used like building blocks, and they can be placed horizontally or vertically and combined in any number to create virtually any size sign. Once you begin to picture a sign you can appreciate the number of LEDs that will beneeded for this application. For example: the dimensions of the Toshiba module are 128 mm x 256mm, and it contains 2,048 discrete LEDs. A relatively modest sign of 1.28 meters x 2.56 meters requires one hundred modules, or 204,800 LEDs. Something more impressive, say 12.8 meters by 25.6 meters, requires one thousand modules, or more than 20 million LEDs. In the Sharp module the pixels are closer together, because higher resolution is desirable for indoor applications. The dimensions are half that of the Toshiba module, and each contains 512

1 Multiples of eight are preferred for maximum compatibility with MUX/DEMUX circuitry.

2 Siemens also offers the lamps separately. The author was unable to determine if Toshiba and Sharp follow a similar policy.

lamps, or 1,536 LED chips. To build the same "modest" sign of 1.28 meters x 2.56 meters, you need 400 modules, containing a total of 614,400 LED chips. And to build the same "impressive" sign of 12.8 meters by 25.6 meters (perhaps for use as a replay screen in a ballpark) you would need 40,000 modules, or more than 61 million LED chips. In other words: each sign requires a lot of LEDs. And anyone who has ever been to Tokyo's Ginza district, the Las Vegas strip, or a large sports arena can also imagine the very large number of signs that will be required.

Across the "Green Gulf" to White Light?

Of course this entire application was enabled by the breakthroughs achieved by Cree Research and Nichia Chemical in manufacturing blue LEDs. Further developments in the blue regime will certainly be welcome. For example, Cree's first product was a simple SiC homojunction structure, and that is the chip that Siemens uses in the current version of its integrated lamp. However, Cree is now ramping up production of a higher brightness product made from GaN on SiC, and Siemens will be switching over as soon as is practicable.

However, the real need for improvement lies with the green LEDs. Steve Lester of Hewlett-Packard describes the current problem as "the green gulf": high brightness blue LEDs are now available on the shortwavelength end of the visible spectrum, and, on the opposite end, very high quality red LEDs have been available for sometime. But between the two lies the green region where direct bandgap emitters have not been available in mass-produced form. Thus in the Toshiba example described earlier it is necessary to use two green LEDs to provide enough output for outdoor use. According to Siemens' Jonathan Wafer, "green is the weakest link right now, and it needs to be improved by at least one order of magnitude brighter than the current best". It appears that help is on the way. Nichia has recently begun mass production of 6 Cd GaN green LEDs; Siemens hopes to be using GaN/SiC green LEDs from Cree by mid-1997. After that, according to Wafer, it may be possible, in 4-5 years, to begin introducing dedicated white light LEDs that are sufficiently bright and efficient to compete with incandescent bulbs. But for now, the display application should be sufficient to keep the LED production lines running at full capacity for quite some time.

For more information about blue and green LEDs, see page 22.

DVD Laser Diodes

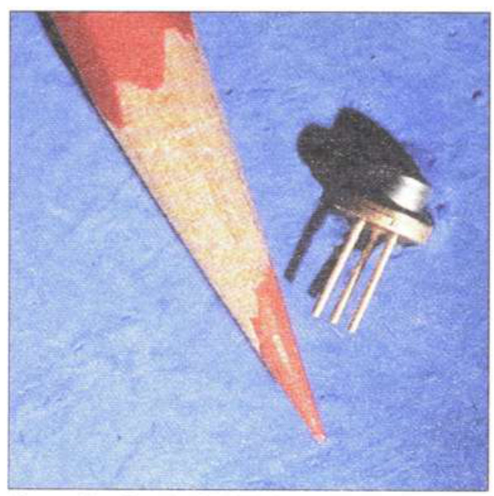
Decreasing laser diode wavelengths from 780 nm to 650-635 nm greatly enhances data storage capacity for audio, video and computer applications

ROBERT A. METZGER

The use of AlGaAs/GaAs-based infrared laser diodes operating at 780 nm radically altered the mode of data storage in audio and computer marketplaces. The once vinyl and magnetic tape dominated audio market has now been replaced by that of CDs, while the magnetic floppy used for computer data storage has been replaced for many read only applications by CD-ROM. The next evolution in the storage of data will be the advent of the new DVD (digital versatile disc/digital video disc) format, in which the diode wavelength used in these devices is reduced from the current 780 nm to the 635-650 nm region, which promises to not only expand current system capabilities (audio and computer), but open up the video market to laser-based players.

New standards

There is much more to the new DVD standard than simply decreasing the laser wavelength from 780 nm to 635-650 nm. If that were all that had been done for this new standard, in which storage density dependence on wavelength (λ) typically increases by λ^2, an increase in storage density by only a factor of 1.5 would be obtained. However, many other modifications have been incorporated into the DVD standard in order to further increase storage density. Because the DVD standard specifies that the laser need only focus to a depth of 0.6 mm beneath the surface of the disc, as compared to the CD standard which requires focusing to depths of 1.2 mm, the DVD laser can establish a 0.4 μm spot , while in the CD format, a 0.8 μm spot is generated. This reduced spot size not only permits data be compressed within a given data track, but also allows the tracks to be spaced more closely together, where in this case the pitch of the data tracks has been reduced from 1.6 μm to 0.725 μm. In addition, video compression techniques as spelled out in the MPEG-2 standard (set up by the Motion Picture Experts Group (MPEG) originally developed for the transmission of high-definition TV) will be used in DVD products which further increases storage capacity. When all these enhancements are taken together, it results in the standard 4.75 inch diameter disc being able to store 4.7 GB of data - a greater than 7 times increase over the current CD standard using the 780 nm AlGaAs/GaAs laser. This improved density will permit the storage of movies with run times up to 133 minutes - making DVD video players one of the most visible applications to utilize the new DVD standard. The key to the implementation of DVD technology is the 635-650 nm AlGaInP-based red diode laser.



Example of typical DVD laser diode. Courtesy of Toshiba.

AlGaInP vs AlGaAs

One of the major challenges of manufacturing laser diodes for the red portion of the spectrum is the requirement of using the larger bandgap AlGaInP materials system (635-650 nm), as compared to the AlGaAs system which is utilized for the near IR laser diodes currently being utilized for current CD formats (780 nm). The AlGaInP alloy system can be characterized by the expression: $(Al_yGa_{1-y})_{0.5}In_{0.5}P$ where for all values of y, this alloy will be lattice matched to GaAs. Under the conditions of $0<y<0.7$ the resultant alloy will have a direct bandgap (a requirement for laser operation) which ranges from 1.9 eV for $Ga_{0.5}In_{0.5}P$ to about 2.3 eV for $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$, where $Ga_{0.5}In_{0.5}P$ will emit in the red region of the spectrum. The higher bandgap alloys which contain Al are required for barriers used in quantum well (QW) structures, as well is in waveguiding and cladding layers of the device.

As compared to AlGaAs-based heterostructures, AlGaInP-based heterostructures can not obtain as high p-type doping levels, exhibit very low hole mobilities, have higher thermal resistivity, and a relatively low conduction band offset - all of which make laser operation more difficult to obtain in this materials system. For MOCVD growth, in which Zn is the typical acceptor dopant used, under the conditions of increasing Al composition, the acceptor activation energy increases and is accompanied by a decrease in Zn incorporation - both effects limiting the upper limits of p-type doping, which is critical for p-type cladding layers. Mg and Be can also be used as acceptor dopants, and do give better hole concentrations than Zn, but exhibit much poorer mobilities. Other difficulties in working with the AlGaInP system are due to the fact that the maximum conduction band offset for a heterostructure in this material system is 270 meV, as compared to 350 meV for the AlGaAs system, which results in poorer electron confinement. This effect worsens at higher Al concentrations, which are needed for the shorter wavelength devices needed for DVD applications. In addition, AlGaInP alloys only span a bandgap energy of 450 meV, as compared to 750 meV for AlGaAs alloys, which results in less bandstructure design latitude of cladding and optical confinement layers. Both of these bandstructure limitations contribute to an enhancement of minority carrier electrons getting into the p-cladding layer of a laser diode, which can then diffuse or drift to the p-contact, contributing to an electron leakage current which raises threshold, reduces efficiency, and makes the threshold a much more sensitive function of temperature.

Besides issues of bandstructure, which make the AlGaInP system much more challenging for laser applications as compared to the AlGaAs system, their are unique growth challenges involved in the AlGaInP system. During growth, AlGaInP alloys can spontaneously order, forming AlGaP/InP superlattices along the {111} direction, which result in a material which exhibits a bandgap which is 70-100 meV lower than that of a random AlGaInP alloy. This smaller bandgap energy alloy can further degrade electron confinement and degrade laser performance. Two approaches have been utilized to minimize ordered growth in this alloy system - by growing on misoriented substrates (5-15° from nominal (100) direction) and by growing at high temperatures. Off-axis growth produces a surface with more atomic steps, which also improves interface and surface quality, while also enabling more efficient p-type doping (while n-type doping with Se or Te becomes less efficient). High temperature growth imparts more energy to adsorbed surface atoms, permitting them to randomly incorporate, and overriding their tendency to incorporate into lower energy ordered surface sites.. Both these approaches are now typically used to reduce, or even eliminate ordered growth.

Further enhancements of laser performance are obtained by utilizing strained material in order to alter the bandstructure of AlGaInP alloys, which in turn alter the optical/electrical characteristics of the material. AlGaInP alloys typically have higher effective masses than in the AlGaAs system, which means that these alloys have a greater density of carrier states, and therefore require higher carrier concentrations to reach lasing threshold. However, when these alloys are placed under compression, the valence band's state density is reduced, thereby reducing threshold current. On the other hand, when the material is put in tension, a very high effective mass exists at the band edge, but the poorer k-space overlap of the electron and hole distributions reduces the spontaneous emission coefficient, thereby reducing threshold currents. The use of both compressive and tensile strain are routinely utilized in the fabrication of QW structures in this alloy system to reduce threshold currents and improve carrier confinement.

AlGaInP laser structures

Several manufacturers are in pre-production and initial production of AlGaInP-based laser diodes for 635-650 nm operation, includ-

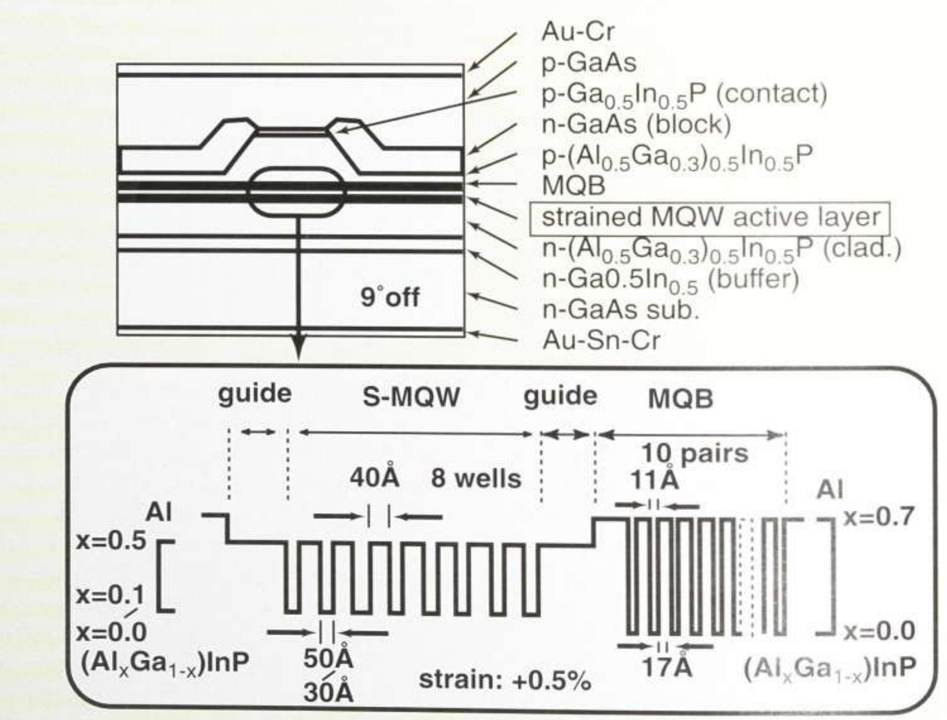


Figure 1 - A typical AlGaInP-based red laser suitable for DVD applications, incorporating both a strained MQW structure as well as a MQB confinement enhancing structure. Courtesy of Sanyo Electric Company [Osaka, Japan].

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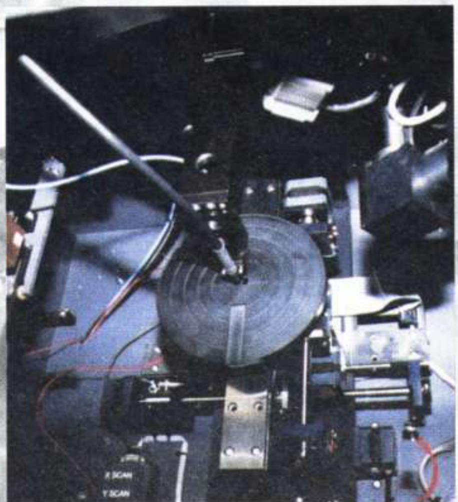

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ing Mitsubishi Electric, Sharp, Pioneer, Sanyo Electric, Matsushita, Toshiba, Goldstar and Samsung - where all of these devices are based on AlGaInP multiquantum well (MQW) laser diode structures. A typical example is that of Sanyo's 635 nm laser as shown in Figure 1, which uses compressively strained QWs (other manufacturers utilize tensile strained QWs). As shown in this example, the wells consist of $(Al_{0.1}Ga_{0.9})_{0.45}In_{0.55}P$ which result in a compressive strain of 0.5%, while the barriers in the QWs consist of lattice matched $(Al_{0.5}Ga_{0.5})_{0.50}In_{0.5}P$. In some experimental device structures being investigated, the compressive strain can be further increased in the wells, by introducing tensile strain in the barriers, thereby creating strain-compensated structures. In addition to using the strained MQW to reduce lasing threshold, a multiquantum barrier (MQB) is introduced between the MQW and the p-type cladding layer. The MQB structure consists of $Ga_{0.5}In_{0.5}P$ wells and $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ barriers which act to reduce the flow of minority carrier electrons into the cladding layer and to the p-type contact, which would degrade laser performance. The active MQW layer is surrounded by narrow 50 nm undoped $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ optical confinement layers, which use the same bandgap alloy as is used in the barriers of the MQW structure. The active and optical confinement layers are then surrounded by a larger bandgap $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ cladding layers..

MOCVD growth takes place on vicinal substrates which are misoriented from 9-15° towards the (011) direction in order to improve morphology and reduce spontaneous ordering (some manufacturers such as Sharp utilize MBE growth). In the case of the Sanyo 635 nm laser diode, a three step MOCVD growth process is used to incorporate a selectively buried ridge (SBR) waveguide - a typical structure used for DVD lasers. See Figure 1. In the three step approach, the entire structure through the top p-type $Ga_{0.5}In_{0.5}P$ contact layer is first grown. Next, a stripe with a width of 3-5 μm is lithographically defined and patterned with Si_3N_4 or SiO_2. This stripe is then used as an etch mask, and the material is etched back into the cladding layer to form the laser stripe. With the Si_3N_4 or SiO_2 stripe still in place, a selective MOCVD n-GaAs growth is performed to cover the area outside the stripe, as well as on the stripe sidewall. This sidewall n-type GaAs layer serves as a current blocking layer (confining current to the p-type stripe), and enhances index guiding. The Si_3N_4 or SiO_x stripe is then removed and the final p-GaAs contacting layer is grown. In the case of the Sanyo 635 nm laser, the resulting output power is 5 mW - suitable for reading applications.

Markets

The two major markets for DVD technology will be DVD players for video applications and DVD-ROMs. Estimates of both the size and the growth rates of these markets vary widely. Yoshi Umemoto, marketing manager for Sanyo Electric, explains "it is difficult to determine both the size and ramp up rates of these markets. Many of the manufacturers of DVD products are also manufacturers of current technology - especially in the area of CD-ROM. They have large investments in existing technology, and even though they may have the new DVD technology in hand, they may not want to see it enter the market place until they have generated more revenues with their existing technology." Sony has presented optimistic estimates, stating that they believe that by 1998 that DVD ROMs may capture half of the estimated 100 million unit ROM market, while Infotech Inc predicts that DVD-ROMs will grow very slowly during the next few years due to the introduction later this year of enhanced CD-ROMs, which are expected to compete head-to-head with the new DVD-ROMs. In the area of DVD players, the Electronic Industries Association of Japan, has predicted that the demand for DVD players in Japan is expected to grow from 250,000 in fiscal 1996 to 2 million in fiscal 2000.

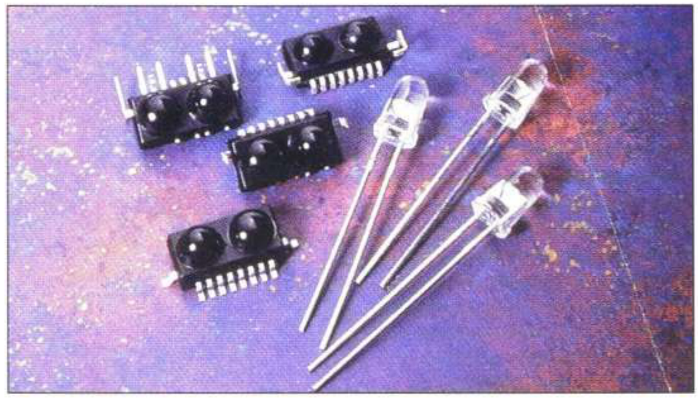
Despite the wide variations in estimates of market size and growth, all manufacturers seem to agree that 1996 will be the year in which DVD technology will first reach the commercial market place, and this will require a readily available source of AlGaInP-based 635 and 650 nm lasers. Umemoto of Sanyo, says "we are currently ramping up production of our 635 nm product, and plan to be at the 500,000/month production level by the end of the year." Two major manufacturers of both laser diodes and DVD players, are Sony which has announced that by August they plan to producing DVD players at a rate of 100,000 per month, and Toshiba, which has announced that by December of 1996 that they will be producing 300,000 DVD players per month. The laser diodes for these systems will be supplied by their own internal sources.

It has been reported that a potential shortage of AlGaInP red lasers is looming on the horizon, especially if the optimistic market estimates for DVD-ROMs become true. However, until commercial products begin to enter the market place in the later half of 1996, and it seen how these new products compete against current products, as well as against enhanced versions of CD-based products, estimates of market size and growth will be difficult to estimate.

Infrared LEDs

Data links will be the next big growth area in the already large market for IR LEDs; they may also become a high volume market for VCSELs.

MARIE MEYER



One of the fastest growing applications for IR LEDs are data link transceivers (shown on the left) that allow cordless data transfer between office peripherals at rates up to 4 Mb/s.

Of all compound semiconductor devices, the IR LED is one of the most the common.[1] Its most obvious applications are in "low tech" items such as TV remote controls. But the most important application, as is shown in Figure One, is computers and office equipment. According to John Day of Strategies Unlimited, the growing demand for mobility and low-cost connectivity is creating a dramatic increase in the demand for infrared products. His firm recently released a report[2] which forecasts a 66.5% compound annual growth rate for IR LED components for the period from 1995-1999, which will mean an increase in value from $685 million in 1994 to $1.3 billion in 1999

Leading the growth in demand for IR LEDs is the relatively new phenomenon of incorporating IR transceiver modules in various types of office equipment to allow cordless data transfer. The most common use today for an IR data link is "point and shoot" file transfer between peripherals such as a printer and a laptop computer, at a typical distance <1 meter. Much more sophisticated applications are in development which will be able to support speedy transfer of large files such as audio and video data, and IR technology developers believe that the transceivers can be made sufficiently fast and versatile to allow IR data links to play an important part in wireless local area networks (WLANs). IR data links have already become standard equipment on virtually all portable computers, and are also included on most new printer models and many desktop PCs. Siemens recently announced that it believes the market for IR data links will grow from ~18 million units in 1995 to over 47 million units in 1997.

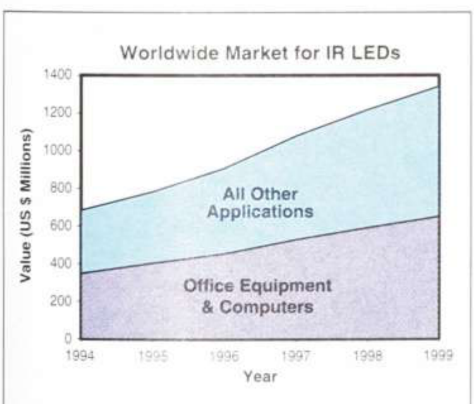


Figure One: *The forecast for the IR LED market, showing total sales and sales for the computer/office equipment sector.*

Hewlett-Packard began offering IR data transfer on some of its calculators as early as 1979. However, for many years the technology looked like a good idea which was waiting for its time to come. Several companies hoped to use the technology to help popularize personal-digital-assistants (PDAs), but for the most part those devices never caught on with the buying public. In 1993 HP took matters in its own hands and set up the Infrared Data Association (IrDA) to promote open standards for the area. HP's 115.2 Kb/s Serial Infrared (HP SIR) standard was adopted at that time. Since then the IrDA has grown to more than 100 members, and in April, 1995 it approved a faster standard. The new spec, which was proposed jointly by HP, IBM and Sharp, runs at 4 Mb/s and 1.15 Mb/s and is backward compatible with the original 115.2 Kb/s standard. The old standard was aimed at transfer of text files and relatively small amounts of information between machines. The new standard targets more data intensive applications such as networking, and the transfer of larger amounts of data, including color graphics files. And the IrDA is already exploring another new standard which would allow data rates of 10 Mb/s and faster, which should enable possibilities such as IR docking stations, multimedia in computing products, and very fast data transfer with imaging products.

IR transceivers for use as IR data links are available from several companies (including HP, IBM, Siemens, TEMIC, Sharp and Rohm) for $2-$5 a piece. Figure Two provides a schematic of HP's HSDL-1000 Transceiver, which contains a 875 nm LED, a PIN Si photodiode, and an IC containing an LED driver, amplifiers and a quantizer. The module is designed to interface directly with selected I/O chips that incorporate logic which performs pulse width modulation/demodulation. The AlGaAs LED in this module uses HP's transparent substrate technology (see *CS* 2(1), p. 22) to provide high radiant efficiency over a wide range of currents up to 500 mA peak current. According to HP's Northe Osbrink, in the next generation of IrDA compliant modules (those based on 10 Mb/s transfer rates) will likely see the LED replaced with a IR vertical cavity surface emitting laser (VCSEL). VCSEL technology is attractive because it is a

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[1] *See page 24 for a comparison of the market for IR LEDs compared to other optoelectronic components.*

[2] *"Infrared LED and Data Link Market Review and Forecast 1995", 108 pages, 75 illustrations. Available for $2,950 from: Strategies Unlimited, 201 San Antonio Circle, Suite 205, Mountain View, CA 94040 TEL [1] 415 941 3448; FAX [1] 415 941 5120; e mail: ix.strtultd@netcom.com.*

good compromise between conventional lasers and LEDs. VCSELs offer the coherent output and high modulation rates of a laser, features which are believed to be necessary to achieve the higher data rates. However, VCSELS also maintain the ease of manufacturing and packaging of an LED, because the mechanical processing requirements for a VCSEL chip are much less than for a non-surface emitter such as a quantum-well or double-heterostructure device. HP recently introduced its first mass-produced VCSEL product (see box), and although it is intended for use in higher -end applications, it is nevertheless said to be indicative of the likely direction of the next generation of IR emitters for the growing data link market.

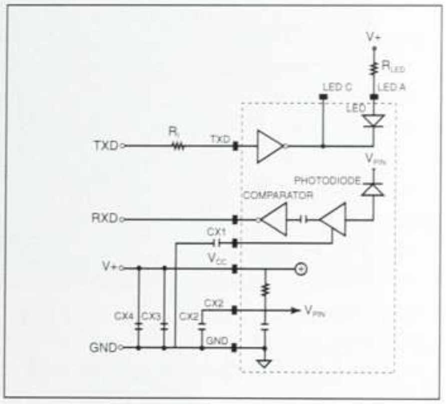
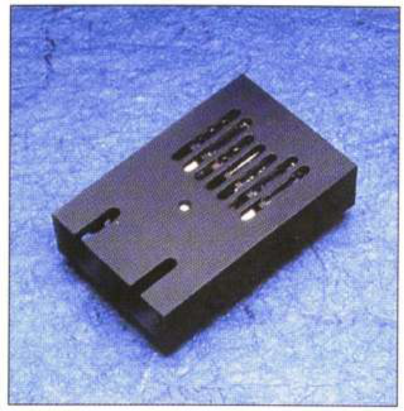


Figure Two: Schematic of HP's HSDL-1000 IrDA-compliant transceiver, which contains a high speed 875 nm LED, a PIN Si photodiode, and an IC containing an LED driver, amplifiers and a quantizer. The module is designed to interface directly with selected I/O chips that incorporate logic which performs pulse width modulation/demodulation.

HP Launches VCSEL-Based Transceiver



Hewlett-Packard has introduced its next-generation multimode transceiver which enables multimode fiber transceivers to achieve gigabit+ data-rate performance on links up to 500 meters. It is targeted toward applications such as full-motion video and other multimedia-information transmissions. This new product is unique in that the light source is a 850 nm VCSEL. The VCSEL is driven by a custom Si bipolar IC that converts differential positive electron-coupled logic (PECL) signals into an analog drive current. HP says that the new transceiver will be priced "between the costs of high-speed 1300 nm LED transceivers at $70 and 1300 nm laser transceiver products at $400". The company hopes that the low cost (as compared to models using edge emitting lasers) will pave the way for a number of emerging applications for gigabit-rate data links, including mass storage and computer system input/output channels, high-speed peripheral interfaces, and computer networking equipment. Volume production is targeted for the second half of 1996.

A Different Blue Laser: Second Harmonic Generation in VCSELs

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Recently there has been extensive work on short-wavelength, compact light sources. These light sources are of great interest for a variety of applications such as full-color displays, analytical and medical measurements, and high-density optical data storage for digital video disks.

Some of the most promising short-wavelength sources are laser diodes (LDfs) with wide-bandgap semiconductors such as the GaN-based and the II-VI (ZnSe)-based material systems. The feasibility of these devices has already been shown. For GaN laser diodes, stimulated emission from edge facets was reported by Akasaki *et al.* in November 1995, and pulsed operation of LDs at room temperature was reported by Nakamura *et al.* in December 1995. However, at the present time, there are still many problems including difficulty in making ohmic contacts, controlling the doping, and making mirror facets for the laser cavity. The development of II-VI LDs is much more advanced so far. Following the first announcement of blue-green lasers in this material system by Haase *et al.* in 1991, several laboratories have achieved CW room temperature operation with tens of mWs of power output. Although the Sony Corporation has recently reported II-VI LDs with more than 100 hours of operating lifetime, much improvement in reliability is needed for a practical device. Thus, the practical application of short wavelength LDfs is not possible yet.

We have been working on a novel approach to realizing short-wavelength monolithic compact laser diodes.[1,2] This is based on the second-harmonic generation (SHG) inside a vertical-cavity surface-emitting laser diode (VCSEL). We call it an "SHG-in-VCSEL" device. This type of device should emit coherent laser light at twice the frequency or half the wavelength of the fundamental laser light. VCSELs are very suitable for SHG since

1) The intracavity intensity of the fundamental light in a VCSEL is extremely high. This is very favorable for SHG since the conversion efficiency is proportional to the intensity of the fundamental light; and
2) VCSELs are usually made from III-V or II-VI materials with a zincblende crystal structure. These materials have a large second-order optical nonlinearity.

One favorable structure for an SHG-in-VCSEL device is shown schematically in Fig.1. This structure differs from a typical VCSEL in two ways. First, we must grow on a substrate with orientation tilted away from (100) where the nonlinear optical coefficients are zero due to the crystal symmetry. Second, we incorporate layers within the cavity of the VCSEL optimized for the highest overall efficiency in converting fundamental light to second harmonic (SH) light. We have recently fabricated a VCSEL grown on an n-(311)B GaAs substrate and observed

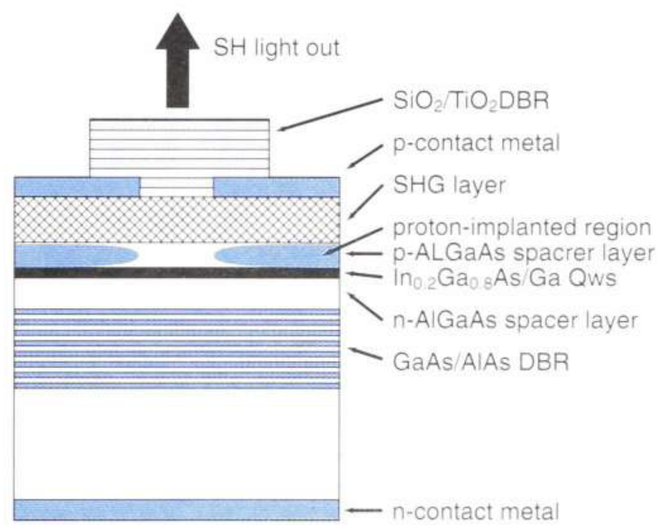

Figure 1: Schematic of a SHG-in-VCSEL device. Blue light emission from similar devices has recently been observed for the first time.

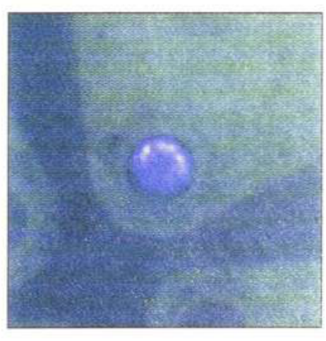

Figure 2: Although the light output power from the SHG-in-VCSEL device is not very high, it is visible to the eye, as shown here.

SH blue light for the first time.[3] It consists of a GaAs/AlAs semiconductor n-DBR bottom mirror, n-AlGaAs spacer layer, InGaAs/GaAs QWs, p-AlGaAs spacer layer, p-GaAs cap layer and $aSiO_2/TiO_2$ dielectric DBR top mirror. The top mirror has high reflectivity at the fundamental wavelength but transmits SH light. This was our first SHG-in-VCSEL device and it did not incorporate the optimized SHG layers but the p-GaAs cap layer and the p-AlGaAs spacer layer, to some extent, function as the SHG layers. This VCSEL lases under pulsed operation at room temperature and lases under CW operation only at low temperature (130-270K). The lasing wavelength of the fundamental light is 965 nm, and that of the SH blue light is 482 nm. The maximum CW output power of the fundamental and the SH light are 1.5 mW and 1.0 nW, respectively, at 135 K. More than 10 nW of SH light is observed under pulsed operation. Although the blue light output power is not very high, it is visible to the naked eye, and is shown in the photograph in Fig.2.

Pros and Cons

The main disadvantage of this device technology is the low output power of the SH laser light. Our simulations indicate that it can be improved to several hundred µWs by incorporation of an optimized GaAs/AlAs SHG layer structure.[2] An even greater output power is possible by making the SHG layers of other nonlinear materials more transparent at the SH wavelength. However, it is doubtful that VCSELs made from these materials will give much higher power than 1 mW. Edge-emitting laser diodes made from II-VI and GaN-based materials are likely to provide higher output powers.

However, there are many advantages to the SHG-in-VCSEL device inherited from all the advantages of conventional VCSELs such as 1) wafer level testing and characterization, 2) low threshold current, 3) a single-mode, single-frequency circular beam, 4) small numerical aperture, 5) 2-D arrays and integration with other devices, and 6) high volume manufacturability. Another advantage of the SHG-in-VCSEL device in III-V materials, is its potentially high reliability, since the fabrication technologies are quite mature and devices made from these materials have been found to be reliable. It should also be mentioned that SHG-in-VCSEL devices provide coherent light at two wavelengths simultaneously.

The SHG-in-VCSEL device technology could provide a wide range of possible wavelengths, since we can obtain a wavelength half of the fundamental wavelength of any existing VCSEL. For example, when a 660 nm AlInGaP VCSEL can be made, it will provide an SHG-in-VCSEL device with 330 nm SH light.

Our goal is to achieve an SHG-in-VCSEL device with an output power on the order of 1 mW. The key issues are optimization of the device structure and the SHG layers, and establishment of high-quality crystal growth for the necessary non-(100) substrate orientation.

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The Cooled IR Detector Market Heats Up

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New competition and an evolving market are placing considerable pressures on conventional high performance detectors in the mid-wave infrared and beyond. Traditionally, InSb and HgCdTe detectors have dominated imaging systems in the 3-5µm and 8-12µm atmospheric transmission windows, with extrinsic detectors meeting requirements at longer wavelengths. However, stringent demands on system performance, cost, and manufacturability, added to interest in multispectral imaging, on-chip signal processing, and optical interconnects, have stimulated considerable efforts in alternative technologies.

Narrow gap IV-VI's are once again receiving some attention, but foremost among the competing technologies are superlattice-based sensors and quantum well intersubband photodetectors, or QWIPs. The two share advantages of compatibility with established electronic and optoelectronic devices (unlike the II-VI's and lead salts), but are in other respects very different. At present, QWIPs appear to offer a near term alternative to HgCdTe without excessive development costs, while the superlattices promise higher performance levels but are a less mature technology.

As illustrated in the figure, superlattice and multi-quantum well devices employ very different optical transitions, making them analogous in some regards to conventional intrinsic and extrinsic detectors, respectively. Considerable differences in expected performances derive largely from this distinction.

QWIPs employ intersubband transitions, relying on photoexcitation of carriers from conduction or valence band minima to higher lying, more conductive, bound or continuum states. Fast phonon relaxation processes typically yield picosecond lifetimes for these excited states, resulting in detectivities or operating temperatures lower than those of more conventional structures (see B. Levine and M.A. Kinch, et al., Appl. Phys. Lett. 56, 2354-6 (1990)). Furthermore, much of the work on these devices has centered on power-hungry photoconductive detectors, rather than photovoltaics. Nevertheless, AlGaAs QWIPs have matured rapidly, with imaging having been demonstrated in focal plane arrays as large as 256x256, albeit at temperatures appreciably lower than required by HgCdTe systems. Some effort has also been devoted to Si/SiGe implementations, offering the possibility of monolithic integration with Si readout circuitry. Anticipated problems such as low quantum efficiencies and considerable cross-talk, deriving primarily from low normal-incidence absorption coefficients, have been mitigated by use of 2-D reflective gratings and thinning of arrays. While the impact of these refinements on manufacturability is unclear, groups at Martin-Lockheed and elsewhere are gambling on a market eager for alternatives to HgCdTe, with the hope that QWIPs might ultimately better meet multispectral needs and prove more compatible with read-outs and optical interconnects. Arguments of incremental improvements in uniformities have also been made, although these are suspect as the advantages appear insufficient to obviate use of standard gain and offset corrections.

Unlike QWIPs, strained layer superlattices promise state-of-the-art performance. As in HgCdTe, detection in such a structure derives from photogeneration of an electron-hole pair across a forbidden energy gap. Potential advantages of this approach are both fundamental and practical. Auger processes, increasingly important at longer wavelengths and higher operating temperatures, are readily suppressed in appropriately designed superlattices. Tunneling cross sections are often significantly lower, reducing junction leakage. While the magnitude of the benefit is highly system-dependent, both of these effects can yield operating temperatures and/or detectivities higher than can be achieved in HgCdTe. The capability of creating a single III-V technology plausibly covering the 3-20μm spectral range is also appealing, and there is promise of compatibility with III-V electronic and OE devices for readouts and interconnects, leveraging off an established materials processing and manufacturing base.

Interest in superlattice-based IR detectors began with work on InAsSb/InSb structures at Sandia in the mid-1980's. This research contributed greatly to the maturity of molecular beam epitaxial growth of antimonides, paving the way to today's record high-speed Sb-based electronic devices and IR lasers (see *CS* 1(2), p. 12). However, work on these particular detectors has slowed, due in large measure to problems of microcracking and the emergence of more promising GaInSb/InAs superlattices.

The strength of the GaInSb/InAs system lies in its large band offsets; the availability of high quality, lattice matched GaSb substrates; and compatibility with other structures and devices already demonstrated in the InAs/GaSb/AlSb system. The magnitude of the offsets yields high optical absorption for arbitrarily long cutoff wavelengths, and allows Auger and tunneling processes to be greatly suppressed. The projected result is operating temperatures appreciably higher than are currently available, particularly at longer wavelengths. Such an improvement would lower both weight and power consumption, and could greatly reduce system price, as cooling requirements drive the cost of many IR imagers. Further afield, innovative multicolor arrays employing wide gap, AlSb/InAs blocking layers or bistable shunts should make possible improved spectral discrimination or detection of three or more spectral bands employing a single top contact per pixel.

While the theoretical performance of superlattice detectors makes these attractive next-generation devices, their comparative immaturity has lent considerable impetus to the development of QWIPs. Whether recent improvements in the quality of GaInSb/InAs structures are sufficient to reverse this trend remains to be seen. The performance of single element superlattice detectors now rivals that of state-of-the-art HgCdTe arrays at long wavelengths. We have measured zero bias impedances of $10\Omega\text{-cm}^2$ at 85K in 12μm GaInSb/InAs superlattice homojunctions, comparable to 77K values in HgCdTe arrays. The speed with which these results can be translated into 2-D imaging arrays will likely determine the success or failure of this technology in conventional IR markets. That quantum structures will have a role in the increasingly sophisticated imaging systems of the future seems more likely.

Richard Miles heads the Superlattice and Quantum Well Device Project at the Hughes Research Laboratories. He received B.S. and Ph.D. degrees from Caltech.

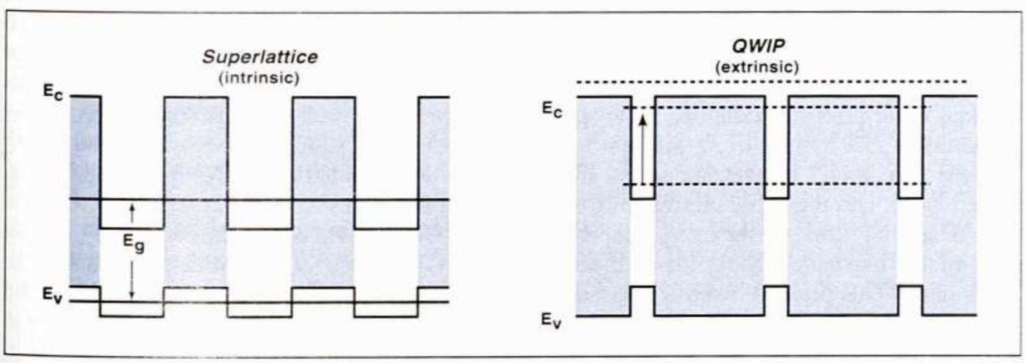

***Figure 1:** A schematic representation of the fundamentally distinct excitation processes which distingusih the competing IR technologies.*

Silicon on Insulators

Do Silicon-on-Insulator based devices have the Low Power and RF characteristics to compete with GaAs devices? Yes!

ROBERT A. METZGER

It is well recognized that one the intrinsic advantages that GaAs-based devices have over Si-based devices is the availability of high resistivity (10^6 ohm-cm) substrates. These high resistivity substrates allow devices to be placed directly on a highly isolating layer, which can lead to higher packing densities, and does not require the sophisticated and area hungry implant schemes required to avoid latch-up, improve isolation and lessen device leakage, all of which can be problems in CMOS and BiCMOS devices. The high resistivity substrate also improves RF performance, by not only reducing parasitic capacitance, but by greatly reducing RF coupling to the substrate which can degrade RF signal propagation. For both high speed and RF applications, the performance of Si-based devices and circuits could be greatly enhanced, and the technology would be much more competitive with GaAs-based devices, if an equivalent high resistivity Si-based substrate were available. In fact, such a substrate is now commercially available through silicon-on-insulator (SOI) technology.

SOI substrates

There are two basic methods to fabricate SOI substrates. The first method to form SOI substrates is by Separation by Implanted Oxygen (SIMOX). In this approach, a high current, high energy O^+ implantation (100 mA at 200 keV, for a total dose of $1.8x10^{18}$ cm^{-2}) is performed into a silicon wafer to produce a buried layer of oxygen below the silicon surface. This implant is typically followed by 6 hours of annealing at 1320°C which regenerates the crystalline quality of the silicon layer remaining over the oxide and drives the formation of a buried stochiometric oxide layer (SiO_2). This typically creates a 400 nm buried oxide (BOX) beneath a 200-400 nm single crystal silicon layer and the process is referred to as standard dose SIMOX. A lower dose SIMOX process is also used which utilizes a total dose of only $4x10^{17}$ O^+/cm^2 which produces a thinner 80 nm thick BOX. Crystalline defects such as threading dislocations and small stacking fault pyramids on the order of 3-$15x10^5$ cm^{-2} are typically obtained in the top silicon layer utilizing this technique. SIMOX wafers are now commercially available from such companies as Ibis [Danvers, MA] and SOITECH [Grenoble, France].

The second method is that of Bond and Etch Back SOI (BESOI). In this approach, two silicon wafers, both with thermally grown oxide layers, are bonded together using Van der Walls forces, in which the combined oxide layer formed by the two bonded SiO_2 layers will become the BOX. Subsequent annealing increases the mechanical strength of the bonded oxide interface. After wafer bonding, one of the substrates is thinned down, such that the remaining silicon on the thinned wafer is now situated above the BOX. This thinning process can be performed by mechanical means (polishing or grinding), or by wet etch means in which epitaxial etch stops are placed in the original wafer prior to oxidation. Final silicon thicknesses can range from 50 nm to 50 microns, depending on the amount of silicon etched away, and the BOX can range from 50 nm to several µms in thickness, depending only on the thickness of the oxide on the original wafers. This process requires two starting wafers, adding to the expense of the process as compared to the one wafer required for SIMOX fabrication, but offers much greater latitude in both the final silicon thickness and BOX thickness. BESOI wafers are now commercially available from such companies as SiBond [Hopewell Junction, NY] and Hughes Optical Systems [Danbury, CT].

Variations of these typical approaches include the use of H^+ implantation through the oxidized layer, such that after wafer bonding, the stresses generated by the H^+ implantation cause the H^+ wafer to shear, leaving behind a silicon layer on top of the BOX. This BESOI technique, referred to as Smart Cut Technology, is offered by SOITECH, and needs only 1 wafer for fabrication, since the sheared wafer can be reused, unlike the case of conventional BESOI, in which the second wafer is etched back to produce the silicon layer atop the BOX.

Business

It is estimated by Rose Associates [Los Altos, CA] that the current SOI market is at \$40 million per year and growing at a CAGR of 40-50%, with an estimated market by the end of the decade of \$400 million. Al Alioto, Vice President of Sales and Marketing of Ibis estimates that the current market is 45% SIMOX-based and 55% BESOI-based. Of all the SOI approaches, at the moment, the low energy SIMOX approach is probably the least expensive, although this approach can only produce relatively thin Si and BOX layers - suitable to some applications, but not for all. Alioto says that "our goal is for SIMOX to cost roughly 3 times that of bulk silicon, and we are able to do that for large orders". Typical wafer sizes used in SOI production are the same as used in conventional silicon production - 150 mm and 200 mm. In the case of SIMOX, Ibis offers 200 mm SIMOX for \$450 (substrate cost \$120). When using BESOI techniques, this cost can often be twice as high. Ibis is not only using oxygen implantation to produce SIMOX wafers, but is also manufacturing a commercial oxygen implanter, the Ibis 1000. One of these systems has recently been funded by Motorola [Mesa, AZ], in which the machine will be built and installed at Ibis, but Motorola will receive its dedicated capacity for the next five years. Other oxygen implanter systems are being offered by Hitachi, which have sold two to date, to Komatsu and Nippon Steel in Japan.

SOITECH, which had originally been a SIMOX driven company, actually using the same type of implanter as Ibis originally did (NV-200 produced by Eaton), is beginning to shift its production away from SIMOX to BESOI using their Smart Cut process. Although currently in the start up phase, they have produced 2000-3000 wafers with their Smart Cut process, and plan by the end of 1996 to be at the 20,000 wafer/year level, with a capacity by the end of 1997 of 200,000 wafers. As explained by Andrew Wittkower, president of SOITECH USA, "we feel that the total capacity of SIMOX wafers for each O-implanter is limited to about 15,000 per year, due to the long implant times, and limited number of wafers which can be run in each with each implantation batch (maximum 25). However, using just standard fabrication equipment, we believe that each Smart Cut processing line can produce 100,000 wafers per year. This is the direction that we plan to move in."

Subramanian Iyer, Vice President and Chief Technical Officer of SiBond, explains that the flexibility of using BESOI, allows them to produce a wide range of SOI types, offering varying thickness of both silicon and BOX which simply can not be produced by SIMOX. However, he does agree that if an application can be satisfied with SIMOX wafers (thin Si and thin oxides), that it is very difficult for a BESOI approach to compete with SIMOX on a cost basis. SiBond finds that the bulk of its market is for silicon thicknesses greater than 500 nm, a market which the SIMOX approach can not produce material for.

Applications

Even though the SOI manufacturers all utilize different approaches in the fabrication of SOI substrates, they all seem to agree on what the key applications are. At the moment, the driving application is that for low power electronics - those applications which include such things as wireless handsets, pagers, and any electronic equipment dependent on batteries - the very markets that GaAs is currently penetrating. The governing equation of power consumption (P) for an IC is:

$$P = CV^2f + VI_{leak}$$

where C is the total capacitance, V is the supply voltage, f the operating frequency, and I_{leak} is the standby current required when the device is turned off. As is apparent from this equation, large reductions in power consumption can be made by lowering operating voltages. The reduction of power supplies from 5 V to 1 V reduces power consumption by a factor of 25. It is generally felt that conventional CMOS on bulk or epi wafers will be able to operate at turn-on voltages as low as 1.5 V, but levels lower than this will be difficult to achieve. Using SOI substrates, the subthreshold slope for turning PMOS and NMOS devices on and off is much steeper than that for devices on conventional Si substrates, thereby permitting lower turn-on voltages, while at the same time ensuring that I_{leak} is sufficiently small when the device is turned off. It is believed that CMOS/SOI will be able to operate with supply voltages of 1 V. These lower voltages become especially critical as the operating frequency increases (this increases power consumption), which is the current trend for many wireless devices, especially cellular phones and WLAN devices which are moving from the 800-900 MHz regime and into the 1.8-2.4 GHz range. Due to the buried oxide layer, both the capacitance, C and the I_{leak} are reduced, which further reduces the power consumption. I_{leak} can also be significantly reduced since the junction area of the device can now be reduced since it sits directly on an insulating layer (and no longer requires implants for isolation). In the case of GaAs, the semi-insulating substrate serves the same function to reduce both C and I_{leak}. DARPA is very interested in low power electronics for future military needs, and has established a low power electronics (LPE) program, with the objective of reducing power consumption by a factor of 100 as compared to current systems. The principal substrate technology that this program is investigating and investing in is SOI.

Other applications include using CMOS/SOI for radiation hardened ICs, as well as using thicker Si layers which can be used to form mechanical structures, such as sensors, actuators and accelerometers, all of which have potentially large markets in automotive applications. A potentially very large application is that of memory devices and very large circuits such as microprocessors. Reduction of leakage currents and the ability to design smaller devices on the insulating oxide are very attractive characteristics for these devices. Significant savings in capital investments may occur if the use of smaller devices can forestall the shift from 200 mm to 300 mm silicon wafers. DRAM and microprocessor manufacturers are currently investigating the use of SOI, but most SOI manufacturers believe that this application is at least several years away.

Commercialization

In light of the advantages that SOI substrates offer, it is an obvious question to ask when will commercial devices and circuits be available which use SOI substrates? Currently, Honeywell [Minneapolis, MN] does offer some commercial SOI-based circuits aimed at the satellite market, where the low power consumption characteristics of SOI are effectively used in the power-tight environment of a satellite. In addition, using an in-house SOI capability, Harris [Melbourne, FL] offers CMOS/SOI RF circuits for wireless applications operating up to 2.4 GHz. This is primarily the extent of commercial SOI at the moment. However, the technology is poised for rapid expansion.

An excellent example of this is based on recent work performed by T. Ipposhi and coworkers at Mitsubishi Electric [Hyogo, Japan] and reported upon at the 1995 IEEE International SOI Conference. Using a 0.5 µm CMOS/SOI process, they have demonstrated several key circuits required in both communications and computing applications. They have fabricated a 1:8 frequency divider, a key component for communication systems, and a circuit which is often fabricated in GaAs for both telecom and datacom applications. The maximum operating frequency of the SOI divider is 2.9 GHz at 3.3V, which is twice the speed as obtained for a bulk Si-divider. They have also fabricated a SOI 64-bit adder, a key component for a 64 bit microprocessor. Consisting of 3000 transistors, a delay time of 1.9 ns was obtained, which is 75% of the delay time needed in the same device fabricated in bulk-Si. Looking at a variation of the SOI technology, in which the Si is grown on sapphire (in this case the entire substrate consists of a low dielectric material, which improves RF performance, rather than just the several microns available in SOI), R.A. Johnson and coworkers from the Naval Command, Control and Ocean Surveillance Center [San Diego, CA] and University of California [La Jolla, CA] reported at the 1995 SOI Conference on 0.5 µm NMOS and PMOS devices fabricated in thin film silicon (50-100 nm) on sapphire. NMOS devices exhibited an f_t of 25 GHz and f_{max} above 60 GHz, while the PMOS devices exhibited an f_t of 14 GHz and f_{max} above 30 GHz. This RF performance, especially in the case of the NMOS device is comparable to that utilized in production GaAs MESFET processes. Motorola has used SOI in the fabrication of 8k SRAMs which operate at 65% less power as compared with the same circuit running at the same speed on bulk Si, while when operating at the same power level, runs 3 times faster. With major RF and low power manufacturers such as Motorola, Analog Devices, AMD, DEC, Fujitsu, Honeywell, IBM, Intel, Mitsubishi, National Semiconductor, NEC, Philips, Samsung, Sharp, TI and Toshiba actively investigating the use of SOI substrates, coupled the initial promising low power and RF performance already demonstrated, it would appear that the commercialization of SOI-based devices is near and that GaAs will be facing competition from this new technology.

Vertical-Cavity Surface Emitting Lasers

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Vertical-cavity surface emitting lasers (VCSELs) have been the subject of research for nearly 20 years in laboratories throughout the world. As their name indicates, the VCSEL light is emitted perpendicular to the wafer surface in a round beam with low (≤8°) divergence, in contrast to the elliptical beam emitted parallel to the wafer surface from traditional edge emitting semiconductor lasers. VCSELs incorporate more than 100 layers into their epitaxial structure, but require only standard integrated circuit fabrication technologies. VCSEL fabrication differs from their edge-emitting counterparts and is simpler because the need for facet formation by either cleaving or dry etching is eliminated. This allows for laser testing before packaging as well as simple fabrication of dense 2-dimensional arrays. The on-wafer device testing and batch processing of high density arrays using standard fabrication technologies enables high volume and low-cost manufacturing. These advantages, combined with low drive currents and small thermal budgets, make VCSELs very promising for a variety of optoelectronic applications. Several companies are presently engaged in, or close to, VCSEL manufacture, with the introduction of several commercial products incorporating VCSELs now eminent.

The first VCSELs were reported from the Tokyo Institute of Technology in 1978, though it was not until the latter part of the 1980's that VCSEL research became prominent in the United States and Europe. Due to their epitaxial complexity, the development of VCSELs has depended on scientific and epitaxial growth advances in compound semiconductor technologies. One key enabling innovation is the semiconductor quarter-wave distributed Bragg reflector (DBR) mirror. These mirrors utilize alternating high and low refractive index layers, such as GaAs and AlAs, respectively, and are requisite for monolithic VCSEL structures. In addition, advances in molecular beam epitaxy (MBE) and metalorganic vapor phase epitaxy (MOVPE), including the development of *in situ* diagnostics, have been important. The characteristics and performance of VCSELs (e.g. threshold current/voltage, efficiency, transverse optical modes, polarization, thermal impedance, etc.) are strongly influenced by the device structure and fabrication processes that are employed. In the following, we briefly review the structure of a VCSEL, then discuss the fabrication and performance of state-of-the-art devices. We also indicate the emerging applications of VCSELs and speculate on the directions of future research.

VCSEL Structure

The constituent elements of a VCSEL, shown in the sketches of Fig. 1, are two high-reflectivity DBR mirrors surrounding the optical cavity to form a high finesse Fabry-Parot cavity. The DBR mirrors are required for longitudinal confinement of light within the laser. They consist of repeating pairs of quarter-wavelength thick high and low refractive index layers, made of either monolithically grown semiconductor materials or dielectric materials which are deposited after epitaxial growth. The advantage of hybrid dielectric DBR mirrors is that a large refractive index ratio between the layers can be achieved (e.g. 1.7 for $ZnSe/CaF_2$), enabling high-reflectivity mirrors with only a few number of periods. Monolithic DBR mirrors typically have lower index contrast (e.g. 1.2 for GaAs/AlAs) and thus require a larger number of periods, but are easier to fashion and allow for current injection through the mirror. The composition of the semiconductor layers are chosen to maximize their index contrast, and yet be transparent to the laser light. For example, VCSELs emitting at 980 or 850 nm could use pairs of GaAs/AlAs or $Al_{0.2}Ga_{0.8}As$/AlAs layers, respectively, in the DBR mirrors. In semiconductor systems which lack high index contrast alloys, nonlattice matched DBRs can be grown separately and then wafer bond-

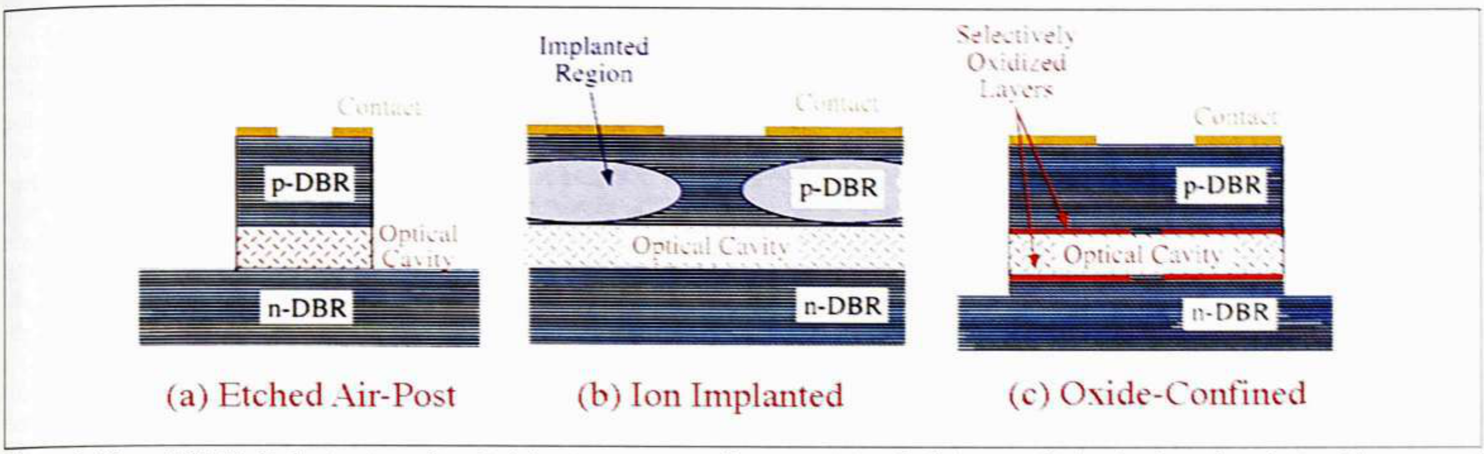


Figure 1. Three VCSEL diode structures for obtaining transverse confinement: (a) etched air-post; (b) ion-implanted; and (c) oxide-apertured VCSELs.

ed to the optical cavity. For example, DBR mirrors composed of GaAs/AlAs layers have been grown separately and then wafer bonded to InP active regions to fabricate 1.3 and 1.55 µm VCSELs. The heterointerfaces between the layers of monolithic DBR mirrors are modified using composition grading or short-period chirped superlattices, along with specific doping profiles, to reduce the band offsets and thus reduce the mirror series resistance. This is an important consideration for VCSELs, since a large mirror series resistance translates to high parasitic ohmic heating, which degrades the laser performance.

The optical cavity of the VCSEL is usually a single wavelength thick, and contains the active region of the laser. The active region, which commonly contains one or more quantum wells, is located at the center of the optical cavity for optimum overlap with the electromagnetic fields. The short optical cavity length implies that a single cavity resonance will overlap with the laser gain bandwidth, as depicted in Figure 2; this insures single longitudinal mode operation. Moreover, the single cavity resonance implies that spectral mismatch between it and the laser gain will dominant the performance of the VCSEL. For example, with increasing temperature the laser gain shifts to longer wavelengths *faster* than the cavity resonance, which leads to lower optical gain and degradation of the laser performance. Because of this, the cavity resonance is often intentionally designed to be at a slightly longer wavelength relative to the peak laser gain at room temperature (see Fig. 2), so that at higher operating temperatures the peak laser gain actually shifts into alignment with the cavity resonance to yield optimum laser performance. The quantum well materials are selected for the desired wavelength regime: InGaP, AlGaAs, GaAs, InGaAs, and InP are used for 650, 780, 850, 980, and 1300 nm laser emission, respectively. As an example of the epitaxial complexity, visible VCSELs employ a phosphorus-based optical cavity (AlInP/GaInP), but use arsenide-based DBRs (AlGaAs/AlAs), implying a complete change of the group V elements during MOVPE growth.

To achieve the required transverse optical and electrical confinement, the various VCSEL structures shown in Figure 1 have been demonstrated using a variety of fabrication technologies. Historically, the evolution of VCSELs has been analogous with the development of edge-emitting lasers. Etched VCSEL structures were first demonstrated, followed by ion implanted and regrown lasers, and most recently, selectively oxidized VCSELs. The simplest means to transversely define the laser cavity is to etch a pillar or post as depicted in Fig. 1(a). Anisotropic dry etching techniques such as reactive ion etching are desirable to achieve small cavity diameters and smooth vertical sidewalls. The former enables low active volume and thus low threshold current, while smooth sidewalls are necessary for the mitigation of optical loss. The strong optical index-guiding effect present in air-post VCSELs implies that lasers with diameters ≥ 5 µm typically exhibit several transverse optical modes just above the lasing threshold. Thermal impedance of air-post VCSELs is typically high (>1000 K/W) due to the removal of heat sink material around the laser, which can exacerbate the thermally-induced spectral mismatch between the laser gain and cavity resonance. Therefore, etched air-post VCSELs have the advantages of simple fabrication, strong index-guiding, and low threshold current. Their drawbacks are nonplanar topology as well as small thermal dissipation and sidewall scattering loss which can lead to poor laser performance.

A means to achieve a planar VCSEL topology is to utilize ion implantation as depicted in Fig. 2(b). Implantation of ions into the top DBR can render the material around the laser cavity nonconductive to funnel the injection current into the active region. Various ion species can be employed (O^+, N^+, H^+), although proton implants are the most common. The maximum implant damage is usually designed to occur in the top DBR mirror to avoid excessive damage in the quantum wells. This implies that detrimental current spreading outside of the laser cavity can occur. Although the implantation defines an electrical current path, no transverse optical confinement is provided by the device structure itself. Instead, implanted VCSELs require "thermal lensing," which is the formation of a thermally-induced refractive index gradient to support the lasing mode. Due to the thermal nature of this process, threshold currents under pulsed and continuous wave operation can vary significantly and turn on delays during VCSEL modulation are apparent if the laser is not biased to its threshold point. Although this thermal index profile tends to promote the fundamental optical mode, higher-order transverse modes do arise with increasing injection current. Finally, in spite of the crystal damage which is inherent to this structure, good laser reliability for implanted VCSELs has been observed, in analogy with implanted edge-emitting laser diodes. Ion-implanted VCSELs have the advantages of relatively simple fabrication in a planar geometry, enhanced heat sinking, and good device reliability; their disadvantages include the lack of any built-in optical confinement to support the lasing modes.

An optimum VCSEL structure is one which possesses inherent index-guiding, but in a planar configuration for thermal management. Regrowth of a lower index semiconductor around the VCSEL will accomplish this, but regrowth on the highly reactive AlGaAs alloys present in the DBR mirrors has proven very challenging. A recent innovation to achieve transverse optical confinement within a planar VCSEL configuration is to employ selective oxidation of buried AlGaAs layers. The electrically insulating low refractive index oxide layers will confine both the current and the light of the laser quite effectively, and thus serve to electrically and optically define the transverse laser cavity. The improved electrical and optical confinement of oxide-apertured VCSELs shown in Fig. 2(c) has lead to record VCSEL performance, including the lowest threshold current and the highest efficiency.

Exposing AlGaAs alloys to temperatures from 350 to 500°C in a steam environment converts them into an oxide phase which is mechanically robust, chemically inert, and electrically insulating with a low refractive index. The lateral oxidation of buried AlGaAs layers exhibits a temperature-dependent linear oxidation rate without any induction time preceding the onset of oxidation. More importantly, the oxidation rate of $Al_xGa_{1-x}As$ is very sensitive to Al composition, where varying x from 1 to 0.8 changes the relative oxidation rate by more than 2 orders of magnitude! Thus layers within the VCSEL epitaxial structure can be selected for oxidation through small variations of Al-content of the layers. As an example, buried oxide layers can be positioned on each side of the optical cavity to form "oxide apertures" which transversely define the laser cavity as depicted in Fig. 2(c). These apertures can be made extremely small ($\approx 1 \mu m^2$) enabling low threshold operation. Oxide apertures have been utilized under both monolithic DBRs and hybrid dielectric DBRs. Also, oxidized AlAs layers have been used as the low index layer in high index contrast DBR mirrors. Evaluation of the reliability of oxide-apertured VCSELs is presently underway, and preliminary results are promising: lifetimes in excess of 3000 hrs. at room temperature under constant power operation have been observed. The impressive performance of selectively oxidized VCSELs has stimulated oxidation-related research at all major VCSEL laboratories around the world.

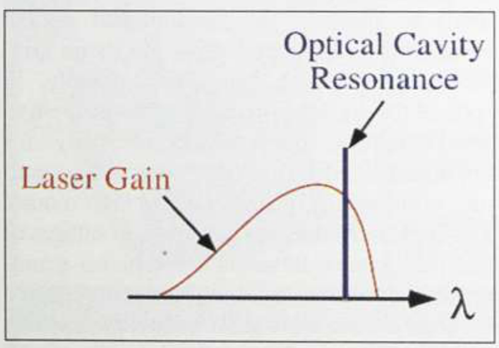


Figure 2. A demonstration of the spectral alignment between the single optical cavity resonance of the (vertical line) and the broad VCSEL gain bandwidth. Since the laser gain shifts faster to longer wavelengths with increasing temperature, the cavity resonance overlaps the peak laser gain shift at higher operating temperature.

To summarize, monolithic oxide-apertured VCSELs have several advantages. Oxide apertures that define the laser cavity provide efficient current injection into the active region, eliminating sidewall nonradiative recombination present in air-post VCSELs and minimizing lateral current spreading outside of the laser cavity. In addition, the smaller refractive index of the Al-oxide layer induces index-guided optical confinement in a device configuration amenable to heat extraction. Oxide-apertured VCSELs have been demonstrated at 1300, 980, 850, 780 and 650 nm, indicating the wide applicability of this VCSEL structure. Disadvantages of this structure include nonplanar topology, the unknown level of device reliability, and the need for developing manufacturable oxidation processes.

VCSEL Performance & Applications

Because small active region volumes are the essential characteristic of VCSELs, the primary focus of their development has been toward low threshold current, low threshold voltage, low power dissipation, etc. Due to the advantages discussed above, monolithic oxide-apertured VCSELs (Fig. 2(c)) have established benchmark levels for lowest threshold current (<10 μA), lowest threshold voltage (<1.33 V), and highest efficiency (>50 %) reported for VCSELs. Combining small active volumes with the typically high photon densities in VCSELs imply high speed modulation, and indeed >16 GHz small signal modulation bandwidth has been observed for oxide-apertured VCSELs. However, because of the relatively small active region volumes, VCSEL output powers tend to be relatively low as compared to edge-emitting lasers. Nevertheless, for certain VCSEL diode structures, continuous wave output power of >100 mW has been obtained from a single broad area laser, and >1 W has been observed from a 2-dimensional array under pulsed excitation. Finally, electrically-injected VCSELs with various structures have been demonstrated at near IR and visible wavelengths, ranging from 1.55 μm to 628 nm.

The first applications of VCSELs are focused on systems which do not require high output power, such as laser sources in optical data links. In this near-term application, the low drive power, low thermal dissipation, low divergence circular output beam, and high modulation speed of 1-dimensional VCSEL arrays are desirable characteristics for coupling to optical fiber. This view is that VCSELs will be well suited for modest (Mbit/sec) data links that are low-cost. Several companies including Motorola and Hewlett Packard, have announced optical data links which employ IR VCSELs. An alternative and potentially low-cost approach is to use 650 nm VCSELs coupled to plastic fiber. An alternative vision for use of VCSELs is highly parallel multi-Gbit/sec data links for extremely high (terabit/sec!) aggregate data rates. These more forward-looking schemes for data transfer employ a free-space approach where large 2-dimensional VCSEL arrays are an enabling technology. Other VCSEL applications under development include compact disk read heads, copier print heads, optical scanners, projection systems, and optical displays. Interestingly, for most of these applications, the crucial market drive toward VCSELs appears to be their potential for low-cost manufacture. However, as VCSELs become more accepted, it is likely that new applications will arise that will specifically exploit their low drive power requirements.

There are several areas of VCSEL research which require further work. An obvious need is for increased VCSEL output power, especially into the fundamental optical mode. Thus, modal control of individual VCSELs and VCSEL arrays need to be further developed, perhaps employing leaky-mode strategies which have proven advantageous for edge-emitting lasers. Moreover, if modest levels of raw power can be attained from 2-dimensional VCSEL arrays, this might enable low-cost (<$10/W) diode pumps for solid state laser systems. Another important research area is increasing the VCSEL modulation bandwidth to 50-100 GHz. Whereas such modulation speeds are theoretically possible for VCSELs, developing the appropriate microwave structures is required. Extension of VCSEL wavelengths into long wavelengths (2-10 μm) for sensor applications and into short wavelengths (e.g. 550 and 480 nm) for display applications will also have a large impact. Finally, it is important to insure that the VCSEL designs, structures, and the requisite fabrication technologies can be transferred into robust manufacturing platforms in order to fully exploit these devices. In spite of these challenges, VCSELs are now emerging into the market place after 20 years of research, and will likely have a defining future role in the optoelectronic industry.

Portfolio Up in Bull Market

Good quarterlies and a strong market raise share prices for all seven companies

MARIE MEYER

A record-setting few weeks for the U.S. stock exchanges and good quarterly earnings reports resulted in all seven of the stocks in the *Compound Semiconductor* Portfolio posting gains for the March-April period. All but one of the stocks are now showing a gain since the first of the year, and the portfolio as a whole is up more than 50% for 1996.

Quarterlies

The biggest gainers for the period were the three GaAs IC foundries, all of whom turned in outstanding results for the quarter ended March 31. Shares in **Anadigics** were up 64% on profits of $0.21 per share, compared to $0.15 per share for the same period last year. Net sales for the first quarter of 1996 increased 24% to $13.6 million compared to first quarter 1995 net sales of $11.0 million, and net income nearly doubled, rising to $1.8 million from $898 thousand in the year-ago period. The company reported that new business for the quarter including the beginning of shipments of 750 MHz wideband line amplifiers to Scientific Atlanta as part of a one year, $1 million contract (see page x). Anadigics also began shipping power amps for use in GSM digital cellular phones, as well as driver amplifiers for Qualcomm's digital CDMA-1900 PCS telephones and receiver ICs for dual mode DAMPS cellular base station applications.

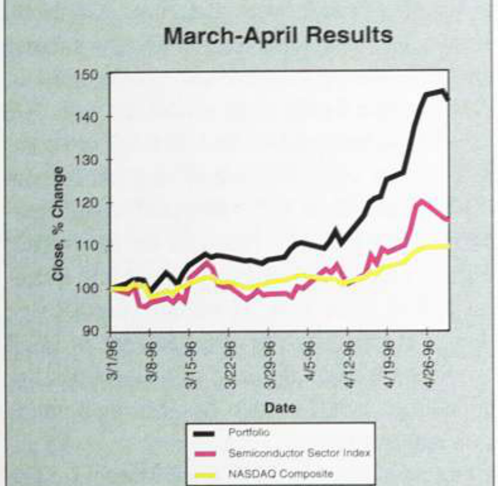
Vitesse was the next largest gainer, up 54% since March 1. The company reported revenues of $15.6 million for the first quarter of 1996, an increase of 56% over the same period last year. Net income was $2.6 million or $0.14 per share compared to a net loss of $1.0 million or $0.07 per share in the year-ago period. The company also completed a secondary offering of stock on March 15, raising $43 million, with the proceeds to be used for cash and debt reduction. TriQuint also reported impressive results, and its share price rose 52% in the March-April period. Revenues for the quarter were a record $13.1 million, a 39% increase over the $9.4 million in the comparable period of 1995. Net income was $910 thousand or $0.11 per share, compared to $227 thousand or $0.04 for the year-ago period. The company reports that it scored 28 new design wins for the quarter (20 in wireless, 7 in telecomms, and 1 in computing). The company also reported that busi-

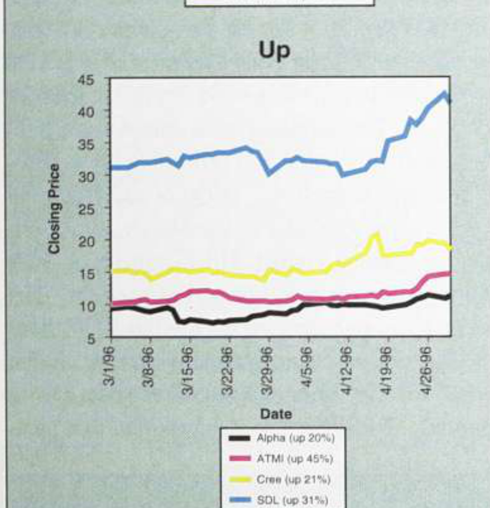
The Compound Semiconductor Portfolio

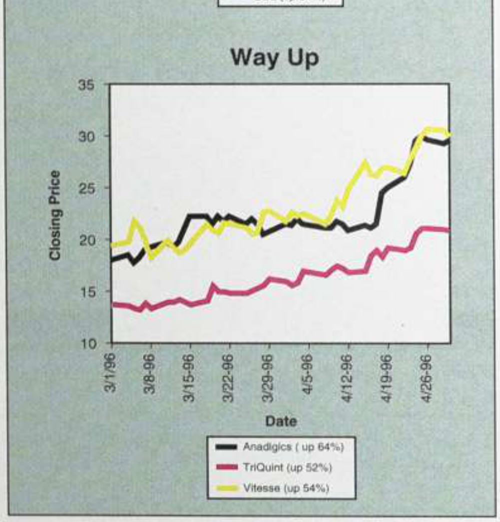
Company	Symbol*	1/2/96	4/30/96	Change
Alpha Industries	AHA	13.625	11.25	-2.375
Anadigics, Inc.	ANAD	21.25	29.56	+8.312
Advanced Technology Materials	ATMI	10.375	14.50	+4.125
Cree Research	CREE	14.75	18.25	+3.5
SDL Inc.	SDLI	25.375	40.75	+15.375
TriQuint Semiconductor	TQNT	14.25	20.75	+6.5
Vitesse Semiconductor	VTSS	13.125	29.875	+16.75
Portfolio Value, 4/30/96 (100 shares of each)				*$16,493*
Change since 1/2/96				*+52%*

ness related to the Japanese Personal Handy Phone market - an area which accounted for 24% of TriQuint's revenue in 1995 - has picked up again, after slumping badly in the previous quarter, and CEO Steve Sharp reports that the manufacturing problems which plagued the company in the previous quarter have been resolved satisfactorily.

The other four companies in our portfolio also recorded gains in the March-April period.







SDL, which went public just over a year ago at under $25 a share, ended the period over $40, an historic high. For the quarter ended March 31 SDL reported revenues of $20.4 million and net income of $2.2 million, or $0.27 per share, compared to revenues of $10.5 million and net income of $0.9 million, or $0.17 per share, in the first quarter of 1995. **ATMI** revenues were up 66% to $10 million, and net income was $469 thousand or $0.05 per share, compared to a loss of $158 thousand or $0.02 per share in the year-ago period. **Cree** reported revenues of $4 million for the quarter, with net income of $204 thousand or $0.02 per share, compared to a loss of $0.01 per share for the same period last year. **Alpha's** quarterly earnings report was not yet available as this issue went to press, but the company did issue a press release warning analysts that results would be lower than previously expected due to softness in the North American wireless market.

Other News

The biggest news from the American stock market was the spectacular launch of Lucent Technologies, the spin-off from AT&T than includes the former AT&T Microelectronics operations and Bell Labs. Lucent made its initial public offering (IPO) of stock in the first week of April, raising $3 billion for 112 million shares, or approximately 20% of the company. It was the biggest IPO in American history. AT&T, which owns the other 80%, will distribute the remaining shares to its shareholders by the end of this year.

At the other end of the spectrum, diode manufacturer Semiconductor Laser International Corporation [Vestal, NY] conducted its IPO in April [NASDAQ, symbol SLIC]. SLI is a development stage company which plans to offer high power semiconductor laser diodes, manufactured using MBE growth technology licensed from Wright Laboratories. The company raised $9 million, which will be used to build, equip and commence operations in a new manufacturing facility by the fourth quarter of 1996.

Cree Update

Our previous issue reported that Cree was working to overcome the "volatility" of its epitaxial process in order to increase production of blue LED chips (CS 2(2), p. 49). In its most recent reports the company is claiming to have met their goal of shipping 1.5 million chips in the first quarter of this year, double the output of the previous quarter. They note that "repeatability issues remain with [the] epitaxy process and additional work is needed to refine this critical part of [the] manufacturing process", however, the company reports that it plans to double production of LEDs in the next quarter. Cree received $1.1 million in revenue from LED shipments in the first quarter (equivalent to ~$0.74 per chip), compared to just $141,000 in the same quarter last year.

Cree also announced a significant increase in sales and production of its SiC wafers. The company shipped a quarterly record of $1.4 million worth of SiC wafers during the first quarter of 1996, and increase of 58% over the year-ago period. In addition, the company reported that it produced a record 4,000 wafers in March, eclipsing a previous production peak of 1,800 in February. The wafers are used in Cree's in-house LED production and R&D and are also supplied to outside customers.

Also in our previous issue was a promise from Cree about an announcement regarding "the first significant microwave device in SiC" (CS 2(2), p. 49). That announcement came in mid-April when Westinghouse announced a prototype for a 1.5 KW power amplifier module for HDTV transmission which includes a 500 watt SiC transistor. Cree announced that it had supplied the SiC wafers that were used in that work. Neal Hunter, President of Cree, said "Westinghouse has demonstrated the first of many systems that will be enabled by SiC microwave technology. We initially supplied our SiC material to Westinghouse to meet their technology development targets and now look forward to establishing a long term relationship". However, the company also notes that it does not have a formal supply pact with Westinghouse at this time.

Compound Semiconductor
is now accepting ads
from organizations and individuals
regarding employment opportunities.

Rates & Specifications for Standard Ads. Standard ads with minimum formatting (as shown below) are available at $25.00 per line or fraction thereof (88 characters per line), with a $100.00 minimum. To submit your ad by mail send the ad copy as a text-only file (<filename>.txt) on a 3.5" DOS formatted diskette to: CS Employment, Franklin Publishing, 250 Selby Avenue, Suite 48, Saint Paul, MN 55102 USA. You may also submit your ad copy by E mail by sending it as an plain text file (no encoding) to: jobs@compsem.com.

Orders & Deadline. Check or purchase order must accompany order/ad copy. No agency discounts. *Compound Semiconductor* is published bi-monthly. Orders and copy are due on the 15th day of the month which precedes the cover date.

Display Ads

Black and white display ads are available for companies wishing to use their own formatting style. Sizes and rates and given below. Send camera-ready art to: CS Employment, Franklin Publishing, 250 Selby Avenue, Suite 48, Saint Paul, MN 55102 USA.

Size	Dimensions	Rate
1/4 page	5"H x 3 3/8"W	$1,350
1/2 page	5"H x 8 3/8"W	$2,600
1 page	10 7/8"H x 8 3/8"W	$3,350

Orders & Deadline. Check or purchase order must accompany ad. No agency discounts. *Compound Semiconductor* is published bi-monthly. Orders and copy are due on the 15th day of the month which precedes the cover date. For example: ads for our July/August issue are due on June 15. The magazine is normally mailed in the third week of the first month of the cover date.

Engineering Positions at Vitesse Semiconductor

Vitesse Semiconductor Corporation is the world's leader in the design, development, manufacture and marketing of digital GaAs integrated circuits. Our ICs are used in a wide variety of products in the high performance communications, test and instrumentation, computing and defense markets. We offer a unique group culture based on individual voices in a success-driven environment. Our company president, an engineer himself, takes a personal interest in individual achievements as well as group accomplishments. Our career opportunities include: **Design and Test Engineers** - BSEE/MSEE, C++, 2-5 years experience in VLSI, ATE timing circuit design; **Product Engineers** - BSEE/MSEE, 3 years experience, VLSI fabrication techniques, materials and equipment. Qualified candidates mail/fax your resume to Vitesse Semiconductor Corporation, Human Resources, Department CS296, 741 Calle Plano, Camarillo, CA 93012. FAX: (805) 389-7188. EOE M/F/D/V.

Rockwell: III-V Circuit Design and Processing

The Science Center, Rockwell's corporate research and development laboratory in beautiful Thousand Oaks, CA has **multiple openings for talented circuit design and processing professionals in GaAs, InP and GaN related areas.** We are advancing high frequency semiconductor and packaging technologies for mixed signal device/circuit applications which will produce greater performance at reduced cost. Join us in one of the best working environments available. Experienced candidates with a PhD or MS should forward resumes via fax: (805) 373-4797; e-mail: resumes@scimail.risc.rockwell.com or mail: Professional Staffing EDL, Rockwell Science Center, PO Box 1085, Thousand Oaks, CA 91358. Equal Opportunity Employer - M/F/H/V.

Technical Positions at SDL

SDL is the world's leading manufacturer of high power semiconductor lasers. We offer a professional yet casual working atmosphere with many opportunities for creative technical contributions. SDL's products are used in communications, data storage, medicine, printing, science and materials processing. SDL has opportunities for technical contributions in many areas including: **advanced materials development (such as GaN), semiconductor laser device design, semiconductor laser manufacturing, opto-electronic packag**ing and **system development.** SDL offers competitive salaries and an excellent benefits package including employee stock options, 401(k) and stock purchase plan. Please send your resume to: SDL, Inc., Human Resources, 80 Rose Orchard Way, San Jose, CA 95134, FAX to (408) 943-9389 or e-mail to HRSDL@aol.com. In your resume please refer to listing #CS-100.

Scientists and Engineers at TRW

TRW has openings for scientists and engineers with education and experience in heterojunction materials and devices. Specific positions include: **senior materials engineer** - PhD EE, Physics, or Materials Science with 5 years experience in MBE growth and characterization of compound semiconductor material; **entry level materials engineer** - BS or MS EE, Physics, or Materials Science with interest in compound semiconductor materials; **heterojunction device engineers** - MS or PhD EE or Physics. Research & development positions and MMIC production positions available for engineers with experience in HEMT or HBT devices, processing, and test. Contact Dwight Streit, TRW D1-1302, One Space Park, Redondo Beach, CA 90278. Fax 310.812.7011, email dwight.streit@trw.com. USA Citizenship or PR required.

Researchers at Hughes Research Laboratories

Hughes Research Laboratories seeks researchers with advanced degrees, excellent communications abilities and experience in: **compound semiconductor devices and circuits,** including characterization, fabrication, design, & microfabrication techniques; **advanced microwave and millimeter wave device and IC technologies,** including antenna design, test and fabrication, C and C++, computer systems/software; **MMIC, Digital, Analog and OEIC Designers,** including SiGe & InP HBTs, GaAs PHEMTs and InP HEMTs - LNAs, SSPAs, VCOs, A/D & D/A Converters, DDS and Transimpedance Amplifiers - mixed-signal & mixed device ICs; **computational electromagnetics,** including radar cross section prediction, antenna modeling, electromagnetic simulation of circuits and packaging. HRL offers an ideal location, competitive salary and benefits package. Send your resume: Department #3031-CSM, Hughes Research Laboratories, 3011 Malibu Canyon Road, Malibu, CA 90265. FAX 310-317-5651. E-mail: lross@msmail4.hac.com. WebPage at: http://www.hrl.com/ Proof of legal right to work in US required. EOE.

Engineering Positions at M/A-COM

At M/A-COM, our expertise in providing high-volume, high-performance gallium arsenide (GaAs) and silicon semiconductors as well as other core wireless technologies is used in a wide range of portable communications applications across a broad and growing frequency spectrum. We've become the driving force behind many of today's leading cellular products through the development of components used by the cellular industry's leading manufacturers. Having also introduced the market's only two-chip WLAN solution for spread spectrum applications, we've become a leading supplier to cellular base stations. In the future, we'll continue to play a major role in the PCS revolution as well as advanced automotive electronics, interactive television, satellite and navigation systems. Now M/A-COM can be the force behind your progress. Increased technology, resources and a commitment to both research and development continue to take M/A-COM further into the world of wireless and wired communications. Imagine where you could go as part of the team that's driving the cutting-edge in RF/microwave technology. We are currently recruiting **ENGINEERS for the following areas: Design, Manufacturing, Quality, Process, Sales, Reliability, and GaAs Materials.** Send/Fax resume or letter of interest to: M/A-COM, Inc., Employment and College Relations, 1011 Pawtucket Boulevard, Lowell, MA 01853, FAX: (508) 442-4443. EOE.

Join the Leader in GaAs Technology for Wireless Communications

Combine progressive technology with exceptional talent and the result is Microelectronics, a division of Raytheon Electronics and developer of today's most innovative GaAs-based ICs for wireless communication markets. **MMIC Design Engineers/Scientists, Entry to Mid-Level.** Working in a team environment, you'll be responsible for amplifier, upconverter, downconverter or fully integrated transceiver IC designs used in a range of commercial applications including cellular telephones, wireless LANs, Direct Broadcast TV Receivers and VSAT Tx/Rx module. Designs will be progressions from previous generations and radically new designs. We offer outstanding benefits and compensation, paid higher education and an atmosphere close to Boston, the seacoast and the mountains of New England. If working for the leader in advanced GaAs technology is where you want to be, please send your resume to Microelectronics, Human Resources, 362 Lowell Street, Andover, MA 01810. FAX (508) 470-9211.

UPCOMING EVENTS

3rd Int'l High Temperature Electronics Conference
June 9-14, 1996 at Albuquerque, NM USA
Contact: Donald King
Sandia National Laboratories
Albuquerque, NM 87185-0744 USA
TEL [1] 505 845 7842
FAX [1] 505 845 7708

9th Int'l Conf. on Superlattices, Microstructures, and Microdevices
July 14-19, 1996 at Liege, Belgium
Contact: Prof. Jean-Pierre Leburton
Univ. of Illinois
Urbana, IL 61801 USA
TEL [1] 217 333 6813 FAX [1] 217 244 4333
Net or Web: leburton@ceg.uius.edu

9th Int'l Conf. on Vapor Growth & Epitaxy
August 4-9, 1996 at Vail, CO USA
Contact: Anthony Gentile
American Assoc. for Crystal Growth
Thousand Oaks, CA 91359 USA
TEL [1] 805 492 7047 FAX [1] 805 492 4062
Net or Web: aacg2@gramercy.ios.com

9th Int'l Conf. on MBE
August 5-9, 1996 at Malibu, CA USA
Contact: Dwight Streit
TRW, One Space Park
Malibu, CA 90278 USA
TEL [1] 310 814 1722 FAX [1] 310 812 4378
Net or Web: dwight.streit@trw.com

1996 Topical Workshop on Heterostructure Microelectronics
August 19-21, 1996 at Sapporo, Japan
Contact: Takyiu Liu
Hughes Reseach Laboratories
Malibu, CA 90625-4799 USA
FAX [1] 310 317 5450
Net or Web: tliu@msmailr.hac.com

26th European Microwave Conf.
Sept. 9-12, 1996 at Prague, Czech Republic
Contact: Nexus Media Ltd.
Swanley, Kent BR8 8HY UK
TEL [44] 1322 660070 FAX [44] 1322 661257

Mid-Infrared Optoelectronics Materials and Devices Conf.
Sept. 17-18, 1996 at Lancaster, UK
Contact: Mrs. J. Hesseltine
Lancaster University
Lancaster LA1 4YB UK
TEL [44] 1524 593651 FAX [44] 1524 844037
Net or Web: j.hesseltine@lancaster.ac.uk

23rd Int'l Symp. on Compound Semicondcutors
Sept. 23-27, 1996 in St. Petersburg, Russia
Contact: V. Grigor'yants
Ioffe Institute
St. Petersburg 194021 Russia
TEL [7] 812 247 6805 FAX [7] 812 247 1017
Net or Web: vgrig@eo.ioffe.rssi.ru or http://www.ioffe.rssi.ru/ISCS-23/

1996 U.S. Workshop on the Physics and Chemistry of II-VI Materials
October 22-24, 1996 at Las Vegas, NV USA
Contact: L. Manganiello
Palisades Institute
New York, NY
TEL [1] 212 620 3544 FAX [1] 212 620 3379
Net or Web: lmangani@newyork.palisades.org

CALL FOR PAPERS

1st European Conference on SiC and Related Materials
ECSCRM '96 will be held October 6-9, 1996 at Heraklion, Crete, Greece. The scope of the conference is the entire spectrum of SiC related activities with an interdisciplinary approach. Materials and device studies, whether theoretical or experimental, will be considered.
Abstract Submission Deadline: May 20, 1996
Contact: Georgia Papadaki
FORTH/IESL, PO Box 1527
GR-711 10 Heraklion, Crete Greece
TEL [30] 81 239 779 FAX [30] 81 239 735
Net or Web: georgia@iesl.forth.gr

International Workshop on Growth, Characterization and Exploitation of Epitaxial Compound Semiconductors on Novel Index Surfaces
NIS '96 will be held October 7-9, 1996 in Lyon, France. The use of substrates oriented on non-(100) surfaces has rapidly grown during the last years due to the novel physical properties that structures grown on these substrates exhibit (e.g. piezoelectricity, dopant incorporation, etc.). In addition, regrowth on patterned substrates to achieve low dimensional structures is accomplished on high index surfaces. The aim of this workshop is to discuss these aspects and to systematically emphasize new directions a prospects in this rapidly growing field. The workshop will provide a context of interdisciplinary discussions about the material, technical, device and theoretical aspects between delegates from academia and industry.
Abstract Submission Deadline: May 15, 1996
Contact: Prof. G. Guillot
INSA Lyon, LPM, Bat 502
69621 Villeurbanne, Cedex, France
TEL [33] 72 438 161 FAX [33] 72 438 531
Email guillot@insa.insa-lyon.fr

Symposium On Novel Device Structures 190th Meeting of the Electrochemical Society
The 190th Meeting of the Electrochemical Society will be held October 6-11, 1996 in San Antonio, TX USA. Symposium L3, "Novel Device Structures", is devoted to recent developments in novel devices which utilize new materials, processing approaches and/or transport mechanisms.
Abstract Submission Deadline: June 3, 1996
Contact: April Brown or Kevin Brennan
Georgia Institute of Technology
ECE Department, Atlanta, GA 30332-0250
TEL [1] 404 894 5161 FAX [1] 404 894 0222

Microwaves & RF Conference and Exhibition
The 1996 Microwaves & RF Conference and Exhibition will be held October 8-10, 1996 at the Wembly Conference and Exhibition Center, London, UK. This is an annual event for companies involved in RF, microwave and millimetre wave components and application technologies.
Contact: Nexus Media Limited
Nexus House
Swanley, Kent BR8 8HY UK
TEL [44] 1322 660070 FAX [44] 1322 661 257

43rd National Symposium of the American Vacuum Society
The 1996 AVS National Symposium will be held October 14-18, 1996 at the Pennsylvania Convention Center in Philadelphia, PA. Papers are solicted in several areas, including Electronic Materials and Processing, Surface Science, and Magnetic Surfaces, Interfaces and Nanostructures.
Abstract Submission Deadline: May 10, 1996
Contact: AVS
120 Wall Street, 32nd Floor
New York, NY 10005 USA
TEL [1] 212 248 0200 FAX [1] 212 248 0245
Net or Web: avs96@vacuum.org or http://www.vacuum.org

2nd International Symposium On Control of Semiconductor Interfaces
ISCSI-II will be held October 28-November 1, 1996 in Karuizawa, Japan. This symposium will cover all the fields concerning solid-solid interfaces between semiconductor and metal, insulator or semiconductor. The scope includes but is not limited to formation and control of interfaces, characterization, and device related phenomena.
Abstract Submission Deadline: May 31, 1996
Contact: Prof. T. Ito
Secretary, ISCS-II
Osaka Univ., EE Dept.
2-1 Yamada-oka, Suita
Osaka 565, Japan
TEL [81] 6 879 7702 FAX [81] 6 879 7704

1996 IEEE GaAs IC Symposium
The 1996 GaAs IC Symposium will be held November 3-6, 1996 in Orlando, FL USA. The focus of this conference is on recent developments in integrated circuits using GaAs, InP, and other compound semiconductor devices. Coverage embraces all aspects of the technology, from materials issues and device fabrication through IC design and testing, high volume manufacturing and systems applications.
Late News: August 9, 1996
Contact: Phil Wallace
Anadigics
Box 4915, 35 Technology Drive
Warren, NJ 07060 USA
TEL [1] 908 412 5985 FAX [1] 908 412 5986
Net or Web: wallacepw@aol.com

4th IEEE International Workshop on High Performance Devices for Microwave and Optoelectronic Applications
EDMO '96 will be held November 25-26, 1996 at the University of Leeds, Leeds, UK. The purpose of EDMO '96 is to provide a forum for microwave and optoelectronic device fabricators, modelers, designers and users to discuss the interaction between system needs and advanced devices and circuits. There will be three main underlying themes to the workshop: 1) electronic devices for mobile radio and wireless LANs; 2) electronic and photonic devices for optical communications, especially in the local loop; and 3) the convergence of microwave and optoelectronics technologies.
Abstract Submission Deadline: September 2, 1996
Contact: Stravos Iezekiel
University of Leeds, EEE Dept.
Leeds LS2 9JT UK
TEL [44] 113 233 2000 FAX [44] 113 233 2032
Net or Web: s.iezekiel@elec-eng.leeds.ac.uk or www.elec-eng.leeds.ac.uk/een6si/edmo96.html

Gallium Arsenide VLSI '96
A course entitled "Gallium Arsenide VLSI '96: Circuits & Systems" will be offered by the Centro Microelectronica Aplicada on November 26-29, 1996 at Maspalomas, Gran Canaria, Spain. The course, which is taught by well-known instructors from around the world, is directed towards digital circuit and system designers and researchers in information technology, telecommunications, image and signal processing, and computer and multimedia engineering.
Registration Deadline: October 1, 1996
Contact: Gallium Arsenide VLSI '96
Centro Microelectronica Aplicada
Universidad de Las Palmas de Gran Canaria
Campus Universitario de Tafira
E-35017 Las Palmas de Gran Canaria Spain
TEL [34] 28 45 12 32 FAX [34] 28 45 12 43
Net or Web: gaas96@cma.ulpgc.es or http://www.cma.ulpgc.es/GaAsVLSI96/

1996 Conference on Optoelectronic and Microelectronic Materials and Devices
COMMAD '96 will be held December 9-11, 1996 at Canberra, Australia. The aim of this conference is to bring together industrial collaborators, scientists, engineers and students to discuss new and exciting advances in the fields of optoelectronic and microelectronic materials and devices. It will provide a forum to present and discuss recent advances in materials growth, processing, characterization as well as device physics, design, fabrication, testing and applications.
Abstract Submission Deadline: September 2, 1996
Contact: C. Jagadish
Dept. Of Electron. Matls Eng.
RSPhysSE, Australian Nat'l Univ.
Canberra, ACT 0200 Australia
TEL [61] 6 249 0363
FAX [61] 6 249 0511
Net or Web: cxj109@phys.anu.edu.au

9th European Workshop on MBE
Euro-MBE IX will be held April 6-10, 1997 at Oxford, England. The meeting will be run on a workshop format and will cover all materials systems produced by MBE, including III-V, II-VI and elemental semiconductors, metal, oxides, insulators and organic films. The main themes will be: in-situ diagnostics, growth processes, growth on patterned and other non-planar substrates; interfaces and heterojunctions. Contributions on other topics will be welcome, but papers on devices will only be considered where a large element of growth is involved.
Abstract Submission Deadline: TBA
Contact: Di Pullar-Macmillan
Secretary to Euro-MBE IX
Semiconductor Materials IRC
The Blackett Laboratory, Imperial College
Prince Consort Road
London SW7 2 BZ UK

Advertiser Index

Would you like your conference to be included in future issues of *Compound Semiconductor*? Send the information by E mail to calendar@compsem.com, or by FAX to [1] 612 227 5499, attention "Calendar"

Contributions must be received byJune 14 to appear in our next issue.