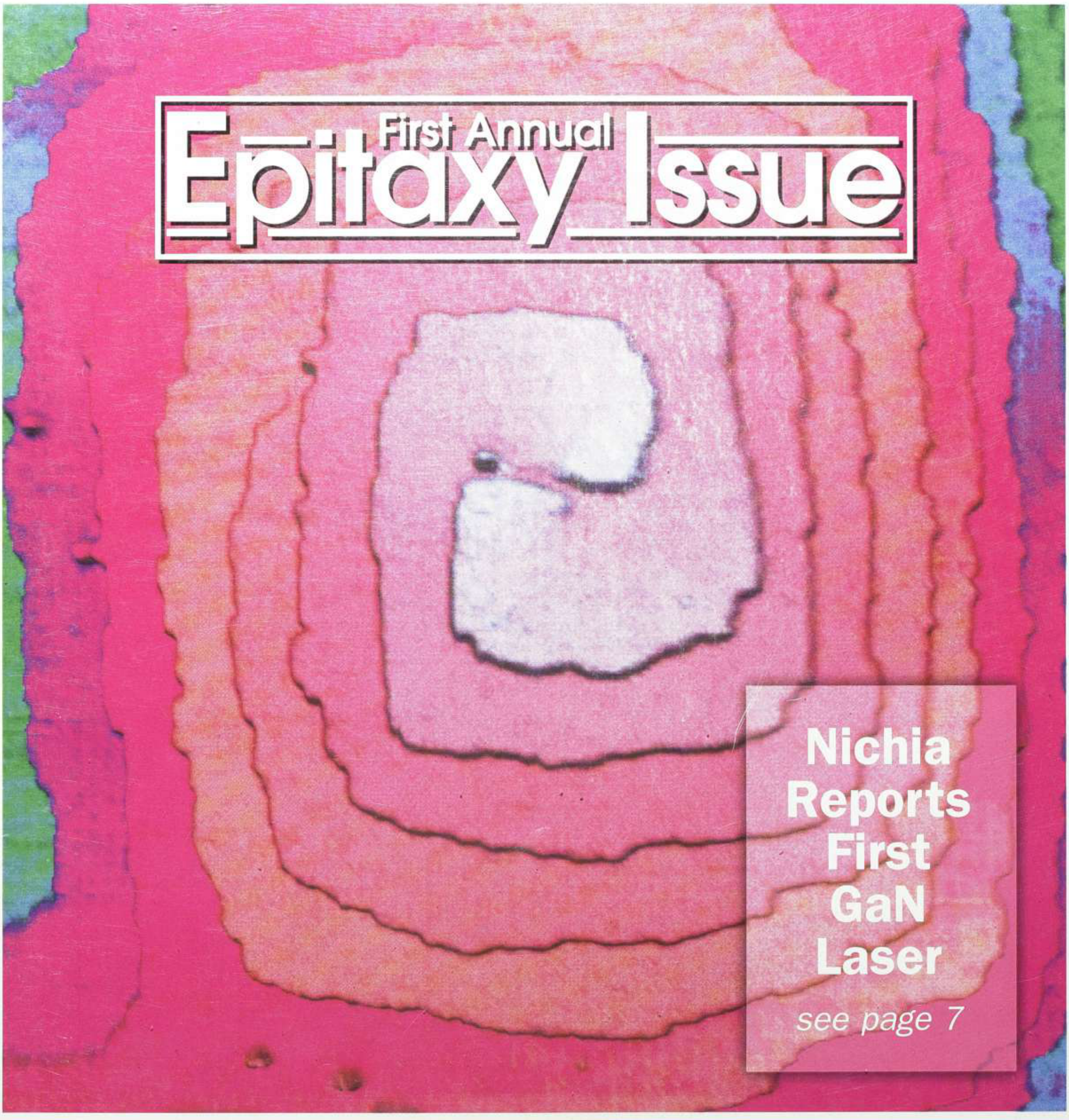
COMPOUND SEMICONDUCTOR

January/February 1996 Volume 2 Number 1



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And We're Still Growing!

To support growing demand in 1996, we're adding a third multi-wafer MBE production system and doubling the size of our manufacturing facility. With all these changes, one thing remains constant, our commitment to grow with you.

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See page 2 for a description of the image on this issues's cover

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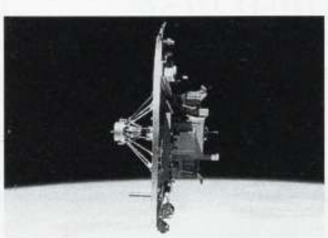
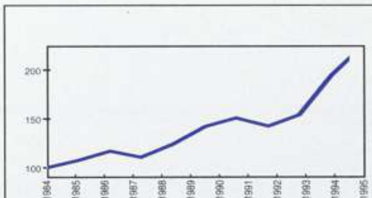


See page 16

SPECIAL FEATURE

COVER STORY

OTHER FEATURES



Growth in the value of compound semiconductor wafer shipments reported by Japanese manufacturers from 1984 to the first half of FY 1995. CAGR = 7.5%

See page 10

DEPARTMENTS

From the Editor

Over the past six months many voices from Wall Street have proclaimed that "technology is the industry of the future". In a list of statements of the obvious this would likely rank near the top, right beside "buy low, sell high". Nevertheless, it does come as a relief to see that after years of infatuation with companies like the Home Shopping Network and Snapple Beverages the brokers are at last turning their attention to more substantial matters.

According to the Wall Street Journal, individual investors account for less than 35% of the holdings in the technology sector of the American stock market. The reason is obvious - given that the average American doesn't really know what a semiconductor is, and isn't interested in much of an explanation beyond "computer chips and stuff like that", is it any wonder that they would prefer to invest in consumer goods or familiar industrials? Investment analysts have likely stayed away from high tech longer than they should for the same reason. But, now that it is a hot topic, more and more money will be piling into the technology sector, and this time not all of it will be thrown at "glamorous" issues like Intel, Netscape and everyone's favorite, Microsoft.

Given that the first of the year is always a good time for predictions and new ventures, we've decided that it is time for us to put our money where our mouth is, so to speak. Therefore we are launching our new "Portfolio" section, wherein we will track the performance of a handful of compound semiconductor-related stocks. You can check it out for yourself on page 46. And, of course, there are several other interesting features in this issue, including our report on Shuji Nakamura's demonstration of the first semiconductor laser fabricated from the GaN material system. See page 7. We'd like to take this opportunity to offer our congratulations to Dr. Nakamura and his colleagues at Nichia on this tremendous achievement.

Marie Meyer
Editor
Compound Semiconductor

About the Cover

The cover of this issue shows a false-colored scanning tunneling microscopy image of the surface of a 4 µm thick GaSb (001) film grown by MBE on GaAs (001) at 490°C. The image, 0.5 µm x 0.5 µm, was acquired in situ following the growth of the film. Spiral-like structures like the one seen here grow around threading dislocations in the film caused by the 7% lattice mismatch with the substrate. Note the pair of dislocations emerging from the surface at the top of the spiral, along with a third emerging half-way down on the side. Each one creates a 0.3 nm-height "step". This image is courtesy of L.J. Whitman and colleagues at the Naval Research Laboratory [Washington, DC].

An Important Reminder About Your Subscription

All of the free introductory subscriptions to Compound Semiconductor expired at the first of the year. This means that anyone who wishes to continue receiving our magazine must purchase a subscription. You will find a subscription form on page 27.

The subscription form should be returned to us no later than March 1st to ensure that you receive a copy of our next issue. Be sure to indicate your preferred payment method. If you wish to qualify for the courtesy discount rate, you must complete the entire form.

This is an exciting time for the compound semiconductor industry, but the rapid pace of progress makes it difficult to keep up with all the important areas. Compound Semiconductor can help you stay informed by providing both a "big picture" perspective on the industry as well as a detailed analysis of important aspects of science and technology. If you haven't done it already, send in your subscription form today to ensure an uninterrupted supply of reliable news and information about compound semiconductors throughout this new year.

Sony's SPDT Switches

Sony Semiconductor's new 1.9 GHz SPDT (single-pole-double-throw) switch, which are designed to operate from a single voltage supply for the new PCS standard.

Sony Semiconductor Offers 1.9 GHz JFET-Based Switches for Wireless Applications

Many digital phone standards* require the use of a transmit/receive switch to perform time division duplexing (TDD), which permits transmission and reception to occur at the same frequency, but at unique positions in time. The next North American standard will be the 1.9 GHz PCS (Personal Communications Systems) band, which also uses TDD. In anticipation of this new market opportunity Sony Semiconductor Company of America [San Jose, CA] has introduced the first 1.9 GHz SPDT (single-pole-double-throw) switch which can operate from a single voltage supply. These new devices are designed to improve signal performance and simplify RF design for PCS handsets and base stations. According to Joe Martinez, Marketing Manager of Sony's Communication Products Division, "PCS-based phones are already being designed to include our SPDT switches, and wireless products using these SPDTs should begin to appear in the marketplace in the latter half of 1996."

Design

The SPDTs consist of Junction Field Effect Transistor (JFET) MMICs fabricated on 3" semi-insulating undoped LEC GaAs substrates at Sony's LSI Division in Kanagawa, Japan. Sony's Yoshikazu Murakami describes the structure as follows: a p-layer is buried beneath the channel by Mg^+ implantation to suppress short channel effects, and a Si^+ implantation and a capless anneal are performed to form the n-channel and n^+ ohmic contacts. The p^+ gate region is formed by selective Zn diffusion using an open-tube reactor with DEZ (Diethyl-Zinc). A gate length of 0.5 µm is formed by conventional optical lithography. Resistors are formed by Si^+ implantation, and MIM capacitors are formed by sandwiching a 200 nm thick Si_3N_4 dielectric layer inside the two-level metal interconnection layer.

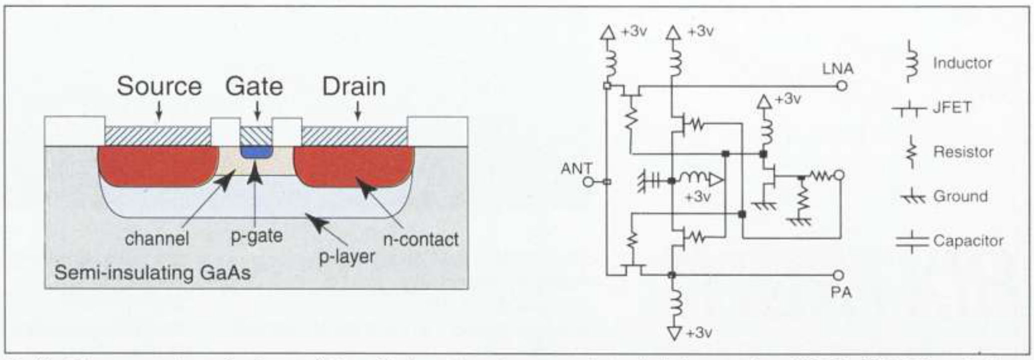
An airbridge structure is used both for connecting the source electrodes of the FETs and for contacting the top metal plate of the MIM capacitor. The completed SPDT occupies 1.5 mm x 1.8 mm.

The switch has been implemented by using a pair of series/shunt depletion-mode JFETs, along with an enhancement-mode control JFET. The depletion-mode JFETs are used within the switch because of their low series resistance in the "on" state. According to Murakami, when the switch is "on", a series FET is in the "on" state, and a shunt FET is in the "off" state. Conversely, when the switch is "off", a series FET is in the "off" state, and a shunt FET is in the "on" state. In order to design a switch with low insertion loss, FETs with large gate widths are preferable. However, a large gate width degrades the isolation performance. Based on simulations, the optimum gate width was determined to be 1 mm, which resulted in a simulated 0.45 dB insertion loss and 34 dB isolation at 1.9 GHz. In order for the switch to be controlled by 0/+3 V, an enhancement-mode JFET was also included to be used as an inverter FET. The entire switch can be modeled as a single effective FET, in which the FET in the "on" state can be expressed as a resistor (R_{on}) between the drain and the source, and the FET in the "off" state can be expressed as a capacitor (C_{off}) between the drain and the source. R_{on} and C_{off} were determined to be 3.3 ohm/mm and 0.27 pF/mm from S-parameter measurements taken from 500 MHz to 8 GHz.

Options

Sony offers two different versions of the SPDT MMIC: (1) the CXG1008N, which is suitable for high isolation, low power requirements, exhibiting 43 dB isolation at 2 GHz with a power handling capability of 10 mW and an insertion loss of 0.8 dB; and (2) the CXG1012N, which is suitable for moderate isolation, high power requirements, exhibiting 23 dB isolation at 2 GHz, and providing power handling capabilities of 400 mW with a 3 V supply and 1 W with a 4 V supply, and an insertion loss of 0.5 dB. Both are offered in 8-pin plastic SSOP packages.

Other JFET-based MMICs have also been implemented by Sony in order to create a complete wireless RF chip set, including a transmitter power amplifier, a LNA, a low distortion amplifier, and a mixer for a receiver front end. All of these chips can be operated by a +3 V single biasing supply. According to Martinez, "the SPDT switches are currently available in sample quantities, with production quantities available in the near future." In 10,000 piece quantities, they will sell for around $5 each.

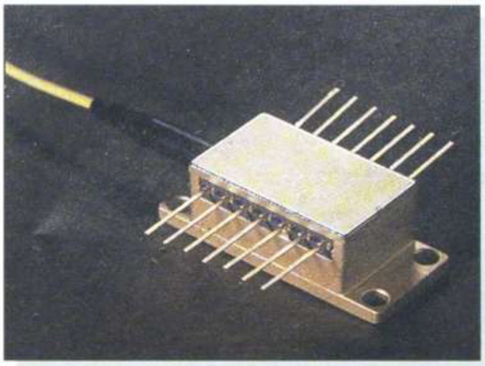


Left: Cross-sectional view of the GaAs structure used to fabricate the JFET SPDT switches. Right: Configuration of the SPDT switch.

**Including, but not limited to, GSM, DECT, CT-2, and PHP.*

TriQuint High Speed Data Transceiver

The Telecom Division of TriQuint Semiconductor has introduced the TQ8105 Transceiver for high speed transmission at 622 million bits of information per second (Mb/s) - the data rate known as SONET OC-12 in North America, and SDH STM-4 in the rest of the world. The new chip serves as the interface between the optics of the data network and CMOS VLSI communications processors. It provides multiplexing, demultiplexing, framing and clock synthesis PLL, in addition to enhanced line and clock diagnostic functions. TriQuint claims that the chip provides "the industry's highest level of functional integration" for SONET/SDH applications. The TQ8105 operates on a single +5V supply. Due to the combination of a thermally enhanced plastic package, the low power dissipation of the devices, and the wide case temperature range (-40° to +125°), it can be operated in most environments without a heat sink. U.S. unit price for the TQ8105 in 1,000 piece quantities is $53. Samples are available now, with production beginning in the second quarter.



850 nm Superluminescent Diodes from EG&G

EG&G Canada is now offering superluminescent diodes (SLDs) operating in the 850 nm region. The devices are designed to address fiber optic sensor applications where short coherence length and high output power are primary concerns. Strained layer multiple quantum wells of InGaAs grown by MOCVD are used to provide high output power. Through the use of a proprietary epitaxial design and unique geometries, the SLD chip provides a broad spectrum with low spectral modulation. High coupling efficiencies to single mode polarization maintaining fiber are achieved due to the chips' near diffraction limited source size. Packaged devices are available in standard coax and SOT outlines for windowed versions and 14 pin "Longhorn" and "Butterfly" modules for fiber pigtailed versions.

LED Fiber-Optic Transceiver from Hewlett-Packard

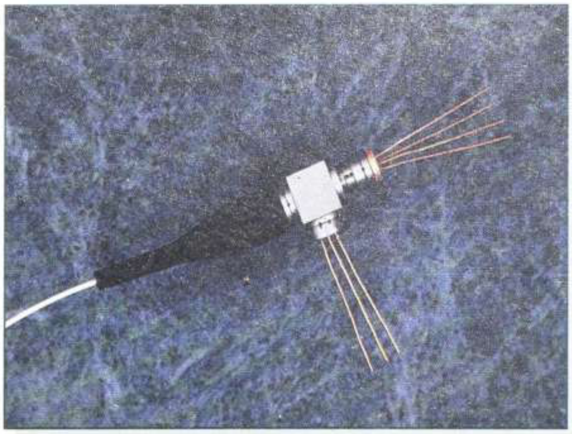
Hewlett-Packard has announced a new LED-based "low-cost" fiber-optic transmitter and receiver pair, designed to allow Ethernet backbones to operate over single-mode fiber. The transmitter incorporates a 1300 nm edge-emitting LED, and the receiver contains an InGaAs PIN photodiode and low-noise transimpedance preamplifier that also operates in the 1300 nm wavelength region. The pair are designed to be a more cost effective option than typical laser-based single-mode fiber transmitters and receivers. The target application is enabling conversion of a multimode fiber Ethernet product to single-mode operation to achieve longer distance capability (up to 14 km vs 2 km for multimode fiber backbone connections) or to anticipate future bandwidth requirements. U.S. unit pricing for the pair in 1-99 piece quantities is $172. They are available from stock.

2400 mcd Green LEDs from Toshiba

Marketech International Corporation has announced a new ultrabright green LED from Toshiba. The new LED, fabricated from InGaAlP, has a typical luminous intensity of 2400 mcd at 20 mA, making it the brightest green LED on the market. The typical wavelength is 574 nm. Target applications include outdoor signs, exit signs, safety equipment, and medical equipment. A "pure green" version is also available. It has a typical luminous intensity of 700 mcd @ 20 mA and a typical wavelength of 562 nm. US pricing for both parts is $0.89 in quantities of 5,000 pieces. Marketech International is Toshiba's designated LED sales group for North America.

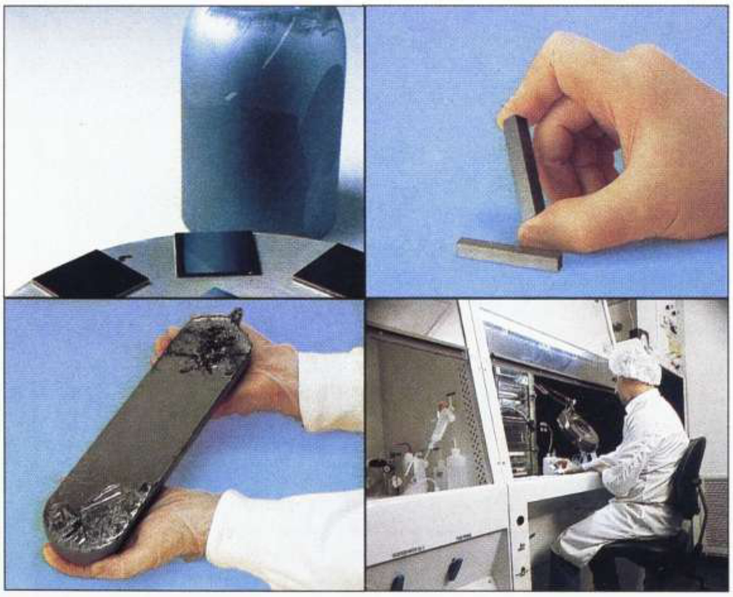
Bi-Directional Laser Module from AT&T

AT&T Microelectronics has announced the availability of a new family of 1.3 micron Fabry Perot bidirectional laser modules. The 1420C/D Astrotec™ line is designed for use in fiber-in-the-loop and fiber-to-the-home applications. Because these modules can transmit and receive 1.3 μm signals over a single fiber, fewer fibers are required for system integration. They are designed to operate between DC and 650 megabits per second, making them well suited for the endpoints of fiber delivery systems in remote terminals or nodes, or in network interface units (NIUs). The module consists of a laser capsule with a backface photodetector monitor, a detector capsule, and an integral beam splitter with a single-mode fiber pigtail. The laser is fabricated from InGaAsP using AT&T's Capped Mesa Buried Heterostructure (CMBH) Fabry Perot laser chip. Both the monitor and the detector are InGaAs PIN photodetectors. The module is capable of high power output, with 1.0 mW CW typical, and higher powers available by request.



Hewlett-Packard High-Speed IR Transceiver

Hewlett-Packard has introduced a new low cost IrDA compliant high speed infrared transceiver. The new components transmit data at 4 Mb/s over distances up to one meter, eliminating the need for cables to exchange files between PCs and peripherals or other types of data terminals. Hewlett-Packard believes that the market for IR technology will more than quadruple in the next 2 years, thanks to the IrDA standard and advances in LED technology. Volume pricing for the new transceiver is in the $5 range. Samples are available now.



Nichia Demonstrates the First Nitride Laser

InGaN multi-quantum well structure produces the shortest wavelength ever reported for a semiconductor laser

On December 12, 1995, Nichia Chemical Industries [Tokushima, Japan] announced that Shuji Nakamura and coworkers had successfully demonstrated an InGaN-based multi-quantum well (MQW) laser diode operating at 417 nm under pulsed conditions at room temperature. This is the first report of lasing from the nitride materials system as well as the shortest wavelength ever generated by a semiconductor laser. This breakthrough is widely seen as a critical step toward realization of production-worthy blue lasers for applications such as optical storage.

The laser diode was operated under pulsed current-biased conditions at room temperature with pulse widths of 2 microseconds and pulse periods of 2 msec. Stimulated emission was not observed until an injection current of 1.7 A was reached, which corresponded to a threshold current density of 4 kA/cm^2, and a turn-on voltage of 34 V. See Figure 1, which illustrates output power as a function of current. Nakamura attributes the high turn on voltage to high contact resistance, and says that improvements will require either an increase hole concentration or the use other p-type electrode materials. There is currently no data on the lifetime of the devices, but Nakamura says, "we operated our device for 2 hours under pulsed current at room temperature and couldn't observe any degradation of the device."

At injection currents below the threshold the spontaneous emission exhibits a FWHM of 20 nm and a peak wavelength of 410 nm. For currents above the threshold a strong stimulated emission at 417 nm is observed, exhibiting a FWHM of 1.6 nm, as shown in Figure 2. Nakamura reports that very recent monochrometer measurements of the laser emission showed a spectrum width of 0.05 nm. He also reports the observation of multi-modes in the emission spectrum. Below the threshold the far field pattern showed a spreading out in all directions, while above the threshold current an elliptical far-field pattern was observed. When asked if he believed that the multi-modes and far-field patterns indicate true lasing action in this device, Nakamura replied "there are no doubts".

Blue LEDs Show the Way

As the congratulatory e-mails and faxes pour into Nichia's headquarters, many observers claim they are not surprised that Nakamura was the first to reach this important milestone. Nichia and Nakamura rose to prominence in the compound semiconductor industry in 1993 when they demonstrated the first bright blue GaN-based LED. Since then Nakamura has steadily refined the Nichia designs to obtain improved performance and an extended color range (see *CS* 1(3), p. 8). His most recent work has been particularly promising. By focusing on single quantum well structures (instead of the double heterostructure designs which were used in Nichia's first LEDs), Nakamura has realized LEDs with very high luminous intensity and excellent color purity, demonstrating that he has achieved a high degree of mastery over this challenging material system.

The epitaxial layers used for the laser were grown using the proprietary two-flow atmospheric MOCVD method which Nakamura developed for his LED work. The first flow in the reactor is a high velocity stream of reactant gases injected parallel to the surface of the substrate. The second flow transports an inert mixture of H_2 and N_2 perpendicular to the substrate, to change the direction of the reactant gas flow in order to bring it into contact with the substrate. Substrates used in this work were (0001) orientation C-face sapphire, and trimethyl Group III species (TMG,

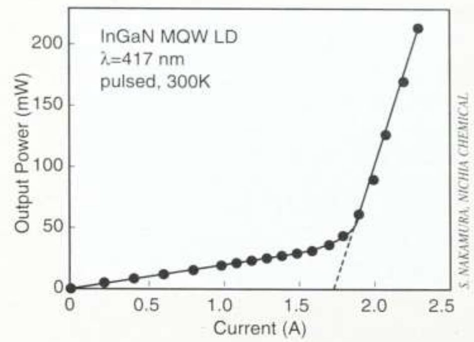


Figure 1. Output power vs. current of the InGaN laser diode.

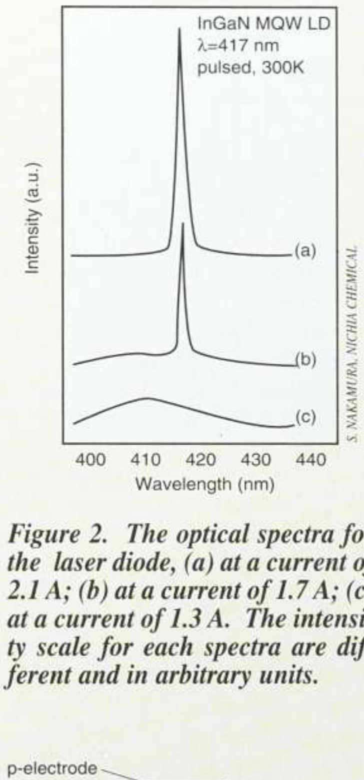


Figure 2. The optical spectra for the laser diode, (a) at a current of 2.1 A; (b) at a current of 1.7 A; (c) at a current of 1.3 A. The intensity scale for each spectra are different and in arbitrary units.

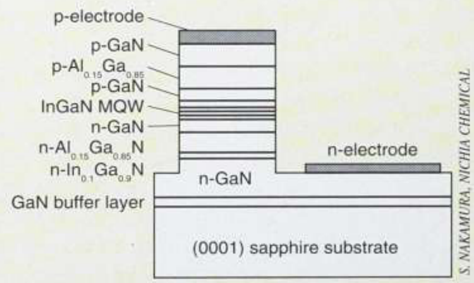


Figure 3. The structure of the InGaN multi-quantum well laser diode. The successful device was 30 μm wide and 1500 μm long.

TMA, and TMI), monosilane (SiH_4), bis-cyclopentadienyl magnesium (Cp_2Mg), and ammonia (NH_3) were used as the sources. Before initiating nitride growth the substrate is heated to 1050°C in a stream of H_2, and then lowered to a temperature of 550°C to commence growth of the low temperature GaN buffer which is needed in order to improve the material quality of subsequent layers. AlGaN and GaN layers are typically grown at 1020°C, while InGaN layers are grown over a temperature range of 750 to 850°C, with the optimum growth temperature dependent on In content of the films.

The Laser Structure

A schematic of the successful laser structure is shown in Figure 3. The MQW structure consists of 26 periods of 25 Å thick $In_{0.2}Ga_{0.8}N$ wells and 50 Å thick $In_{0.0}5Ga_{0.95}N$ barrier layers. The n-type and p-type GaN layers on either side of the MQW structure are light-guiding layers, and the n-type and p-type $Al_{0.15}Ga_{0.85}N$ layers are cladding layers used for the confinement of light emitted from the active region of the InGaN MQW structure. The layer of n-type $In_{0.1}Ga_{0.9}N$ located beneath the lower $Al_{0.15}Ga_{0.85}N$ cladding acts as a buffer layer to prevent cracking. The p-type $Al_{0.2}Ga_{0.8}N$ layer above the MQW structure is used to prevent dissociation of InGaN layers during the growth of the subsequent p-type layers.

Due to the difficulty of cleaving GaN grown on the C-face of sapphire, reactive ion etching was used to form mirror cavity facets in order to make a stripe laser diode with an area of 30 µm x 1500 µm. The roughness of the facet surfaces was approximately 500 Å, and high reflection coatings were applied in order to reduce the threshold current. Ni/Au contacts were used to make p-type contacts, while Ti/Al was used to make the n-type contacts.

Nakamura indicates that the next steps in the development of the nitride-based laser are to improve the contacts in order to reduce the turn-on voltage, as well as investigating the effect of varying the number of QWs in the active region.

The first published report of this work will appear in the January 15, 1996 issue of *The Japanese Journal of Applied Physics*. Nakamura plans to give the first public presentation of his results in an invited talk at the SPIE Photonics West Conference in San Jose, CA in late January. However, millions of Japanese TV viewers have already seen the device. The original announcement was broadcast on the evening news along with video footage of the laser in operation - further confirming Nakamura's status as the closest thing we have to a celebrity in the compound semiconductor industry.

The Other Blue Laser

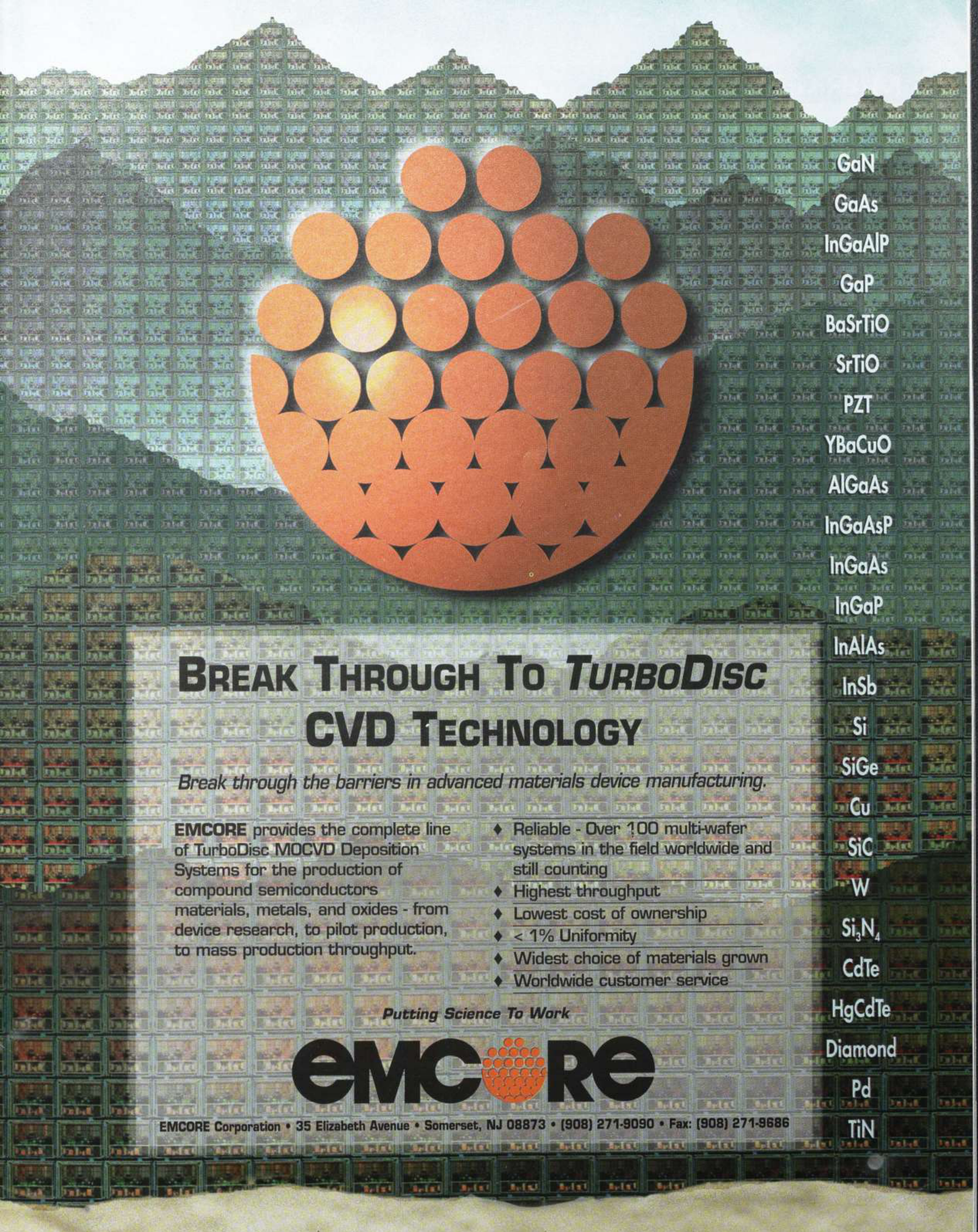
Although the Nichia result is the shortest wavelength semiconductor laser ever reported, it is not the first blue semiconductor laser. In 1991, Michael Haase and coworkers at 3M announced the first operation of a blue-green laser (490 nm) based on ZnSe. Their original diode could only operate under pulsed conditions at temperatures of 77 K, but by 1993 they had demonstrated cw operation at room temperature.

The subsequent development of II-VI lasers has focused on improving material through the reduction of stacking faults and related threading dislocations. 3M now reports that defect levels have been reduced from the 10^5 - 10^6 cm^{-2} level to around 10^3 cm^{-2}. Most of the improvement has resulted from careful attention to the interface between the GaAs substrate and the II-VI layers. ZnMgSSe cladding layers are now commonly used, as they can be lattice-matched to GaAs. As a result, the 3M lasers now exhibit lifetimes of 3.5 hours. Sony has also been making materials improvements, and has reported lifetimes of 4.3 hours. They have also reduced threshold current densities down to 200 A/cm^2 by using a channeled-substrate planar waveguide structure.

Most observers say that a blue semiconductor laser will need to demonstrate at least 3 mW output power with lifetimes of 10^4 hours before it can be considered marketable. Both the II-VI and the nitride efforts have a long way to go. The II-VI lasers need further reductions in defects, probably resulting from modification or manipulation of the substrate/epi interface. The new nitride lasers will require significant effort to reduce threshold voltages and currents in order to obtain cw operation. Although researchers will always vie for the honor of demonstrating "firsts", any implication of some sort of race between the two material systems is misguided. Experts within the optical data storage industry say they don't plan to institute a "blue laser format" for consumer goods for another ten years or so, which should provide both camps enough time to work out their problems - provided that their funding holds out.

Who Needs It?

At the risk of throwing a tiny pall over the celebration, it must be noted that not everyone thinks that a blue semiconductor laser is essential to the future of high density data storage. One alternate method, based on scanning interferometric apertureless microscope (SIAM) technology, has been announced by Kumar Wickramasinghe and coworkers at IBM [Yorktown Heights, NY]. Rather than controlling light with standard optical components such as lenses, mirrors or diffraction gratings, IBM is using the phase shifts generated by a sharp vibrating tip (similar to tips used in a scanning tunneling microscope) to "see" objects as small as 1 nm - a resolution 500 times smaller than a conventional microscope. An optical microscope has been developed based on this concept, in which a semi-transparent sample is mounted on a thin sheet of semi-transparent mica. A laser beam focused on the back of the mica plate travels through the sample and is scattered when it hits the tip just beneath the plate, causing a small portion of the photons to bounce back through the sample and add their phase to a small amount of light that is reflected from the mica. This change in phase between the two reflected light beams can be detected by an interferometer in order to register the effect of the sample on the scattered light - in effect "seeing" the sample. It is this ability to detect phase differences, rather than using the light to "image" the object, which results in the large increase in resolution. Electronic Engineering Times reports that IBM scientists have been able to read 50 nm sized bits at a data rate comparable to those of high-end data-storage systems. An optical storage system based on this approach could achieve storage densities 25 times greater than that of a system based on a blue laser using conventional optics. Just thought you'd want to know.



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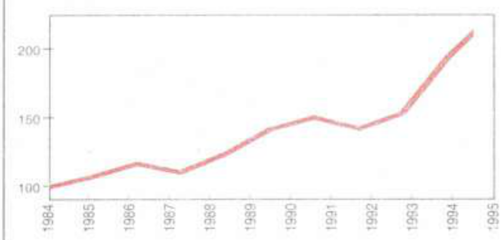
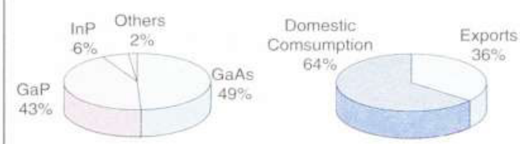
Japanese Shipments of III-V Substrates on the Rise

GaAs shipments surge 42% on the strength of demand from mobile communications

Round Figures



Growth in the value of compound semiconductor wafer shipments reported by Japanese manufacturers from 1984 to the first half of FY 1995. CAGR = 7.5%



Breakdown of shipments for the first half of FY 1995 by crystal type (left) and destination (right)

Statistics recently released by the Japan Manufacturers' Society of Compound Semiconductor Materials (JAMS-CS) show that buoyant demand for LEDs, mobile communications equipment and optical communications applications boosted shipments of compound semiconductor materials by 29% in the first half of fiscal 1995 (April-September) compared to the same period last year. Japanese substrate manufacturers recorded sales totaling ¥20,755 million, the highest ever for the period. This is the first time that the value of shipments has passed ¥20,000 million in a six-month period. However, JAMS-CS also reports a temporary halt in growth of demand from the LED application market in the second half, prompting a cautious assessment from industry observers, who say that future demand trends are unpredictable.

The JAMS-CS statistics, which go back to 1984, reveal that demand for compound semiconductor wafers stagnated in 1991-1993. However, a strong recovery is now underway, driven by the growth of the wireless and optoelectronics industries. Demand for compound semiconductors has risen by double-digits in each of the last four six-month periods. Particularly strong growth was recorded in the second half of fiscal 1994, when shipments surged 39 percent. The current report demonstrates that this trend was maintained through the first half of fiscal 1995.

Crystal Types

JAMS-CS breaks down the statistics for wafer shipments by crystal type and destination (domestic or export).

Shipments of GaAs grew to ¥10,137 million in the wake of substantially higher demand from LED and mobile communications applications. Domestic shipments accounted for ¥7,402 million or 73% of shipments, with exports accounting for ¥2,735 million or 27% of the total. Overall, GaAs shipments rose by 42% over the figures for the same period last year.

GaP shipments were also supported by LED demand, rising 13% to ¥8,960 million. But despite the double-digit increase, this marks the first time since the second half of fiscal 1993 that GaP shipments have failed to maintain the pace of at least 20% annual growth, indicating a general slowing of growth. Shipments were fairly evenly divided between domestic consumption (¥4,774 million or 53%) and exports (¥4,186 million or 47%).

A substantial increase was recorded for InP shipments, which expanded 56% due to firm growth in demand for optical communications components. Total sales of ¥1,336 million were reported, the first time that InP has exceeded ¥1,000 million in a six-month period. Domestic shipments totaled ¥941 million (70% of the total) and exports equaled ¥395 million yen (30% of the total).

The JAMS-CS also reports that shipments of unspecified "other" compound semiconductor materials rose 106% to ¥322 million, of which domestic shipments made up ¥267 million, or nearly 83%.

Of the total ¥20,755 million in shipments in the first half, domestic shipments accounted for ¥13,384 million or 64% of the total, and exports reached ¥7,371 million, or 36%. This half-year marks the first time that the figures have been broken down by domestic and export shipments.

Japanese manufacturers produce approximately 80% of the compound semiconductor substrates consumed world-wide.

Shipments by Japanese manufacturers of compound semiconductor wafers in the first half of fiscal 1995 (April-September)

	Domestic Shipments			Export Shipments			Total		
Materials	¥M	US$M	%	¥M	US$M	%	¥M	US$M	Growth*
GaAs	7,402	74	73%	2,735	27.3	27%	10,137	101.3	42%
GaP	4,774	47.7	53%	4,186	41.8	47%	8,960	89.6	13%
InP	941	9.4	70%	395	3.95	30%	1.336	13.3	56%
Other	267	2.6	83%	55	0.55	17%	322	3.2	106%
Total	**13,384**	**133.8**	**64%**	**7,371**	**73.7**	**36%**	**20,775**	**207.7**	**29%**

**Compared to first half of FY 94*

Source: JAM-CS

Also in the issue:

ATMI Acquires Epitronics, Reports Awards and Patent

Advanced Technology Materials (ATMI) [Danbury, CT] has acquired Epitronics, Inc. [Phoenix AZ], a merchant vendor of III-V epitaxial materials specializing in MOCVD growth of structures for microwave and other electronic applications, with emphasis on C-doped AlGaAs for HBTs. Epitronics was formed in 1984 and currently employs ten people.

ATMI plans to integrate Epitronics into its Diamond Electronics Division, which also includes ATMI's SiC program. According to Tim Murray, Director of Marketing for Wafer Products for that division, ATMI's strategy is to build a distribution system which offers one-stop-shopping for a broad range of alternatives to silicon. The range of technologies offered now includes diamond films, SiC wafers and epi, GaN epi, conventional III-V epi (both arsenides and phosphides), and silicon-on-insulator (SOI). While the list seems diverse, Murray says the key organizing principle is the simple fact that the potential end-users for these technologies are the same. He adds that ATMI is now in a unique position which will allow it to work cooperatively with its customers to help them select the most appropriate solutions.

The Epitronics operation will remain in Phoenix and will be managed by its former president, Robert Adams. The terms of the deal were not disclosed.

In other news, ATMI also announced the receipt of $5.1 million in new contracts in support of its SiC development program, as well as a recent US patent award for a process to manufacture contacts on SiC. The first set of contracts, worth $3.6 million, are primarily in support of expansion of ATMI's SiC substrate manufacturing capability, with funding from a number of sources, including ARPA, NSF and the State of Connecticut. ATMI also received new contracts worth a total of $1.5 million from the Ballistic Missile Defense Organization (BMDO) and the US Air Force. Previous contracts from the same organizations led to the development of a process to manufacture low resistance contacts on SiC, for which ATMI was recently awarded US Patent No. 5,442,200. Under the new contracts ATMI will optimize the contact fabrication and demonstrate its applicability for high power MOSFET devices.

SDL Acquires Seastar Optics

Semiconductor laser manufacturer SDL, Inc. [San Jose, CA] has acquired the assets of Seastar Optics, Inc. [Victoria, BC, Canada], a privately held company which designs and manufacturers fiber optics products. According to SDL, Seastar's single mode packages are widely used in telecommunications, cable television and optical sensors, and their multimode products serve data communications and local area network markets. Seastar currently has 75 employees. It will be operated under the name SDL Optics.

The total purchase price for assets purchased, liabilities assumed and transaction costs is approximately $17 million. The acquisition will result in a write-off of approximately $10 million of in-process R&D for SDL. According to a company spokesperson, the new operation is expected to make a positive contribution to SDL earnings in 1996 and to have a significant positive impact over the long term. For the 12 months ended September 30, 1995 Seastar Optics recorded revenues of approximately $10 million.

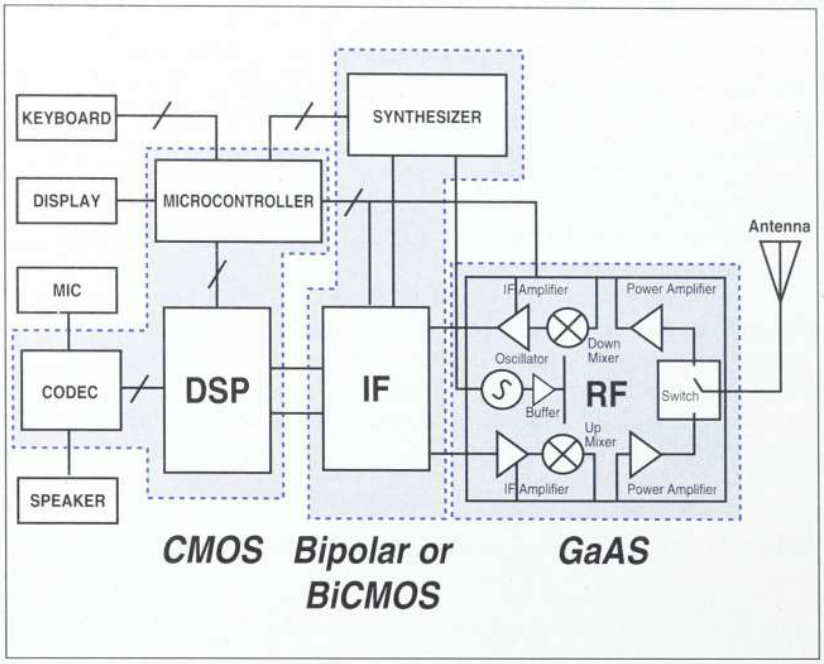
TriQuint Enters RF Power Amp Market, Forecasts a Three-Chip Phone

TriQuint Semiconductor [Beaverton, OR] has announced plans to round-out its offerings for the wireless market by launching a line of GaAs RF power amplifier ICs. Both catalog products and foundry services will be available. The company's Wireless Communications Division currently offers receiver ICs for cellular phones and transceivers for the PHS (Personal Handyphone System) and the 2.4 GHz ISM (industrial/scientific/medical) band. The first new power amp offering will be a 1W product targeted toward the 900 MHz AMPS standard. Additional products will be developed for the GSM, DECT and PCS markets, with products up to 3W planned.

Market forecasts by Strategies Unlimited project that the total sales for power amplifiers into wireless applications will increase from $144M in 1995 to $239M in 1997. The GaAs portion is forecast to grow from 33% to 58%, a 67% compound annual growth rate. Of course TriQuint will find competition in this new arena, from companies such as Anadigics, Motorola, Siemens and TRW/RF Micro Devices, and they acknowledge that they may seem a relative late-comer. However, they believe that this market provides an opportunity to leverage their GaAs MESFET high volume manufacturing experience and to achieve a strategic advantage by providing a higher level of integration. A company spokesperson promises "exceptional price/performance value and a time-to-market advantage over competing discrete-transistor GaAs or silicon solutions".

This new move has the potential to add up to $20 million in sales per year to TriQuint's current total of around $50 million. But perhaps more interesting in the long run is what it reveals about the company's vision for the future of handheld wireless products. According to TriQuint's president Steve Sharp, "whereas there are typically eight ICs or more in a next generation phone, we believe that the next breakthrough will be a three chip, three technology solution involving a single CMOS baseband chip, a bipolar or BiCMOS IF chip, and a single GaAs RF chip." TriQuint is openly critical of the often mentioned "single-chip phone" concept, on the grounds that the variety of functions required in the handset can be implemented with the optimum price/performance ratio only by using different technologies. (See *CS* 1(3), p. 48). In fact, Sharp believes that even the silicon parts of the phone will not be integrated in the foreseeable future. "If a single silicon solution to combine the IF and baseband functions could be built, it would have to be BiCMOS, which would be more expensive than the keeping them separate" he says. As for the RF portion, he envisions "a single GaAs chip that is a full function RF section which allows low cost and power consumption and high integration. This will provide the optimum architecture for low cost, minimal battery requirement phones." He concludes that his company's role in making this vision a reality is "to vigorously pursue a path of RF LSI to bring wireless equipment manufacturers the same benefits of integration in the RF section of the phones that is enjoyed in the remainder of the system".

TriQuint believes the overall worldwide cellular and PCS handset volume will exceed 30 million units per year by 1997.



The "three chip phone": TriQuint's vision of the future of wirleless handsets as a mixture of GaAs, CMOS and BiCMOS.

Cree & Siemens Team Up

Cree Research and Siemens have signed a license, development, and supply agreement which allows for the joint development and manufacture of light emitting diodes (LEDs) using Cree's G•SiC (GaN on SiC) technology. The contract involves license payments to Cree for blue and green LED technology as well as a supply agreement under which Cree will sell LED chips and silicon carbide wafers to Siemens Optoelectronics. Cree is already supplying its superbright blue LED chip to Siemens.

Cree President and CEO, Neal Hunter, stated, "We've been supplying materials and devices to Siemens for many years and we're pleased that we can now join forces in continuing to enhance our G•SiC technology. Our manufacturing ramp for the DH-85 superbright blue LED is behind schedule and we believe this partnership will help us achieve our high volume objectives."

Lasertron & SDL Announce Contracts

Lasertron [Waltham, MA] and SDL [San Jose, CA] have both announced the receipt of large contracts from AT&T Network Systems [Andover, MA] for the supply of 980 nm pump lasers to be used in AT&T's Next Generation Lightwave Network (NGLN) program. Neither company disclosed the precise terms of the deals. Nevertheless, these reports offer further evidence of growing marketplace confidence in the use of 980 nm pump lasers in erbium doped fiber amplifiers (EDFAs) for boosting light signals at the 1550 nm wavelength. EDFAs can amplify optical signals without converting them to electronic pulses, which simplifies network design and enhances reliability.

MAFET Project Awards

On December 11 the US Department of Defense's Advanced Research Projects Agency (ARPA) announced the 17 projects that will be funded under the Microwave and Analog Front End Technology (MAFET) program. The purpose of the program is to develop the technologies required to extend the performance of RF systems while correspondingly reducing the cost to produce them. It emphasizes millimeter wave systems and technology for the RF systems used by the military for radars, smart weapons, and other electronic warfare applications.

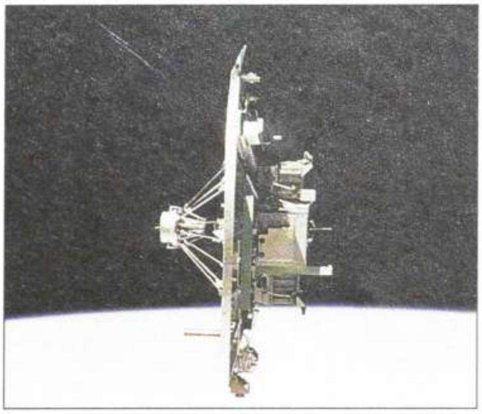
The MAFET program consists of two thrusts. The first is the development of a comprehensive environment for low-cost, rapid design of microwave and millimeter wave circuit assemblies (MCA) and related technologies. Over half of the total funding ($57 million) has been awarded to the "Microwave Design Consortium", consisting of Texas Instruments, Hughes, TRW, Raytheon, Cadence, Compact Software, and HP EEsof. This consortium will develop computer-aided engineering design environments to reduce the time and cost required to develop MCAs. It is hoped that these efforts will reduce a major barrier "hindering the widespread insertion of MMIC technology into DoD and commercial systems".

The second thrust includes a range of contracts targeted at specific problems. A total of 15 contracts were awarded in this area, including a $22 award to TRW for GaAs and InP MMICs which had been announced earlier (see *CS* 1(3), p. 14). Other awards include $2.5 million to Lockheed Martin for "millimeter wave InP HEMT MMICs with 70% RF yield" and "high In low-cost FET materials on GaAs for MMICs". Under these contracts Lockheed will develop a 0.1 micron InP process that will make high-performance InP MMICs affordable for adverse-weather missile seekers and communications systems, and will develop a materials process producing InP-like or better device performance at GaAs chip cost. Westinghouse also received a $2 million contract to develop HBT high power amplifier MMICs.

1995 MRS Medal Awards

Two scientists active in the compound semiconductor field received the 1995 MRS Medal Awards, which recognize recent distinguished and innovative achievements or discoveries that are expected to have a major impact on the progress of a materials-related field. Federico Capasso, head of the Quantum Phenomena and Device Research Department at AT&T Bell Laboratories was honored "for his seminal contributions to compositionally-graded materials using bandgap engineering, and their innovative application in electronics and optoelectronics." He has made pioneering contributions to the design of compositionally graded materials grown by MBE, described their unique transport and electro-optic properties, and pioneered their use in detectors, high-speed transistors, and quantum cascade lasers. Ruud Tromp, manager of Interface Science at the IBM T.J. Watson Research Center, was recognized "for his pioneering experiments on the role of atomic structure, surface stress, and in surfactants in heteroepitaxial growth." He has made several major experimental contributions to understanding of interface formation and growth, especially with regard to Si and Ge, culminating in the discovery and development of surfactant mediated epitaxial growth.

Down to Earth Results



The Space Vacuum Epitaxy Center (SVEC) [Houston, TX] has released preliminary characterization results for the III-V epitaxial layers grown in low earth orbit on-board the Wake Shield Facility (WSF) in September. SIMS measurements of the four GaAs/AlGaAs samples grown during the flight showed oxygen and carbon levels which were quite high for the first two samples ($O \approx 10^{20}/cm^3$; $C \approx 10^{18}/cm^3$), but at or below the detection limits for the latter two ($O \approx 1 \times 10^{17}/cm^3$; $C \approx. 6 \times 10^{15}/cm^3$). However, similarly low results are possible for samples grown using more conventional methods. Mobility figures and other electrical characterization measurements are not yet available. It appears that only the fourth sample grown will be suitable for further study and transistor processing. The first two are too contaminated to be of further interest, and SEM of the third sample showed columnar growth. SVEC plans to release more detailed analysis and device results later this year.

The WSF, shown above, is essentially an MBE reactor which is designed to utilize the vacuum of space to provide a growth environment which is superior to that which is obtainable on earth. See (*CS* 1(2), p. 8.) SVEC reports that the on-board mass spectrometers measured vacuum levels "for elements other than hydrogen" at 1×10^{-12} torr, the detection limit for the instrument, prior to growth. Again, it is not clear that this is significantly better than terrestrial results. However, the total environment, including hydrogen, stayed below 5×10^{-11} torr during growth, which seems to confirm SVEC's prediction that the vacuum of space would provide nearly infinite pumping for the experiment.

The next flight for the WSF, which is put into orbit and retrieved by the space shuttle, is scheduled for November, 1995.

M/A-COM Reports Record Year

GaAs substrate manufacturer M/A-COM [Lowell, MA] reported record sales and orders for their fiscal year 1995, which ended in September. Shipments, expressed in terms of square inches, were up 46% over the previous year. They also record orders for nearly 600,000 square inches of GaAs, the equivalent of 50,000 4" wafers. M/A-COM offers semi-insulating GaAs exclusively, and they reports that 4" wafers now account for over 75% of their shipments.

AXT Breaks Ground On New GaAs Substrate Plant

American Xtal Technology (AXT) [Dublin, CA] has begun construction of a new 50,000 sq. ft. facility which will be "the largest production facility dedicated to GaAs substrates ever built in the US". The total company-funded investment, including building and equipment, will be approximately $20 million over the next five years.

AXT was founded in 1987 by brothers Morris and Theodore Young. Today Morris is President of the company and Ted is the Vice President in charge of marketing. In a speech given at the ground breaking ceremony for the new plant, Morris described the new plant as "a major step on our way to realizing our American dream". He recalled starting the company in a garage with money borrowed from family and friends. And, as he tells the story, "in 1987 we had only one half-time employee, and Ted and myself who worked late at night after working all day at Livermore National Laboratory. Our first sale did not occur until 1989. Today, only 6 years later, we are the largest gallium arsenide manufacturer in the Untied States and the most rapidly growing gallium arsenide manufacturer in the world." He attributes their success to a number of factors. Significant among them is being the first to master the vertical gradient freeze (VGF) crystal growth technique in a practical and cost effective manner. AXT has also benefited from simple good timing, in that they are maturing now, in concert with the current expansion in demand for GaAs, having skipped the general industry slow-down in the late 80's. AXT is also one of the major beneficiaries of the US Title III program, which is designed to ensure the availability of materials which are critical to the country's defense needs. In 1994 AXT received $9M contract for technical and marketing support.

AXT employs 120 people in the San Francisco Bay area, and has annual sales in excess of $15 million. The new facility, when complete, will allow a 3x increase in production.

Facility Expansion for Sensors Unlimited

Sensors Unlimited [Princeton, NJ] has opened at new 1,500 square foot clean room facility for use in detector and array fabrication starting with 2" or 3" diameter wafers. Previously the company had processed wafers via cooperative agreements with Princeton University and the SRI David Sarnoff Research Center. According to Mike Lange, Director of Device Fabrication, increasing commercial demand necessitated the move to an in-house facility. The company plans to commercialize a 320x240 InGaAs focal plane array in early 1996, and they will also use the facility to expand their production of 0.7 - 3.3 µm distributed feedback (DFB) lasers for near-infrared gas sensing.

MKS Acquires UTI; Reports Additional Expansion

MKS Instruments [Andover, MA] has announced the acquisition of UTI Instruments Company [San Jose, CA], a manufacturer of process monitoring systems for the semiconductor industry and a leading supplier of RGAs. Terms were not disclosed. The acquired company will operate as the UTI Division of MKS Instruments, and MKS will incorporate its NGS Division into the UTI Division operations. The NGS Division offers the PPT Series RGAs and vacuum/pressure and gas flow rate calibration systems. The UTI Division will be headed by Nick Samiotes, former president of NGS, and will operate out of facilities in Walpole, MA and San Jose, CA.

In other news, MKS has announced the establishment of a new division and the expansion of its existing operations. The Advanced Products Integration (API) Division has been formed "to provide solutions to vacuum and gas management problems through integrated subsystems". Delton Hyatt, former Director of Product Development at the HPS Division of MKS, has been named president of the Phoenix-based API Division. MKS has also expanded its Massachusetts-based manufacturing operations with addition of a new 84,000 sq. ft. facility in Metheun. The new facility will house the MKS electronic controls and valve operations as well as the calibration/service center presently located in the Andover, MA headquarters. According to a company spokesperson, an increased demand for MKS Baratron© capacitance manometers will be met through the expansion of pressure products manufacturing and operations groups in the Andover plant.

Praxair Announces On-Site Generators for AsH_3 and PH_3, Increases LN_2 Prices.

Praxair, Inc. [Danbury, CT] has reached an agreement with Electron Transfer Technologies, Inc. (ETT) of Princeton, NJ for the marketing and distribution of ETT's fully automated systems for on-site generation of arsine and phosphine. Existing systems product gases at purity levels of 99.999 percent or greater, at varying flow rates and capacities, up to several liters per minute. The agreement allows for development of on-site systems with higher flow rates and greater capacities, and for development of generators for other gases.

Praxair also recently announced an increase in U.S. prices for liquid nitrogen, oxygen, argon and hydrogen, effective November 1, 1995. Increases will average 6 percent for nitrogen and 8-12 percent for the other gases, with variations possible depending upon local supply conditions and other factors. According to a company spokesperson "record levels of demand for industrial gases continue to drive our production and distribution costs higher. Praxair has worked hard to keep customers fully supplied during this period of tightness, but price adjustments are now necessary to address those added costs, and to sustain Praxair's long-term investments to ensure reliability of supply to our customers." Praxair is the largest industrial gas company in North and South America, with 1994 sales of $2.7 billion.

Spectrolab Orders 4th Emcore Reactor

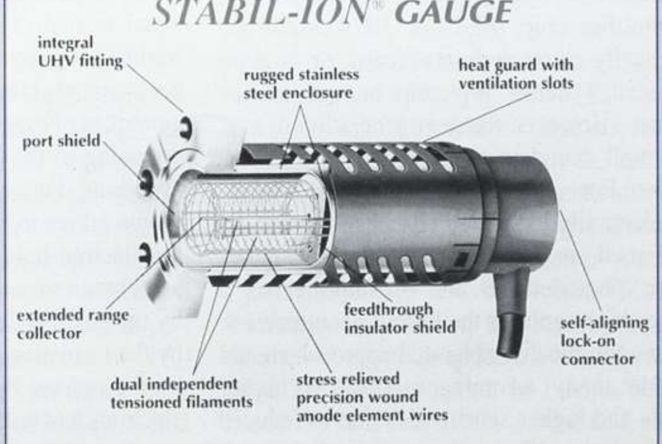
Emcore Corporation has announced the receipt of an order for an Enterprise 400 MOCVD system from Spectrolab, Inc. [Sylmar, CA], a subsidiary of Hughes Electronics. This is the fourth system of this type ordered by Spectrolab in recent months, boosting their manufacturing capability for complex compound opto-electronic semiconductors to more than 200,000 four inch wafers per year.

Aixtron MOVPE Reactor for Siemens

Aixtron GmbH has announced the sale of an AIX 2400 Planetary Reactor© MOCVD systems to Siemens AG. The reactor will be installed at Siemens' Regensburg facility and will be used for the production of AlGaInP yellow-red ultra-high brightness LEDs. The AIX 2400 system can accommodate up to 15 two inch substrates. The Siemens Opto Semiconductor Business Unit reports that this purchase represents a major investment in production capacity at the Regensburg facility. Siemens goal is to replace conventional bulbs used in many areas such as autos, traffic lights and displays by high-brightness LEDs.

Kudos

Oxford Plasma Technology [Yatton, Bristol, UK] has recently achieved the International Quality Management System standard, ISO9001. Established in 1981, the company supplies advanced Plasma and Ion Beam processing systems to R&D and small scale users throughout the world, with annual sales of around $16M. It is part of Oxford Instruments plc, one of Britain's leading high technology groups...VG Semicon [East Grinstead, West Sussex, UK], the MBE division of Fison's Instruments, has also received ISO 9001 accreditation. They are the first MBE equipment manufacturer to achieve this standard... MKS Instruments Deutschland GmbH has also announced the successful completion of its ISO9001 certification process. Its parent company, MKS Instruments, Inc., obtained ISO Certification in 1993 for its manufacturing facilities in Massachusetts...Granville-Phillips Company [Boulder, CO] was recently awarded patents on a Bayard-Alpert style vacuum gauge which includes a shield that completely encloses the electron source, the anode, and the collector electrode so that potentials external to the shield do not disturb the electric share distribution within the shielded volume, thus stabilizing the sensitivity of the gauge. The company claims a 10-times increase in long-term accuracy when compared against other commonly used gauges.



For more transaction information see page 34

OEIC Photoreceivers

Monolithically integrated photoreceivers using MSMs, PINs, FETs and HBTs exhibit bandwidths of 20 GHz at data rates up to 20 Gb/s

ROBERT A. METZGER

A key component in any optical communication system, whether it is being used in long distance communication, or for bussing data over short distances, is the front end photoreceiver. Photoreceivers are used to detect the incident light generated by a transmitter (typically a modulated laser signal sent through an optical fiber), and convert it to an electrical signal which contains the information which had been encoded into it. Current optical transmission systems (SONET, ATM and CATV), typically operate at data rates of less than 500 Mb/s, but many new systems will operate over the range of 622 Mb/s to 2.5 Gb/s. Current high speed systems generally utilize a hybrid integration approach for the photoreciever, in which a separately packaged photodetector chip (PIN- or MSM-type) and preamplifier chip (FET- or HBT-based) are electrically connected on a board, or in more advanced systems, flip chip bonded to one another. However, the next generation of systems will see data rates in the 10-40 Gb/s range. For these, a monolithic OEIC (Optelectronic Integrated Circuit) approach is envisioned, in which an integrated photoreceiver (photodetector and preamplifier on a single chip), replaces the hybrid photoreceiver. The monolithically integrated approach should provide many advantages, such as higher speeds and higher sensitivities due to reduced parasitics. In addition, the integrated approach should permit the fabrication of devices which take up less volume, require less power, have simpler packaging, higher reliability, and eventually lower manufacturing costs. The inherent challenge in the monolithic approach is in the growth and fabrication of dissimilar device types (detectors and preamplifiers) onto a single substrate.

Detectors

The detectors typically utilized in monolithically integrated photoreceivers are either the PIN or MSM (metal-semiconductor-metal) type, as illustrated in Figure 1. The PIN detector is a vertically structured p-n diode with a nearly intrinsic (I) region (typical thickness 1.0 µm) inserted between the heavily doped p and n contact regions. The PIN detector is operated in a reverse biased mode, so that the entire intrinsic region is depleted of free carriers. When a photon with energy greater than or equal to that of the bandgap of the depleted intrinsic region enters into the device and becomes absorbed, an electron-hole pair is generated. For optical communication systems operating in the 1.55 µm region, this requires absorbing layers of InGaAs, which can be grown lattice matched to InP substrates. Once the electron-hole pair is generated, they create a photocurrent as they are swept out to contacts by the electric fields within the diode (created by the formation of the p-n junction, as well as by the reverse bias applied voltage), with the electrons and holes collected at the positive and negative contacts. The width of the intrinsic region effects device performance, with increasing width increasing the quantum efficiency, or responsivity (ratio of photons to be converted to electron hole pairs) of the device -

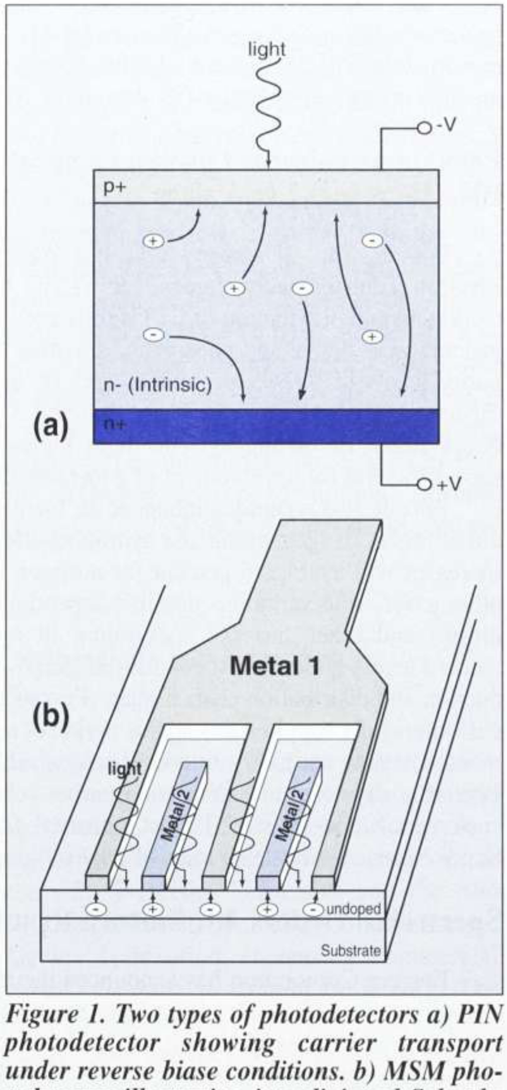


Figure 1. Two types of photodetectors a) PIN photodetector showing carrier transport under reverse biase conditions. b) MSM photodetector illustrating interdigitated Schottky barrier contacts.

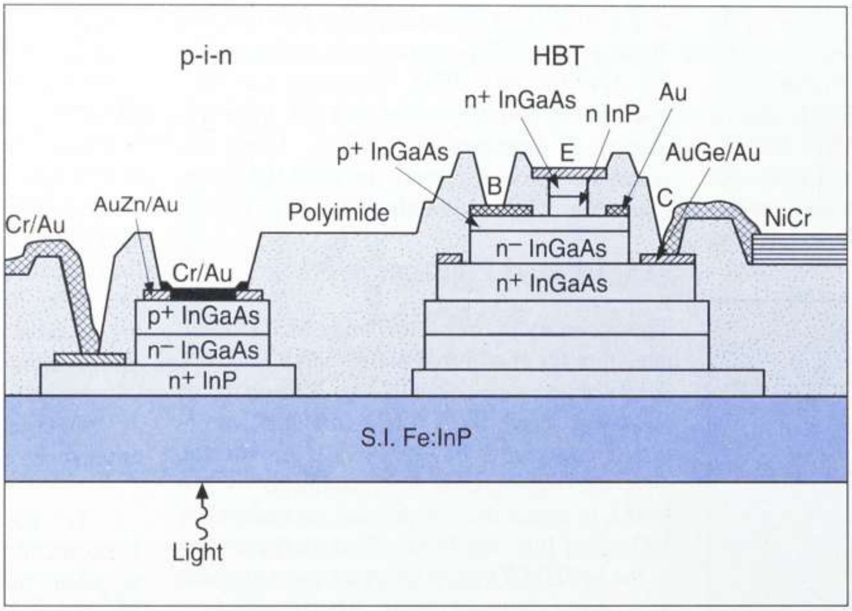
since there is a greater probability for a photon to be absorbed in the larger volume of material. However, the wider the intrinsic region, the slower the photodetector is to respond to a change in incoming photon intensity (change in signal), since it takes a longer time for the electrons and holes to be swept to the contact regions. Therefore, the width of the intrinsic region can be used to tradeoff between responsivity and speed.

The second type of photodetector, the MSM, is typically formed by two interdigitated, fork-shaped metal electrodes that function as back-to-back Schottky diodes when contacting a photon absorbing intrinsic semiconductor layer (GaInAs, typically 1.0 µm thick). Schottky barrier heights are low to GaInAs due to its relatively small bandgap, resulting in leaky Schottky diodes (which in turn result in degraded noise performance). This problem is generally solved by growing thin layers of InP or AlInAs which have larger bandgaps, between the Schottky metal contact and the GaInAs, which increases the Schottky barrier height and thereby reduces leakage current. When the electrodes are biased at potentials of 1 to 3 V, the intrinsic GaInAs region between them becomes depleted, and that region then behaves just like the intrinsic region in the PIN detector. The responsivity of MSMs are typically less than those of PINs because the MSMs interdigitated front contacts block a portion of the incoming light, while the MSMs have potential for higher speed than the PINs because they exhibit an intrinsically smaller capacitance. In practice, it is found that the optimum photodetector for monolithic integration in a photoreciever depends not only on the specific application for the photoreceiver, but also on the type of transistor being used in the preamplifier.

PIN-Based Photoreceivers

The long-time proponents of monolithically integrated photoreceivers utilizing PIN photodetectors include S. Chandrasekhar, L. Lunardi and coworkers at Bell Laboratories [Holmdel, NJ], who utilize HBTs in the preamplifiers. A schematic of this photoreceiver configuration is shown in Figure 2. Typically grown by MOMBE (metal organic MBE), but also having now been grown by MOVPE, this InP-based photoreceiver is fabricated in a single growth run. The PIN (I region InGaAs - 1.0 µm thick) is grown first, followed by the InP/GaInAs-based HBT layer. In the areas where the PIN photodetector will be accessed the HBT layers above it are etched away. The HBT-based preamplifier circuit is a transimpedance design with a dual feedback loop (current and voltage feedback) followed by an output stage. The HBTs used require only modest design rules, with minimum dimensions of 3.0 µms, exhibiting an f_t and f_{max} of 70 and 45 GHz, respectively. For 1.55 µm operation, the PIN detector exhibits an external quantum efficiency of 85% and a corresponding responsivity of 1.1 A/W, under conditions when the detector is illuminated from underneath. Light which is not absorbed on the first pass through the intrinsic region can be reflected from topside metal contacts for a second pass back through the intrinsic region, which results in an increase in responsivity. When integrated with the preamplifier, the photoreceiver exhibits a bandwidth of 10.4 GHz and was found to perform up to 20 Gb/s with a sensitivity of -17.0 dBm. Chandrasaker comments on their choice of using the PIN-HBT approach by saying that " PINs are simple to make - with all the geometries relatively large, and suitable to contact lithography, and unlike MSM detectors, exhibit no nonlinear effects (except at very high optical powers where space charge effects become significant). For integration, they are mesa devices, so become compatible with other p-n junction devices, like the HBTs. In fact, the HBT already has two p-n junctions, one of which is the base-collector junction, which can double as a PIN photodiode." He goes on to say that the only difficult aspect of this approach is "that of doing the epitaxy. Half the battle is won if the epitaxy is optimized for the best performance for both the HBT and the PIN". As Chandrasaker points out, the base-collector structure of an HBT is identical to that of a PIN detector, and the lightly doped collector region of the HBT can double as the intrinsic region of a PIN. However, high speed HBTs typically utilize collectors of 300-600 nm in thickness, while high responsivity PINs typically use intrinsic region thicknesses of 1.0 µm. In order to use the base-collector structure of the HBT for the PIN, compromises in performance of both devices must generally be made. However, this dual use approach decreases the complexity of the growth, and has been implemented by several groups.

R.H. Walden and coworkers at the Hughes Research Laboratories use MBE-grown material, in which the base-collector structure of an AlInAs/GaInAs-based HBT is also used to form a PIN detector. The focus of the Hughes work is on photoreceiver arrays for WDM (wave division multiplexing) applications. The collector width of the HBT structure is 1.0 µm and the resulting PINs formed from it exhibit a responsivity of 0.54 A/W. These HBTs exhibit and f_t and f_{max} of 50 and 90 GHz respectively, where the reduced f_t is due to the relatively thick collector. The resultant bandwidth of the photoreceiver is 19 GHz, making it suitable for 20 Gb/s operation. A.L. Gutierrez-Aitken, P. Bhattacharya and coworkers from Michigan University [Ann Arbor, MI] report on using a similar structure, in which PINs are fabricated from the 600 nm region of InAlAs/InGaAs-based HBTs. These HBTs exhibit an f_t and f_{max} of 67 and 123 GHz, respectively, while the PIN detector exhibits a maximum responsivity of 0.4 A/W. The photoreceiver exhibits a sensitivity of -18 dBm for a 16 GHz bandwidth (suitable of 20 Gb/s data transmission). Both of these approaches have utilized wide collec-

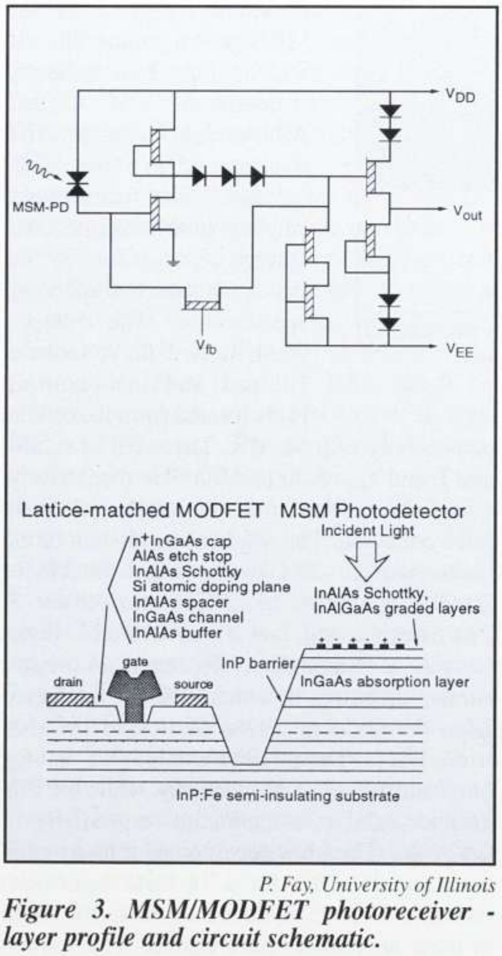


S. Chandrasekhar, Bell Laboratories [Holmdel, NJ]

Figure 2. PIN/HBT photoreceiver layer profile.

tor regions in order to increase PIN responsivity at the expense of the HBT's f_t. The opposite approach is taken by E. Sano and coworkers of NTT LSI Laboratories [Atsugi, Japan], who use an MOCVD-grown DHBT with InP emitter and an InP/InGaAs composite collector (400 nm GaInAs region), where the DHBT exhibits an f_t and f_{max} of 104 and 156 GHz, respectively. Because of the reduced collector thickness, the responsivity of the PIN is only 0.27 A/W, yet the bandwidth of the photoreceiver is 23 GHz, enhanced in part by the good HBT RF characteristics. This photoreceiver is reported to operate up to 10 Gb/s, and this speed is limited by measurement apparatus, and not by device performance.

B.H. Klepser and coworkers at the Swiss Federal Institute of Technology [Zurich, Switzerland], have recently reported on combining a HEMT with a PIN. In this approach a GaInAs/AlInAs HEMT is first grown by MBE, and then the PIN detector layers are grown by CBE (Chemical Beam Epitaxy) within wells which are etched into the HEMT layers. HEMTs were used instead of HBTs because they exhibit the highest cuttoff frequencies and lowest noise characteristics of all three terminal devices. The HEMT was fabricated with



P. Fay, University of Illinois

Figure 3. MSM/MODFET photoreceiver - layer profile and circuit schematic.

0.25 μm E-beam gates and exhibited an f_t of 100 GHz. The resultant bandwidth of the photoreceiver was 18 GHz, a value very comparable to those PIN-based photoreceivers using HBT-based preamplifiers. Although not utilizing a true PIN detector, H. Kamitsuna and coworkers of NTT Wireless [Yokosuka-shi, Japan] have used a InP/GaInAs/InP based HBT, which can also be operated as an HPT (heterojunction phototransistor), and can be viewed as a base-collector defined PIN detector plus an internal amplifier. Utilizing a thin collector width of 300 nm in order to enhance HBT performance, these extremely fast transistors exhibit an f_t and f_{max} of 156 and 200 GHz, respectively. The penalty for using the thin collector is reduced responsivity at 1.3 μms of 0.23 A/W when the HPT is operated only as a PIN (i.e. no amplification). However, when operated in the HPT mode, a gain in responsivity over operating in the PIN mode of 28 dB is achieved, resulting in a responsivity of 5.6 A/W (at 100 MHz). However, the HPT responsivity exhibits rapid fall off with frequency, as compared to the PIN. Using this somewhat novel approach, the HPT-HBT photoreceiver exhibits a bandwidth of 15.3 GHz.

MSM-Based Photoreceivers

The primary group utilizing MSM-based detectors for photoreceivers is that of P. Fay, I. Adesida and coworkers at the University of Illinois [Urbana, Il]. A MSM-MODFET structure is grown in a single MOVPE growth run, with the FET grown first, followed by the MSM, in which the two devices are isolated by 100 nm of InP. See Figure 3 for an illustration of the MODFET/MSM structure and a diagram of a photoreceiver circuit which utilizes a transimpedance amplifier design. The AlInAs/GaInAs-based MODFET uses a 20 nm InGaAs channel, 0.25 μm E-beam gates, and exhibits a $g_m > 800$ mS/mm and an $f_t > 105$ GHz. The MSM utilizes a 1.0 μm thick GaInAs absorbing layer, in which the top 100 nm is graded to an AlInAs layer in order to increase the barrier height of the Schottky diode. The MSM detector exhibits a responsivity of 0.32 A/W, a value lower than the typical PIN photodetector, but due to its lower intrinsic capacitance, the resulting photoreceiver exhibits a bandwidth of 18.5 GHz, comparable to the best PIN-based results, and is suitable for 20 Gb/s operation.

Improvements in MSM responsivity have been recently reported, with R.H. Yuang and coworkers of the National Central University [Chung-Li, Taiwan, ROC] using semitransparent thin Au Schottky barriers and an $In_{0.9}Ga_{0.1}P$-InP-InGaAs structure (1.0 μm InGaAs absorbing layer) to achieve a responsivity of .7 A/W. In other work, O. Vendier, N. Jokerst and coworkers from the Georgia Institute of Technology [Atlanta, GA], report that by using liftoff techniques which allow metallization on the backside of the MSM, not only allows more light to pass into the front of the detector, but also behaves as a reflecting layer so that unabsorbed light on the first pass is reflected back up into the detector for a second pass. This structure saw an increase in responsivity to 0.70 A/W as compared to 0.23 A/W in a conventional MSM structure. Incorporation of these advanced MSM structures will enable further increases in MSM/FET based photoreceiver performance.

Based on these results, there is no obviously superior approach to the monolithic integration of a photoreceiver. Both PIN and MSM detectors, coupled with HBT- or FET-based amplifiers, are capable of producing photoreceivers exhibiting 20 GHz bandwidths, while also being able to handle data rates of up to 20 Gb/s. However, it can be concluded that these performances are now comparable to the best of those achieved with the hybrid integration approach, and they clearly demonstrate that monolithically integrated photoreceivers are a viable technology for future high speed optical communications systems.

Detailed information regarding the approaches discussed above can be found in:

1. 20 Gb/s Monolithic p-i-n/HBT Photoreceiver Module for 1.55-μm Applications", L.M. Lunardi et al, IEEE Photonics Technology Letters, 7(10), 1201 [October 1995].

2. 15 GHz Monolithic MODFET-MSM Integrated Photoreceiver Operating at 1.55-μm Wavelength", P. Fay et al, Electronics Letters, 31(9), 755 [27 April 1995].

3. 23 GHz Bandwidth Monolithic Photoreceiver Compatible with InP/InGaAs Double-Heterojunction Bipolar Transistor Fabrication Process", E. Sano et al, Electronics Letters, 30(24), 2064 [24 November 1994].

4. A 16 GHz Bandwidth InAlAs-InGaAs Monolithically Integrated p-i-n/HBT Photoreceiver", A.L. Gutierrez-Aitken et al, Photonics Technology Letters, 7(11), 1339 [November 1995].

Advances in Epitaxial Growth and Device Performance

Epitaxial growth is the engine for improvement in device performance for both electronics and optoelectronics.

ROBERT A. METZGER

Epitaxial growth and device performance go hand in hand - each driving the other. Long gone are the days when the epi grower was just that - someone studying the physics of epitaxial growth, correlating RHEED patterns to III/V ratios and substrate temperatures, growing MQWs for no reason other than to see how quantum size effects would manifest themselves in PL spectra, or bolting on a new piece of hardware to a reactor just to see what new and interesting materials could be grown with it. Epitaxial growth has now become driven by device needs, whether it is for LEDs, Lasers, MESFETs, HEMTs, HBTs, Solar Cells, OEICs, or Detectors. The requirements for faster, lower noise, higher frequency, less-power-in/more-power-out devices are what drive the capabilities and new directions of epitaxial growth. Here are a few eamples which illustrate how growth techniques have been pushed to new limits in the quest for new and better devices.

Superbright LEDs

If enough current is passed through any p-n junction some of the injected carriers will recombine to emit a photon, and you have an LED. The earliest LEDs were simple homojunction structures which utilized this brute-force approach. But there are two major limitations to such a structure. The first is nonradiative recombination at the p-surface of the LED if it is too close to the p-n junction, and its reverse problem - photon reabsorption resulting from locating the surface too far from the junction. The second is that the electrons which are injected from the n+ region into the p region as minority carriers will diffuse away from the junction and gradually recombine with the majority carriers. Due to the carrier diffusion away from the junction, the creation of photons takes place over a larger volume of material, which in turn reduces internal quantum efficiency and enhances reabsorption.

Fortunately, LED technology has evolved a long way from the simple brute force approach. While blue and green nitride-based LEDs are attracting most of the attention these days, more mature technologies such as GaP- and GaAs-based emitters for the yellow-to-red spectral region have also been making significant strides. For example, consider Figure 1, which plots the evolution of efficiency for these longer wavelength visible emitters. Hewlett-Packard, Toshiba, Siemens, and others now offer 'superbright' LEDs with efficiencies as high as 41.5 lm/W - better performance than is possible with filtered incandescent sources, and two to four times better than the state-of-the art just two years ago.

Much of this progress has been achieved through the clever manipulation of the epitaxial structure, both in and out of the reactor. Hewlett Packard's most recent superbright LED designs solve both of the problems mentioned above by using a double heterojunction structure, shown in Figure 2. The structure shown in this figure is grown on an absorbing GaAs substrate

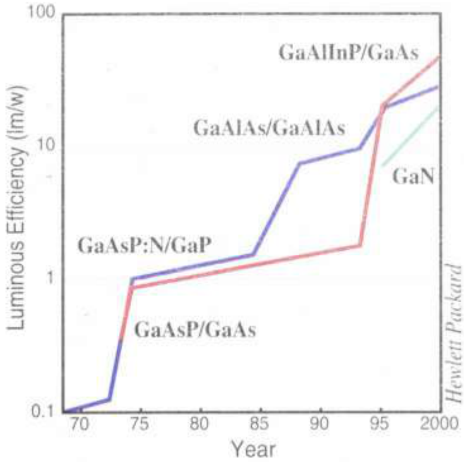
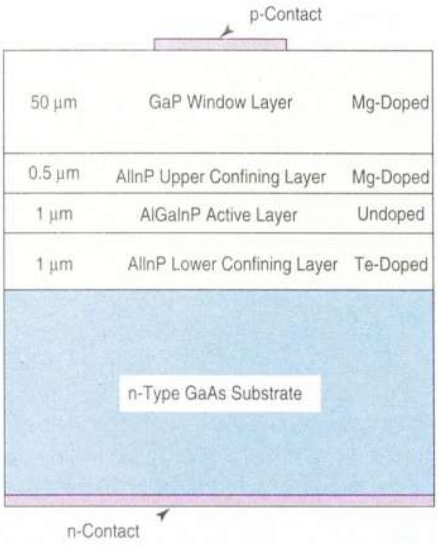


Figure 1. The evolution of LED efficiency.

(AS), in which a portion of the emitted light is reabsorbed in the substrate. Optimum performance is achieved by removing the absorbing GaAs substrate, and replacing it with a transparent GaP substrate (TS). The light emitted into this larger bandgap substrate is transmitted through it, making the LED more efficient. The narrower bandgap $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ material used in both the AS and TS structures acts as a confinement layer, so that injected carriers can not diffuse either into the substrate, or to the surface, and thereby reduce internal quantum efficiency and enhance reabsorption. In addition, the larger bandgap AlInP acts as a window in which the emitted photons with energy close the $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ bandgap are not reabsorbed.

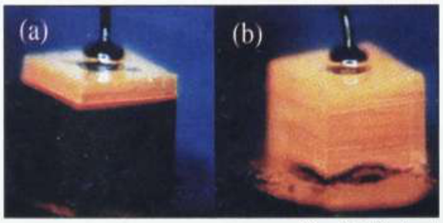
The $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ and AlInP is grown lattice matched to GaAs by MOCVD (using TMGa, TMAl, TMIn and 10% PH_3 in H_2) where x can vary from 0.2 to 0.43 which spans the emission wavelength from red-orange to green (630-560 nm). The top 50 microns of p-type GaP (which is also a window material for the emission wavelengths involved here) growth is done by hydride VPE. Despite the fact that GaP is mismatched from AlInP by nearly 3.6%, it is far enough away from the $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ layer that the dislocations and stacking faults do not penetrate back into this active layer and degrade the LED's



Hewlett Packard

Figure 2. Schematic of Hewlett Packard's MOCVD-grown superbright LED, utilizing a double heterostructure to enhance quantum efficiency.

performance. This GaP layer serves two purposes: to act as a low resistance contact layer (AlInP is relatively resistive) to spread the current from the top contact; and to facilitate handing of the epitaxial layers following substrate removal. After the GaAs substrate is removed by chemical etching techniques, the exposed n-type AlInP layer is bonded to an n-type GaP substrate, thereby allowing the entire structure to act as an emitter, not just the top epitaxial layer. An example of both the TS and AS LEDs are shown in Figure 3, where it is apparent that the TS technique produces a LED with an enhanced optical output.



Hewlett Packard

Figure 3. Hewlett Packard's AlInP/AlGaInP double heterostructure superbright LEDs under operation, (a) utilizing a absorbing GaAs substrate, and (b) utilizing a transparent GaP substrate.

Chirped HBTs

In its simplest form, an HBT would consist of only five different layers: emitter, base, collector, emitter contact and collector contact. However, advanced HBT structures with more than 100 distinct layers are now being fabricated in order to maximize both high frequency and power performance. Most power HBTs are fabricated in the AlGaAs/GaAs or GaInP/GaAs material systems, where the larger bandgaps of these materials can handle the high voltages required for high power applications. However, InP-based HBTs show the best RF performance. The best of both worlds would be to combine the power handling capabilities of GaAs HBTs with the RF capabilities of InP-based HBTs.

Such an approach has been implemented by C. Nguyen and coworkers from the Hughes Research Labs [Malibu, CA], in the form of a Double Heterojunction Bipolar Transistor (DHBT) based on the AlInAs/GaInAs/InP material system. As GaAs-based HBTs have shown, a wide bandgap collector material is needed for power applications, with the natural choice for InP-based HBTs being to use an InP collector. However, a difficulty arises when InP is used as the collector material and GaInAs is used as the base material, due to the formation of a conduction band energy barrier at that heterointerface. This barrier reduces the flow of electrons into the collector, resulting in gain compression at low current densities. The Hughes technique for removing this barrier is to linearly vary the bandgap between the InGaAs base and InP collector, while incorporating two delta doping layers of the same concentration at the ends of the grade - an acceptor at the base end (the heavily doped base can act as this end of the dipole) and donor at the collector end, thereby forming a dipole. This approach results in the entire bandgap difference between GaInAs and InP being transferred to the valence band, with the conduction band becoming barrier free.

Figure 4 illustrates the DHBT structure, which is grown by GSMBE. To linearly grade between the base and collector, an AlInAs and GaInAs chirped superlattice (SL) was used, in which each period of the superlattice has different thickness of AlInAs and GaInAs, in order to effectively form a graded AlGaInAs alloy. The relative percentages of AlInAs and GaInAs are changed within each period to chirped SL, with the base end being GaInAs rich (small band gap) and the collector end being AlInAs rich (large bandgap). This approach simplifies the MBE growth, in that a true graded AlGaInAs alloy does not have to be grown. The base-collector region is graded with a 33 period 1.5 nm/period AlInAs/GaInAs chirped SL (total thickness 50 nm). The chirped approach is also used to grade the emitter-base junction in order to remove the spike in the conduction band and to lessen the sensitivity of the position of the Be-Si interface on the electrical behavior of the junction. The n-type portion of the dipole which is placed on the collector side of the grade, is incorporated in 2.0 nm of InP. The InP used for the dipole can also be replaced with AlInAs which then acts as a launcher, so that hot electrons are injected into the collector, thereby reducing electron transit time. With the AlInAs launcher, and a 1.0 µm collector, the device exhibited an f_t of 71 GHz (the highest reported value for a collector of this thickness with a breakdown voltage exceeding 35 V), and an f_{max} of 80 GHz. The output power of this DHBT when operated at 9 GHz (X-band) is 2 W (5.6 W/mm) with a 70% PAE where the high breakdown voltage allowed the DHBT power cell to be biased at 14 V.

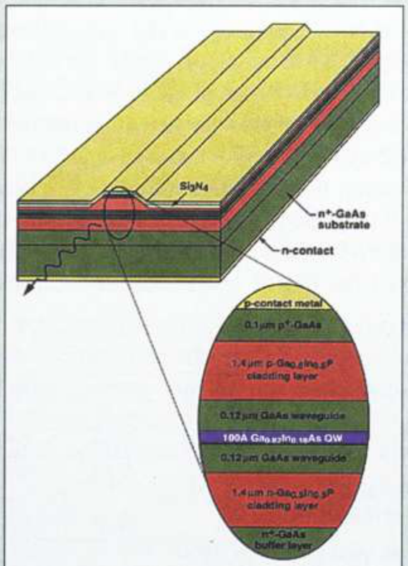
Contact Layer	GaInAs	200 nm	$n^+=1x10^{19}$ cm^{-3}
Emitter	AlInAs	40 nm	$n^+=1x10^{19}$ cm^{-3}
	AlInAs	200 nm	$n^+=8x10^{17}$ cm^{-3}
10x3.3 nm AlInAs/GainAs Chirped Super Lattice	EB SL Grade	22 nm	$n=8x10^{17}$ cm^{-3}
		99 nm	$p=2x10^{18}$ cm^{-3}
EB Spacer Layer	GaInAs	5 nm	$p=2x10^{18}$ cm^{-3}
Base	GaInAs	60 nm	$p=3x10^{19}$ cm^{-3}
BC Spacer Layer	GaInAs	5 nm	$p=2x10^{18}$ cm^{-3}
33x1.5 nm GaInAs/AlInAs Chirped Super Lattice	CB Grade	25.0 nm	$p=1.0x10^{17}$ cm^{-3}
		25.0 nm	$n=2.0x10^{18}$ cm^{-3}
Delta Doping Sheet	InP	2.0 nm	$n=3.5x10^{18}$ cm^{-3}
Collector	InP	1.0 µm	$n=1.4x10^{16}$ cm^{-3}
Sub-Collector	InGaAs	400 nm	$n=1x10^{19}$ cm^{-3}
	InP	10 nm	$n^+=1x10^{19}$ cm^{-3}
	InGaAs	400 nm	$n^+=1x10^{19}$ cm^{-3}

Hughes Research Laboratories

Figure 4. Schematic of Hughes Research Laboratories' AlInAs/GaInAs/InP DHBT utilizing a chirped GaInAs/AlInAs superlattice and dipole doping in the transition region between the base and collector to remove the conduction band energy barrier.

MBE-Grown Phosphide Lasers

Erbium doped fiber amplifiers (EDFAs) in conjunction with wavelength division multiplexing (WDM) techniques are being considered for future high capacity, high reliability optical networks. When operating at 1480 nm, the multiple wavelengths used in WDM techniques can suffer from degraded signal to noise ratios (SNR) which arise from nonuniform wavelength dependent gain profile and saturation characteristics of the EDFAs. It is believed that many of these negative effects can be lessened by reducing the optical pumping wavelength from 1480 nm to 0.98 µm. AlGaAs-based laser diodes using GaInAs Quantum Wells (QWs) were first developed for this 0.98 µm application, but due to reliability issues involving Al containing compounds (including DX-related defect centers and dark line defect propagation through the QW region), these AlGaAs-based compounds are being replaced by GaInP-based compounds. They are usually grown by MOCVD/MOVPE. Solid source MBE (SSMBE) has generally been considered unsuitable for this type of work. Because Phosphorus (P) exists in many allotropic forms (red, white, black), all with different vapor pressures, it is nearly impossible to establish a controllable P flux from conventional effusion cells. PH_3 can be used for the growth of P-containing compounds during GSMBE or CBE, but is highly toxic, requiring significant safety considerations. However, with the recent development of valved cracker-based effusion cells, incorporating cold wall condensers for the storage of high vapor pressure white phosphorus, stable, reproducible, solid-based sources of P_2 have become available for SSMBE growth. Using such a source, J. Baillargeon and coworkers at AT&T Bell Laboratories [Murray Hill, NJ] have fabricated strained QW GaInAs/GaInP-based lasers for 0.98 µm operation. These lasers exhibited threshold current densities of broad area devices as low as 185 A/cm² and slope efficiencies of 0.40 W/cm² - results comparable to GaInAs/GaInP-based lasers grown by both MOCVD and GSMBE/CBE techniques.



AT&T Bell Laboratories

Figure 5. Schematic of GaInAs/GaInP 0.98 micron laser grown by SSMBE.

High Mobility HEMTs grown at reduced temperatures

InP-based InAlAs/InGaAs heterojunction FETs have advantages for low noise and high power devices because of their high electron mobility and high sheet carrier density. Performance enhancements in these devices have been made by increasing the In content in the channel, which increases carrier mobility. However, the increase in In-content strains the material, and if this strain becomes too great (and thereby critical thickness is exceeded), it will be relieved by the formation of dislocations which will degrade device performance. The challenge is to place as much indium in the channel as possible, without generating dislocations. T. Nakayama and coworkers at NEC Corporation [Shiga, Japan], have combined MBE growth at reduced temperatures (420°C, as compared to normal growth temperatures of 500°C) with an In-rich channel structure to obtain a record level channel mobility. Starting from the AlInAs buffer layer beneath the active device, the channel is composed of: 9 nm of $In_{0.53}Ga_{0.47}As$ which is lattice matched to InP, 4 nm of $In_{0.8}Ga_{0.2}As$, 4 nm of InAs, 2 nm of $In_{0.8}Ga_{0.2}As$, and 1 nm of $In_{0.53}Ga_{0.47}As$. The low temperature growth appears to extend the thickness range of the strained channel material before the onset of dislocation formation. RHEED (reflection high energy electron diffraction) studies indicate that up to 6 nm of InAs can be grown at these reduced temperatures before the onset of strain-relieving three dimensional growth. However, in the actual structure, which requires the deposition of $In_{0.80}Ga_{0.2}As$ on top of the InAs layer, only 4 nm could be implemented, because of the large interface and surface free energies of InAs which caused premature three dimensional growth. Using this structure, they obtained the highest room temperature mobility yet reported for an InP-based pseudomorphic structure of 18,300 cm²/Vsec, with a two dimensional electron gas (2DEG) concentrations of $1.9x10^{12}/cm^2$.

Epi-based MESFETs

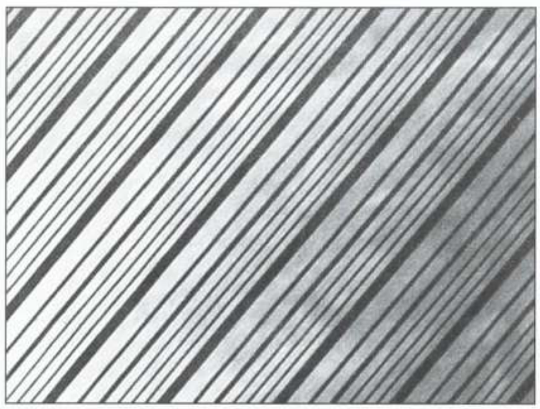
The MESFET is the workhorse of the III-V industry, for both the implementation of digital logic as well as RF wireless applications. GaAs IC manufacturers such as TriQuint, Vitesse and Anadigics using an ion-implanted process to produce both enhancement and depletion mode devices. One of the best ways to improve FET performance is to shorten gate length (currently at the 0.5 µm level) while taking care not to introduce short channel effects which can degrade performance. Short channel effects in MESFETs can be minimized by using a thin active layer with high carrier concentration. Unfortunately, when this thin active layer is formed by ion implantation, both the high doping level as well as the implant's gaussian profile can decrease the Schottky barrier height of the gate and lead to decreased gate breakdown. K. Inoue, S. Sugitani and coworkers at NTT LSI Laboratories [Kanagawa, Japan], have proposed the use of a InGaP/InGaAs/GaAs-based Heterostructure MESFET (HMESFET) in order to lessen short channel effects for MESFETs with gate lengths of 0.1 µm. The typical Si ion implanted GaAs region in a conventional GaAs MESFET is replaced by an MOCVD-grown 120 Å $In_xGa_{1-x}As$ (x = 0.2) channel layer which is doped at $5x10^{18}$ cm^{-3}. This epi-based InGaAs channel layer exhibits a higher carrier concentration, higher electron velocity and better electron confinement than is possible with a GaAs channel. A composite InGaP/GaAs barrier layer (thickness of 100 to 200 Å in which transconductance is traded off against gate-drain breakdown voltage for increased barrier layer thickness) is placed above the InGaAs channel. This composite approach is used in order to increase barrier height and enhance breakdown voltage to the WSiN Schottky gate. Oblique angle ion implantation is used to form a lightly doped drain (LDD) structure to further reduce short channel effects. The NTT researchers chose to use a process-friendly non-recessed gate approach in the implementation of the HMESFET. A gate recess is normally used to improve breakdown characteristics, but is not necessary in this case, due to the improved breakdown behavior of their InGaP/GaAs composite barrier layer. An HMESFET using a 150 Å InGaP/GaAs Schottky barrier, exhibited a very high f_{max} of 167 GHz, a gain of 14.4 dB at 10 GHz, and a large source-drain breakdown voltage of 9.4 V and a large gate-drain breakdown voltage of 8.0 V.

Quantum Cascade Lasers

Narrow bandgap materials such as antimonides are usually used to fabricate emitters in the infrared (IR) regime. See *CS* 1 (2) p. 12. However, a completely different approach to achieving long wavelength lasers has recently been demonstrated - one which does not rely on the bandgap of the material, but on the quantum jumps of electrons between discrete conduction band energy levels within quantum wells. This approach has been implemented in the Quantum Cascade Laser, developed by F. Capasso, C. Sirtori, J. Faist and coworkers at AT&T Bell Laboratories [Murray Hill, NJ]. This structure has stringent growth requirements, requiring sub-nm control over structures which are repeated many times. Although the laser was originally designed to operate based on the transitions between states in neighboring wells in order to facilitate population inversion, the current approach is focused on enabling electrons to make a vertical radiative transition in the same well. The current quantum cascade laser is based on a 25 stage AlInAs/GaInAs structure grown by MBE and lattice matched to an InP substrate. Each stage consists of a graded gap n-type injection layer and a three coupled-well active region, cladded by AlInAs waveguiding layers. Each of the 25 active regions comprise two QWs of thickness 8.2 nm and 6.1 nm, separated by 1.5 nm thick AlInAs barriers. Electrons tunneling into the next injector through a 2.1 nm-thick AlInAs barrier encounter in sequence 4.5 nm, 4.0 nm, 3.8 nm and 3.4 nm QWs, separated by three 1.0 nm barriers, respectively. Electrons in the ground-state of the injectors tunnel into of the adjacent active region through a 4.7 nm-thick injector barrier. Because the energy levels within the QWs are established both by well and barrier widths, precise control of these widths are required and all 25 active regions must maintain the same tight structure tolerances in order for the entire structure to lase. According to C. Sirtori "we are now able to get lasing up to wavelengths of 8.6 μm with cw operation at 110 K, and at temperatures as high as 260 K under pulsed conditions." This unipolar laser approach, which is only made possible by the precise control inherent in MBE, has opened up a new approach to laser diode implementation, and has established a likely competitor to Sb-based IR lasers.

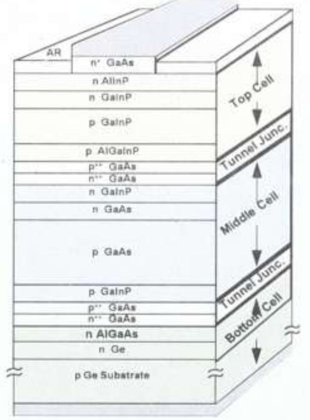
MOCVD-Based Triple Junction Solar Cells

A solar cell is little more than a p-n junction diode. Entering photons which have energy greater than the bandgap of the material form electron-hole pairs, which are collected at the diode's contacts, thereby generating current. The principal application for III-V based solar cells is for space based operation, due to their excellent efficiency/weight ratio (superior to Si-based solar cells). This is an extremely important consideration, since a significant cost of the satellite is in placing it in orbit, and this cost is directly proportional to its weight. By using more than one-type of III-V material within a solar cell, different bandgaps can be obtained, which in turn can convert a larger proportion of incoming light into electron hole pairs - each bandgap converting a specific region of the spectrum. P.K. Chiang and coworkers at Spectrolab Inc. [Sylmar, CA] have used this multijunction approach, in which three different p-n junctions are connected in series through low resistance tunneling junctions. GaInP/GaAs/Ge triple junction solar cells are grown lattice matched to 4 inch Ge substrates by MOCVD in multiwafer reactors. MOCVD is the technique of choice for this application, due to its large throughput, as well as its ability to produce abrupt heterointerfaces. The three p-n junctions used in this cell consist of GaInP (E_g = 1.80 eV), GaAs (E_g = 1.424 eV) and Ge (E_g = 0.66 eV). The structure is illustrated in Figure 7. These cells are now being fabricated, and are projected to have an efficiency of 26.5%, an increase of 2.3% over Spectrolab's production double junction cell which does not have the lower Ge-based p-n junction.



AT&T Bell Laboratories

Figure 6. TEM of several periods of the active region/injector of quantum cascade laser. The well material (GaInAs) is represented in white, while the barrier materials (AlInAs) is represented in dark.



Spectrolab Inc.

Figure 7. Schematic of Spectrolab's triple junction solar cell grown by MOCVD. The three junctioned cell (GaInP/GaAs/Ge) has a projected efficiency of 26.5%.

Conclusion

Much of the progress in silicon device performance has been achieved through reductions in device geometetries. Compound semiconductors have different intrinsic strengths, including easily-obtained heterointerfaces and numerous opportunities for band-gap engineering. (See Tutorial, page 37.) The developments described above are all examples of ways to capitalize on these opportunities. Somewhere between 15-25% of the III-V microelectronic products and all of the optoelectronic products now in production are based on epitaxial structures. While there is undoubtedly a great deal of opportunity remaining for ion-implanted GaAs and InP, epi's "market share" is predicted to increase more quickly as the overall market for GaAs expands - meaning that epi will be gaining a larger piece of a larger pie. There is a great deal of evidence which demonstrates the rapid maturation of the epi-related segment of the industry. For example, see our story on the merchant epi vendors on page 31. The proliferation of advanced, production oriented reactors is also a good sign - see page 34. These developments are all important because, although it is difficult to say whether any of these seven examples will be guaranteed successes, it does seem obvious that in the long run, the majority of compound semiconductor devices will be improved by further extending and refining epitaxial growth.

Epi Economics

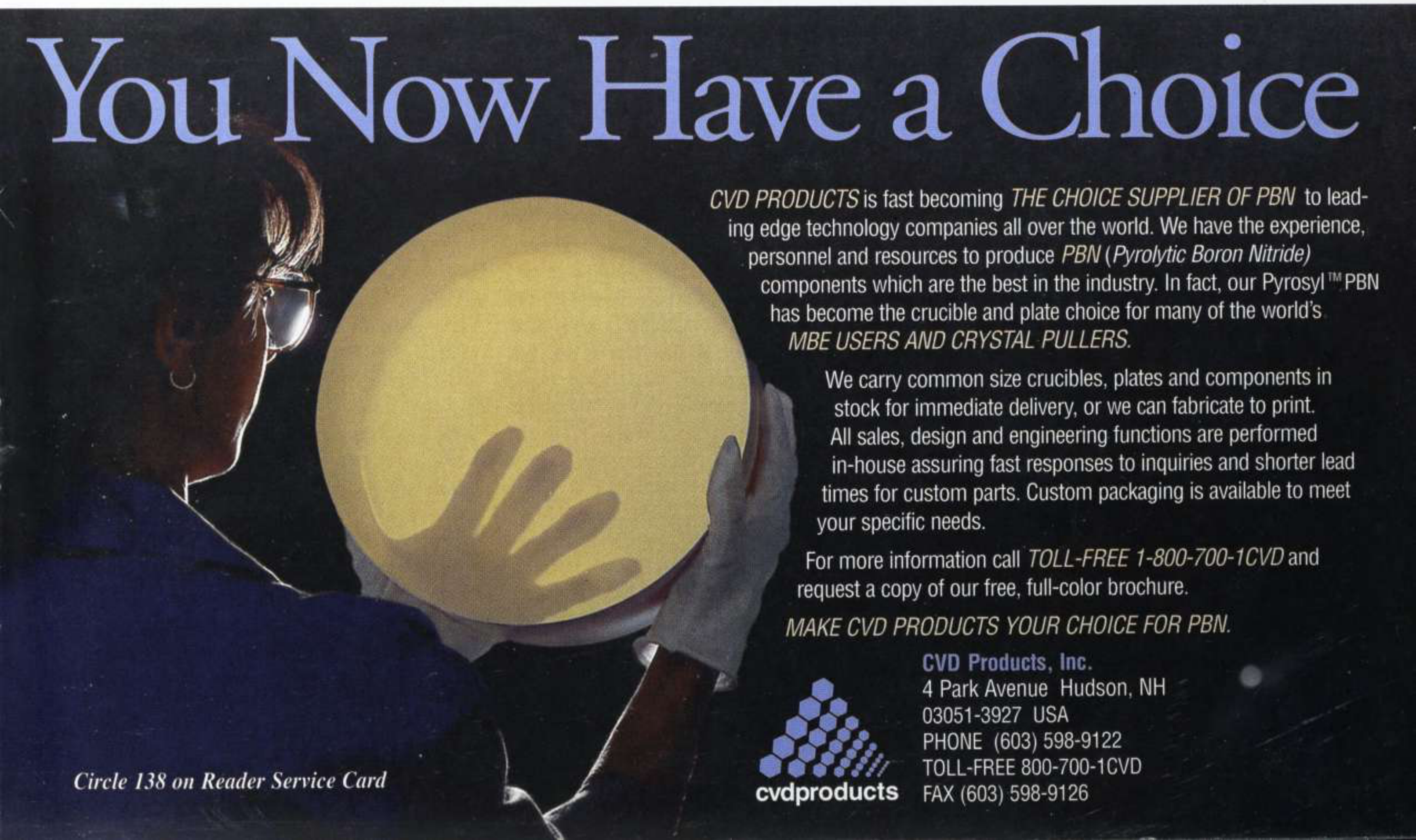
How do companies decide whether they should grow their own epitaxial wafers or buy them from a merchant vendor?

MARIE MEYER

"Outsourcing" is a popular piece of business jargon in the US, along with "rightsizing" (which replaces the newly unfashionable "downsizing") and "core competency". Proper usage is as follows: as companies rightsize to allow greater focus on their profit-making core competencies, they outsource non-core tasks to specialist firms.

The most obvious outsourcing destinations in the compound semiconductor industry are the fifteen or so merchant epi vendors (listed in our directory on page 34). Most of these companies have been around since the days when their business was simply known as "subcontracting". Despite the fact that epi is finding its way into an increasing number of high volume applications, there are few cases where it is mature enough to be available as an "off-the-shelf" commodity, as if it were simply a very sophisticated substrate. One major exception are LEDs in the IR and red to yellow-green region, which are available in wafer or even chip form from a handful of companies. In this case the epi vendor specifies everything, from materials and structures to key characteristics of device performance such as wavelength, luminous intensity, and forward voltage. In most cases, however, the epi requirements are not so clearly defined, and therefore custom or semi-custom epi, requiring the customer's input, is the norm in the merchant epi business.

When they started their ventures, the epi vendors assumed the task of demonstrating that advanced epitaxial growth is not the "black art" that it then seemed to be. They made epi growth their "core competency" and in the process proved that it could be done on a production basis in a reproducible and cost effective manner. But now that the demonstration has been made and the demand for epi is growing, how do companies decide whether to outsource their requirements for epi wafers or set up their own program and produce them internally?

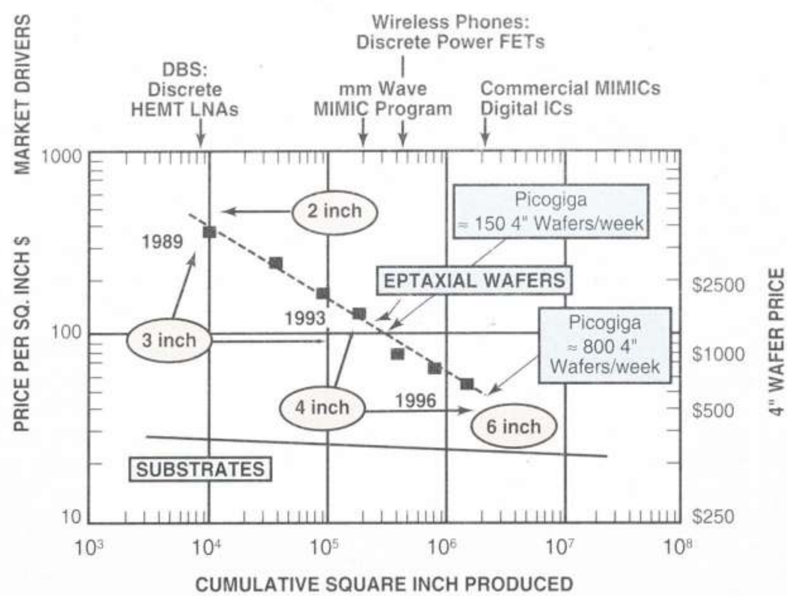


In or Out, Haves and Have-Nots

There are two models which explain how companies decide what to outsource. The first is almost totally cost driven - the company seeks immediate benefit from reduction of the cost of goods sold and overheads. This is considered the typical American model. The second model, pioneered in Japan, is more strategic: it looks at outsourcing as part of an overall long-term strategy for increasing efficiency of production or overall quality.

In the epi business, there are basically two kinds of customers: those who have internal epi capabilities, and those who don't. Somewhere between one-third and one-half of the merchant epi business is built on these "have-nots". It is easy to see why. Imagine a company that wants to make their first foray into the laser or LED or GaAs MMIC area, but they have no prior involvement with compound semiconductors. They could easily find outsourcing their epi requirements attractive using either the cost or the strategic model. Starting from scratch to establish an epi program requires a not-insubstantial investment in capital equipment (epi reactors, characterization equipment), increased overhead costs (clean-rooms, fixed labor), and operating expenses (materials, supplies, production labor). All of this can also create managerial distractions and drain non-financial resources, leading to a decrease in focus. Therefore the company may decide that it is more advantageous to leave the epi to the experts, while they concentrate on their own core competency. They also gain the additional strategic advantage of hedging their bet: if some other material system or Si, SiGe, or SOI becomes more competitive for their application, they can easily switch to the competing technology.

Of course it isn't every day that a new company decides to get into the laser or MMIC business, and most of the companies that are involved in the compound semiconductor field already have some internal epi capability. For them the analysis is slightly different, given that at least some of the initial investment has already been made. In this case the economic justification is more difficult to make, and strategic considerations become more important.



Picogiga's analysis of pricing trends for MBE-grown epi wafers for microelectronics, showing that as their production has increased from around 25 3" wafers per week in 1989 to their current output of 200 4" wafers per week, the price per sq. inch has nearly halved, dropping from $130 to $75. In real terms, this means that whereas a 3" epi wafer cost more than $2,750 in 1989, it had dropped to around $1,000 by 1993. When Picogiga began offering 4" wafers in 1994 they were initially priced at more than $1,750; they too have now dropped to the $1,000 range. These trends suggest that 6" epi wafers, when they become available, will likely be priced at around $1,500.

The graph also shows that substrate prices, in $ per sq. in., have remained relatively flat in comparison to the steep drop in epi prices. Given that the substrate is the major component of the materials cost for an epi layer, this graphic demonstrates that the drop in costs (and therefore prices) is due to more efficient allocation of resources, such as labor, overhead, and capital equipment, as production volumes increase.

Second Sourcing

Companies which have their own growth capability are usually the first to complain about the cost of epiwafers from the merchant vendors. The merchant vendors, especially the smaller companies, have no place to "hide" any of their costs; every penny spent goes into the cost of the wafer. In comparison, a large manufacturer, though they almost certainly have higher overheads and labor costs, can spread their costs around. They may also benefit from older equipment which is already fully depreciated, whereas the epi vendors, if they want to stay competitive, are compelled to keep their production equipment at the state of the art. There is also the important matter of the vendor's profit margin - they won't be interested in the business for very long if they can't make any money at it. As a result, it is not uncommon to find companies that think epi should cost around 2x the price of a substrate, while the merchant vendors want a price around 4x. Fortunately, the market prices for epi wafers are decreasing as volume increases (see box). The key to further improvement? More outsourcing by large volume customers. In other words, it is a classic chicken-and-egg conundrum: customers won't buy more because the price is too high, and the price is too high because customers won't buy more.

Fortunately the cost issues, though important, are not generally considered prohibitive. There are, however, other factors which lead some companies to favor internal production. One is the belief that your supply is more secure if it is internalized. Between them Picogiga and QED command more than 75% of the world's market for MBE-grown merchant epi wafers, but they are both small companies, with 25-30 employees each. As QED's president Tom Hierl puts it, "despite our good track record, our size simply makes some of the big companies nervous". Of course, no single supply is every completely secure, whether it is internal or not. Natural disasters, fires, or equipment malfunctions can happen anywhere. Nevertheless, many of the large companies feel more comfortable their supply comes from under their own roof. There are also historical factors at work. Merchant epi is a relatively new phenomenon, and more time may be required to increase acceptance of the concept.

So do the epi vendors see the manufacturers of multiwafer MBE and MOVPE systems as their competitors? Not at all, it seems. There is general consensus that what is good for epi in general is good for the merchant epi business as well. Although many companies are building up their internal production capacity, the epi vendors are optimistic that these actions will likely increase the overall demand for epi across the board. It can lead to new business from old customers and it may also help to pull new prospective customers into the field. The degree of investment in, and therefore the level of commitment to, epi is seen as particularly important in the microelectronics field where there is competition from other technologies like implanted GaAs, Si and SOI - something that doesn't occur in the optoelectronics field. Both Picogiga and QED are aware that more companies are building up their captive capability, but they report that demand for merchant epi is growing at an even faster rate, and both companies are expanding their production capacity accordingly. According to Picogiga's Linh Nuyen, "In the long run, I think time is on the side of the merchant vendors. I am not disturbed by the fact that there is internal epi production. These companies decide to build up their internal resources for internal reasons, not because we somehow disappointed them. And it helps to keep us sharp - it reminds us that we always have to strive to be better at high volume epi growth than our customers are".

Drew Nelson of Epitaxial Products International agrees: "Good competition, in whatever form it might take, is good for everyone in the business. It helps to create a more mature and robust infrastructure, and it forces the participants to focus on the key issues of internal cost and quality." He also points out that it is possible for a merchant epi vendor to be a second source in terms of capability and technology as well as supply. For example, a company that is busy with its own GaAs program might prefer to outsource new InP-based requirements, rather than try to modify their own resources to accommodate both. Similarly, merchant vendors can supply growth techniques or wafer sizes that aren't available internally. And, although epi wafers are not yet a commodity, certain epi vendors have developed areas of expertise that allow them to contribute to the quality of the overall process. For example, Picogiga and QED specialize in HEMTs, EPI focuses on optoelectronics, and Kopin and Epitronics have created niches for HBT wafers. And all, of course, consider themselves authoritative on epi growth in general, which allows them to capitalize on skills and expertise which complements the customer's own internal capabilities.

Core Competency

A major factor in the strategic analysis model is the company's attitude toward the epi it uses. Epi is an enabling technology in many areas, especially in the optoelectronics field (whereas processing is often the important factor in microelectronics). A good example are the new high-brightness LEDs that have recently been introduced by Hewlett-Packard and others. (See page 22.) The longwavelength LED seems to be the most humble of compound semiconductor devices. In fact, they were referred to earlier as commodities. Nevertheless, recent breakthroughs, driven by epi, have added exciting new market opportunities. As Jeff Miller of Hewlett-Packard puts it, "epi is the major 'value-added' contribution that we can make to many of Hewlett-Packard's products. Here in Silicon Valley, a very expensive place to do business, we cannot compete economically on the routine steps in the manufacturing process. But we can attract well-educated, talented people to design devices and run epi reactors. A lot of our formal intellectual property, such as patents, lies in the epi. So, too, does a lot of 'informal' intellectual input, like skill, experience, and general know how." It is not surprising to find that Hewlett-Packard has one the largest internal epi effort in the US, and that it does rela-

tively little outsourcing.

Hewlett-Packard may be somewhat unique in extending their protective umbrella over both R&D and most of their production requirements. It is more common to see companies who are just as zealous about epi-for-research, but are willing to consider all the options when it comes to epi-for-production. In the end, it seems likely that there will always be some companies who want to be as vertically integrated as possible, and there will also be others who perfer the dynamics of the open market. The merchant epi vendors have already played an important role in the compound semiconductor industry by proving the maturity of advanced epi. They currently occupy an important, and growing, niche in the industry's supply chain. And the future holds several interesting prospects for them, especially if more products acquire a commodity status. And for those of you out there who still grumble that epi is too expensive: buy more, and it will get cheaper. They promise.

VG Semicon Reports Sale of 16th Multi-Wafer MBE System

VG Semicon has announced that 1995 was a record year for sales and shipments, due to increased demand for production MBE equipment. Six V100 Systems, capable of simultaneous growth on three 4" wafers, were shipped in 1995, and orders were received for six more for delivery in 1996. This raises the total number of production MBE systems sold by Semicon to 16. The company also reports that the applications for MBE-grown material appear to be expanding beyond the traditional base of HEMTs and FETs: three orders were recently received for multi-wafer systems to be used to fabricate HBTs, visible lasers, and solar cells.

Aixtron and Emcore Report Record Years

Aixtron reports that 1995 was the best year in their 12 year history, with record sales and shipments of MOVPE systems. Total revenues were up 40% over the previous year, with. More than 30 reactors were delivered during 1995, and Aixtron will carry a $25 million backlog with them into 1996.

Emcore also reports that 1995 was a record year for MOCVD system sales and shipments, with sales having increased 100% over the previous year.

QED Expands

Quantum Epitaxial Designs (QED) reports the expansion of its epiwafer manufacturing capability with the acquisition of additional epi growth capability and facilities improvements. According to QED president Tom Hierl, "With the acceptance of GaAs devices for wireless communications applications we have experienced a significant growth in our business." In December QED accepted its second multiwafer MBE system, and placed an order for a third such system. And, beginning in January, QED will expand its manufacturing facility by 50% to accommodate increasing demand for merchant epiwafers.

Directory of Merchant Epi Wafer Vendors

The following is a brief overview of 15 merchant vendors of III-V epitaxial wafers. To request more information, use the Reader Service Card provided on page 30.

Company	Description	Reader Reply Card Number
Acrotec Semiconductor Materials Japan Energy Corporation 10-1, Toranomon 2-chome Minato-ku, Tokyo 105 Japan N. Okada TEL [81] 3 5573 6592 FAX [81] 3 5573 6779	Offers InP and GaAs (semi-insulating) epitaxial wafers grown by MOCVD and MBE.	171
EMF Limited Winfor Church Road Wentworth Ely, Cambridge CB6 3QE UK Jim Dixon TEL [44] 1223 364 080 FAX [44] 1353 778 221	Offers epiwafers in both GaAs/AlGaAs and InP, including high power lasers from visible to long wavelengths, VCSELs, PIN Detectors, LEDs, Photocathodes and Solar Cells. Can produce custom epiwafers to individual customer specifications subject to confidentiality agreements and can also help customers develop their own independent epi capability.	173
Epitaxial Products International Cypress Drive Pascall Close St. Mellons, Cardiff CF3 0EG UK Drew Nelson TEL [44] 1222 794422 FAX [44] 1222 779929 E mail: 100632.2041@compuserve.com	Very large range of custom III-V epitaxial material structures for use in OptoElectronic, Optical and Electronic applications. These include Quantum Well, DFB, Strained Quantum Well, VCSEL, and visible lasers, HB-LEDs, and FET, HBT and PHEMT structures. Comprehensive array of characterization equipment used to analyze all the material structures shipped to customers. ISO 9002 certified.	175
Epitronics Corporation 21002 North 19th Ave., Suite 5 Phoenix, AZ 85027 USA Robert Adams TEL [1] 602 581 3663 FAX [1] 602 581 3415	MOCVD grown epitaxial films for microwave and optoelectronic applications. Epitaxial wafers used in the fabrication of GaAlAs emitter and InGaP emitter HBT structures are standard products. New products include InGaP PHEMT structures. Also, thick films (> 50 µm) of high purity LP-VPE GaAs are available for applications such as particle detectors and rectifiers.	177
Furukawa Electric Technologies, Inc. 900 Lafayette Street, Suite 401 Santa Clara, CA 95050 USA Ranjit Mand TEL [1] 408 248 4884 FAX [1] 408 248 8815	MOVPE grown AlGaAs, InGaAs, GaAs, InP and InGaAsP, including MESFET, HEMT, Pseudomorphic HEMT and Carbon-doped HBTs.	179
Hitachi Cable, Ltd. Chiyoda Bldg., 2-1-2, Marunouchi Chiyoda-Ku, Tokyo 100 Japan Akihiko Kimura TEL [81] 3 5252 3465 FAX [81] 3 3213 0402 akihiko_kimura@cc.hitachi-cable.co.jp	3" and 4" MOCVD wafers for HEMTs, pseudomorphic HEMTs, low noise FETs, power FETs, and power HEMTs and HBTs. MOCVD wafers with good uniformity of electrical characteristics and epitaxial layer thickness, excellent sharpness of hetero-interface and excellent reproducibility produced using high throughput MOCVD machines. ISO 9001 certified.	181
Kopin Corporation 695 Myles Standish Blvd. Taunton, MA 02339 USA Matthew Micci TEL [1] 508 824 6696 FAX [1] 508 824 6958 E mail: mmicci@kopin.com	Develops and manufactures epitaxial wafer materials for advanced semiconductor device and circuit applications. Major supplier of Heterojunction Bipolar Transistor (HBT) wafer materials. Custom structures are developed using production OMCVD reactors and technique. This approach ensures the development and supply of manufacturable epitaxial structures for client applications.	183
MBE Technology Pte Ltd. 14 Science Park Drive #04-03 Maxwell Singapore Science Park Singapore 118226 Wang Zhong TEL [65] 773 5211 FAX [65] 773 5068 E mail: mbetech@pacific.net.sg	Produces III-V semiconductor epiwafers for manufacture of microwave and optoelectronic devices and ICs. Layer structures include MESFET, HEMT, PHEMT, HBT, LM-HEMT and QW laser. Epilayers are strictly dedicated to customer's specifications. Up to 4" wafers available in multiwafer MBE system.	185

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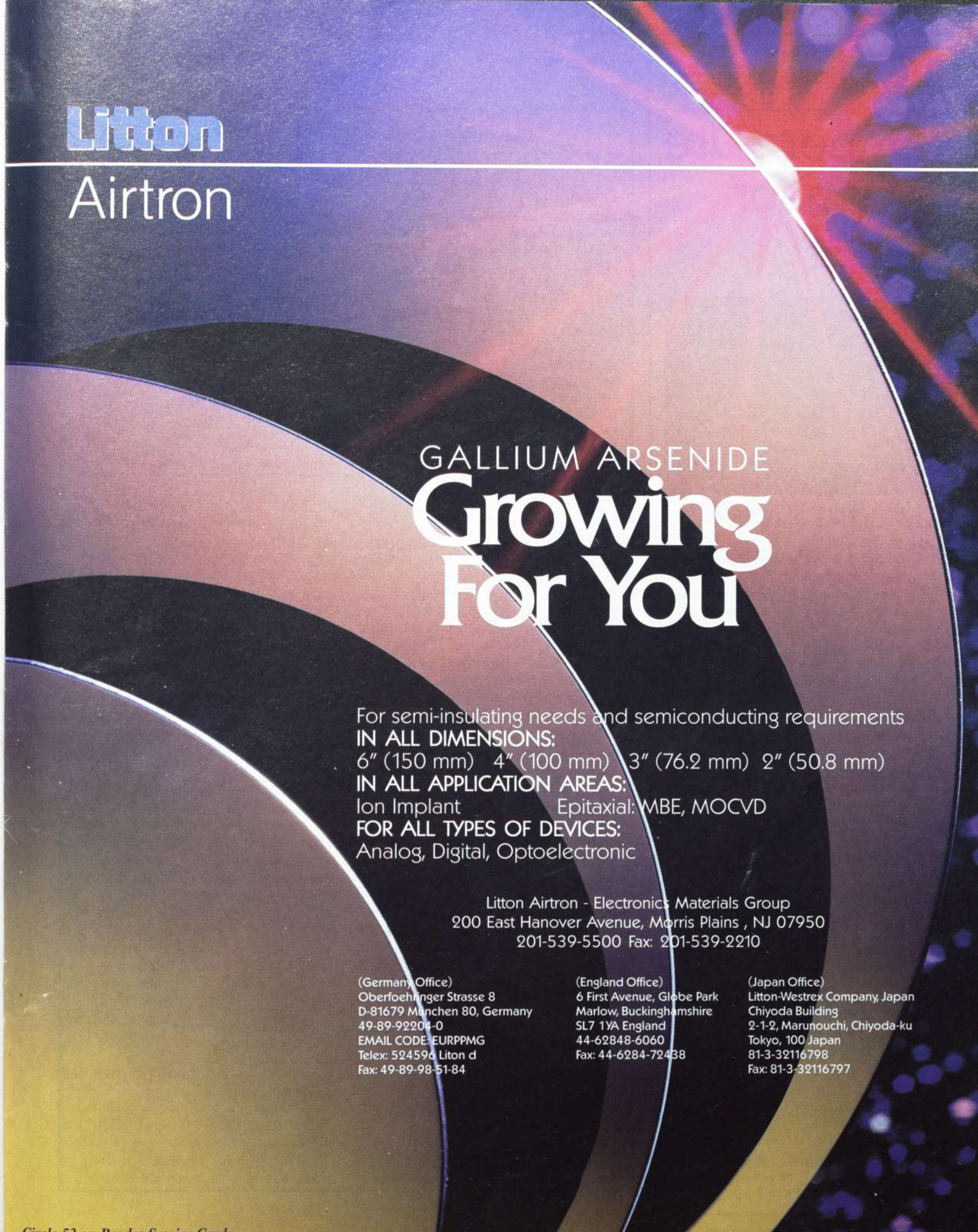
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Airtron
GALLIUM ARSENIDE
Growing For You
For semi-insulating needs and semiconducting requirements
IN ALL DIMENSIONS:
6″ (150 mm) 4″ (100 mm) 3″ (76.2 mm) 2″ (50.8 mm)
IN ALL APPLICATION AREAS:
Ion Implant Epitaxial: MBE, MOCVD
FOR ALL TYPES OF DEVICES:
Analog, Digital, Optoelectronic
Litton Airtron - Electronics Materials Group
200 East Hanover Avenue, Morris Plains , NJ 07950
201-539-5500 Fax: 201-539-2210
(Germany Office)
Oberfoehringer Strasse 8
D-81679 München 80, Germany
49-89-92204-0
EMAIL CODE: EURPPMG
Telex: 524596 Liton d
Fax: 49-89-98-51-84
(England Office)
6 First Avenue, Globe Park
Marlow, Buckinghamshire
SL7 1YA England
44-62848-6060
Fax: 44-6284-72438
(Japan Office)
Litton-Westrex Company, Japan
Chiyoda Building
2-1-2, Marunouchi, Chiyoda-ku
Tokyo, 100 Japan
81-3-32116798
Fax: 81-3-32116797

Directory of Merchant Epi Wafer Vendors (cont.)

Company	Description	Reader Reply Card Number
Mitsubishi Cable America, Inc. 520 Madison Avenue New York, NY 10022 USA Micheal Scott TEL [1] 212 888 2270 FAX [1] 212 888 2276	LPE AlGaAs wafers and dice for red and IR emitters, MOCVD AlInGaP wafers for amber, green, orange, and red emitters. Phototransistors, photodiodes, and IC chips also available, as well as packaging and SMD devices and complete and custom special design services.	187
Picogiga 5, rue de la Reunion ZA de Courtaboeuf F-91940 Les Ulis France Linh T. Nuyen TEL [33] 1 6907 1950 FAX [33] 1 6907 3208	Specializes in MBE-grown GaAs, AlGaAs and InGaAs epiwafers for FET, H-FET, HEMT, and P-HEMT, single and double heterojunction. Also HEMTs and P-HEMTs on InP. Multiple 3" and 4" wafer capability, can produce up to 1500 4" wafers per month.	189
Quantum Epitaxial Designs 119 Technology Drive Bethlehem, PA 18015 USA Will Weisebecker TEL [1] 610 861 6930 FAX [1] 610 861 5273 E mail: qed@fast.net	Merchant supplier of MBE epitaxial wafers (3", 4" and 6") consisting of GaAs, AlGaAs and InGaAs (on GaAs and InP substrates) for MESFET, HEMT, PHEMT, lattice-matched lasers (edge and surface emitting) and quantum well infrared detectors (QWIPs). In 1996 QED will double the size of its manufacturing facility and add a third multi-wafer MBE production system.	191
Showa Denko America, Inc. 951 Mariners Island Blvd., Suite 680 San Mateo, CA 94404 USA Bettye Garrett TEL [1] 415 345 1338 FAX [1] 415 345 5403 E mail: 74211.1145@compuserve.com	US Distributor of Showa Denko (Japan) LPE-grown GaP epitaxial wafers for LEDs and MOCVD-grown epi on InP substrates for PIN diodes and detectors. GaP and InP substrates and ion-implanted wafers also available.	193
Spire Corporation One Patriots Park Bedford, MA 01730-2396 USA Kurt J. Linden TEL [1] 617 275 6000 FAX [1] 617 275 7470 e mail: spire.corp@channel1.com	Custom MOCVD-grown III-V compound semiconductor epitaxial structures using binary, ternary, and quaternary compounds for HBTs, QW lasers, solar cells, and experimental structures. Also available: devices based on MOCVD materials, including high power diode laser bars (pulsed and CW), solar cells, laser power converters, and thermophotovoltaic converters.	195
Sumitomo Electric USA Park Avenue Tower 65 East 55th Street (16th Floor) New York, NY 10022-3219 USA Thomas Miehe TEL [1] 212 308 6444 FAX [1] 212 308 6575	Offers LPE-grown GaAs wafers for IR applications; MBE-grown wafers for GaAs FETs, HEMTs and HIGFET as well as InP HEMTs; VPE-grown wafers for GaAs FETs and Diodes, and InP Detectors; also OMVPE wafers for InP-based laser structures.	197
TLC Precision Wafer Technology, Inc. 661 5th Avenue North Suite #160 Minneapolis, MN 55405 USA Timothy L. Childs TEL [1] 612 341 2795 FAX [1] 612 341 2799 E mail: nohav001@gold.tc.umn.edu	Specializes in advanced custom GaAs and InP epi wafers and custom circuit design. Wafers are manufactured for digital, analog, MMIC and photonic devices and circuits for use in advanced avionics, communications, computers, and other electronic and optical systems. Epi wafer production is complemented with expertise in advanced microwave/mm-wave, digital and photonic monolithic ICs.	199

Emcore
Aixtron ?

Multilayer Heterostructures and Bandgap Engineering

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AUSTIN, TEXAS

One of the most exciting and useful developments in modern semiconductor electronics is the capability of engineering band structure, quantum phenomena, optical properties, and other useful effects by the growth of multilayer heterostructures. With the advent of advanced semiconductor growth techniques such as molecular beam epitaxy (MBE) and organometallic chemical vapor deposition (OMCVD), much of modern III-V compound semiconductor device development now involves quite complex and precise multi-heterojunction structures. Similarly, the use of MBE and various CVD techniques have allowed such multilayer structures to be grown in the SiGe alloy system as well. The availability of high-quality multilayer heterostructures has led to new phenomena having widespread applications such as two-dimensional transport effects, quantum wells, modulation doping, delta doping, carrier and photon confinement, and many more. Recent developments in distributed Bragg reflectors (DBRs) have been incorporated into this collection of capabilities, allowing the introduction of microcavities in both light emitters and detectors. As a result of these dramatic developments, the future for device invention and development is extremely fertile, combining electronic and photonic effects in new ways for novel applications.

Bandgap Engineering

Nothing pleases device engineers more than finding a new way to stretch and modify what nature gives us, to make a useful device. An excellent example of this engineering creativity is the manipulation of the band structures of semiconductors. An early use of what is now known as "bandgap engineering" was the growth of III-V ternary alloys to do wavelength selection for LEDs and lasers. Since GaAs has a direct bandgap in the infrared, and GaP has an indirect bandgap in the green, it makes sense that the alloy GaAsP might have some composition with a direct bandgap capable of emitting photons in the visible range. In fact, $GaAs_{0.6}P_{0.4}$ has such a direct bandgap in the red, and this composition of the alloy has provided many red LEDs over the years. The first visible semiconductor laser was made by Nick Holonyak, Jr. in 1963 at General Electric using such an alloy. Later, as liquid-phase epitaxy became available, alloys in the AlGaAs system were grown lattice-matched to GaAs, and the race was on for using the heterojunction for a wide variety of devices, particularly semiconductor lasers. The development of MBE in the 70's by Al Cho at Bell Labs ushered in a new era in which virtually any composition of alloy in the InGaAlAs system could be grown with extreme precision. In the past decade or so, many more materials have been added to the list, including SiGe alloys grown on Si substrates, and the III-Vs have been extended to the phosphides and nitrides. II-VI compounds and alloys have been used successfully to make blue-green lasers. All of these uses of ternary and quaternary alloys are "bandgap engineering" in the sense that the device designer chooses a composition (and therefore a bandstructure) to do a particular job. Further "messing with Mother Nature" can be done by the appropriate choice of heterostructures having different band offsets, composition grading to achieve built-in fields, and modification of band structures by introducing strain. The latter effect is relatively new to the engineer's bag of tricks (at least its intentional use is!). When a lattice-mismatched layer is grown on a substrate, the epitaxial layer tries to conform to the crystal size of the substrate, thereby introducing strain. If the layer is thin enough (generally a few hundred Angstroms), this strain can be maintained without relaxation into crystal dislocations. As a result of this strain, the bandstructure of the layer is altered in interesting and useful ways.

Building Blocks for New Devices

Carrier confinement. A useful feature of a heterojunction between dissimilar semiconductors is the band discontinuity resulting from alignment of the different band structures. The resulting junction often includes a step and a notch in the valence and conduction bands. In the example of Fig. 1, electrons can be trapped in the conduction band notch, confining the carriers in a two-dimensional electron gas which has very interesting properties. The figure shows a heterojunction between a heavily n-type AlGaAs layer and a lightly doped GaAs layer. The discontinuity in the conduction band allows electrons to spill over from the AlGaAs into the GaAs, where they become trapped in the almost-triangular well of the notch in the GaAs conduction band. If this type of junction is incorporated in a field-effect transistor in which the 2-D gas of electrons forms the conducting channel, extremely high electron mobilities can be achieved (particularly at low temperatures where lattice scattering is minimal). This is the basic notion of the high-electron mobility transistor (HEMT).

Another feature of the electron confinement shown in Fig. 1 is the development of discrete states for the electrons, as is typical of quantum wells.

Semiconductor quantum wells (QWs) have been a rich source of insight into semiconductor physics, and the control of layer thickness with monolayer accuracy has led to novel structures for electronic and photonic device applications. The electron transition giving rise to photons in a quantum well is governed by the fact that only discrete energy states are allowed for electrons and holes in the well. Not only do quantum wells provide transition energies different from the bulk material, but also population inversion is achieved at a lower threshold current in a QW laser.

Confinement of carriers can also be achieved by doping the crystal on a single atomic layer (or a few). This is called delta (δ) doping. Even more substantial confinement can be achieved in δ-doped quantum wells. Carrier confinement to small regions of space can lead to a number of interesting low-dimensional effects including those related to quantum wires and quantum boxes.

Superlattices. From the earliest days of MBE, there has been an interest in artificial periodicities available by growth of multilayer heterostructures. Both compositional and doping periodicities can lead to new "miniband" or "subband" conduction of electrons and holes. This process can be used to create a superlattice quantum well (SLQW) allowing higher-energy transitions which can be varied over a few hundred meV using different layer thicknesses in the SLQWs. It is also possible to use aperiodic layer thicknesses, including random-period superlattices, to further tailor the properties of the quantum wells.

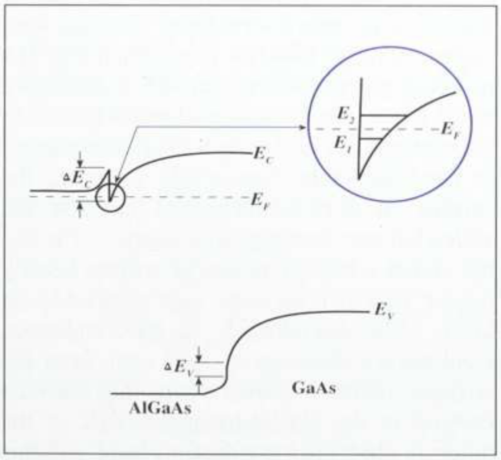

Figure 1. A heterojunction between heavily n-type AlGaAs and lightly doped GaAs, illustrating the potential well for electrons formed in the GaAs conduction band. If this well is sufficiently thin, discrete states are formed as shown in the inset. From B.G. Streetman, Solid State Electronic Devices, 4th edition (Prentice Hall, 1995).

Photonic Devices

Photonics, a blending of optics and electronics, has emerged as one of the world's most rapidly developing technologies. It is clear that photonics will become a core technology for telecommunications, information processing, optical storage and display, and sensors. Photonic devices are used to generate, modulate, switch, and detect optical signals. Among the crucial optoelectronic components for photonic systems are semiconductor lasers, photodetectors, guided-wave devices, and optoelectronic integrated circuits. Applications in telecommunications and data transmission are already well established, and new applications such as optical interconnects in VLSI systems are aggressively being pursued.

One of the clearest examples of bandgap engineering is the graded index separate confinement heterostructure (GRINSCH) laser, illustrated in Fig. 2. This structure employs a quantum well to confine carriers in the active lasing region, and also uses grading of the alloy composition outside the well to do two things—to cause built-in electric fields which shove electrons into the well region, and to provide optical waveguiding for the laser light, resulting from the graded refractive index.

VCSELs. The vertical-cavity surface-emitting laser has a number of advantages in optoelectronic and optical interconnect systems. The VCSEL incorporates a microcavity with DBRs grown above and below the active region (which generally includes quantum wells). This type of structure represents a minimum volume laser, since the Fabry-Perot cavity length is on the order of the lasing wavelength, and thus it has the greatest potential of any semiconductor laser structure for ultra-low threshold current. VCSELs are now routinely made with thresholds below 100 μA. The device's vertical geometry simplifies coupling into a fiber, since light is emitted normal to the epitaxial surface, and the planar geometry is also compatible with 2-dimensional phased array operation. From a manufacturing standpoint, wafer scale testing of vertical-cavity lasers is a major advantage over the traditional edge emitter, which must be cleaved and mounted for testing.

Resonant cavity photodetectors. In recent years photodetector structures have become more complex in response to more stringent performance demands such as higher bandwidth and lower noise. A major technological breakthrough has occurred recently in the use of DBRs to form a resonant-cavity structure that decouples the quantum efficiency from the transit-time. Traditional photodiodes have suffered from a fundamental tradeoff between responsivity and bandwidth. To achieve high quantum efficiency, a relatively thick absorption layer is required, which in turn requires a longer time to collect the photogenerated carriers. This transit-time limit to the bandwidth can be circumvented in the resonant cavity photodiode. This structure absorbs the photons between two parallel Bragg mirrors in a Fabry-Perot cavity whose length is typically a few wavelengths. These resonant cavity photodiodes are highly wavelength selective and, with additional periodicities in the DBRs, can provide efficient detection at two or more well-defined wavelengths. These wavelength-selective mirrors should have a variety of applications in wavelength division multiplexing.

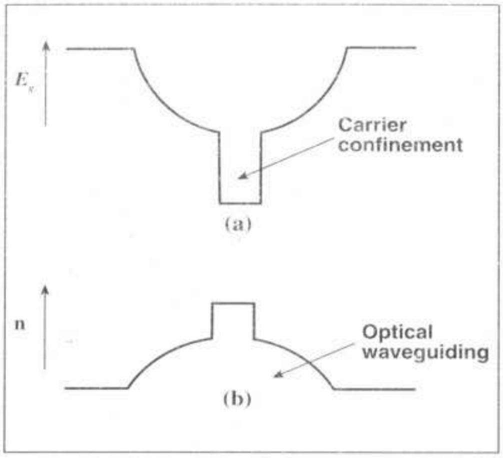

Figure 2. An example of bandgap engineering to provide separate confinement of carriers and waveguiding in the GRINSCH laser. By varying the composition of an alloy such as AlGaAs, a quantum well is surrounded by a grading in the bandgap (a) which causes built-in electric fields to confine electrons. Grading of the refractive index surrounding the quantum well (b) provides waveguiding of the laser light. From B.G. Streetman, Solid State Electronic Devices, 4th edition (Prentice Hall, 1995).

Conclusions

Clearly the ability to grow multilayer structures with monolayer-scale accuracy has revolutionized device engineering. In both electronic and photonic devices we can now choose and manipulate bandgap and other properties in ways that were unthinkable until recently. Since the need for novel devices will surely continue, and the means for bandgap engineering is readily available, it seems obvious that compound semiconductors and their alloys have a very bright future (at least that's true of the light emitters).

LEOS '95

San Francisco, California
October 30-November 2, 1995

With over 400 talks and 100 sessions, LEOS covers the entire spectrum of laser and electro-optic technologies, including such topics as WDM, fiber amplifiers, molecular spectroscopy, optical memory systems, resonators and saturable absorbers, nonlinear laser dynamics, solid state IR lasers, as well as soft X-ray lasers. However, as in years past, it is semiconductor-based lasers that remain the cornerstone of the LEOS meeting, and it is on the progress and breakthroughs in this area, that this report will focus on.

VCSELs

Of all the semiconductor-based laser work presented at LEOS '95, the largest single group of papers was devoted to vertical cavity surface emitting lasers (VCSELs), which are of great interest because their single longitudinal mode, circularly symmetric optical profile, and surface normal light emission make them suitable for both short haul optical fiber communications systems, and free space optical communication systems. Significant improvements in VCSEL threshold currents and optical confinements as a result of selective oxidation of Al containing layers within the VCSEL structure were reported. K.L. Lear et al of Sandia National Laboratories [Albuquerque, NM] used selective oxidation of AlGaAs to form VCSELs with either two aligned apertures above and below the active region, or with a single effective aperture above the active region, where for large devices, low threshold current densities approaching 800 A/cm^2 were obtained. P.D. Floyd and coworkers at the University of California [Santa Barbara, CA], used the selective oxidation of AlAs to improve the characteristics of 965 nm bottom emitting VCSELs, obtaining thresholds as low as 315 µA with external efficiencies of 27%. G.S. Li et al of Stanford University [Stanford, CA] demonstrated that low turn-on voltages can be obtained without resorting to graded heterointerfaces in the DBR or elaborate doping profiles, and were able to obtain low turn-on voltages of 1.46 V by optimizing p$^+$ GaAs/Au annealing.

It is difficult to fabricate VCESLs from InP (to create 1.55 µm emitters) due to low reflectivity in InP-based DBR mirrors. However, C.L. Chua et al of Cornell University [Ithaca, NY], demonstrated that by combining strain compensated InGaAsP QWs, with wafer-fused GaAs/AlAs DBR mirrors, 1.53 µm pulsed, room temperature operation could be obtained with a threshold current of 10 mA. T. Wipiejewski and coworkers from the University of California [Santa Barbara. CA], showed that besides the highly symmetric circular output which is characteristic of VCSEL operation, a donut-shaped optical output could be achieved by using Cl-RIE-based etching of the top DBR to form a ring structure. Lasers with 10 µm diameter rings exhibited thresholds of 2.4 kA/cm^2. G. Gmachl and coworkers at the Institute for Solid State Electronics [Vienna, Austria], demonstrated that frequency tuning in VCSELs could be obtained by carrier injection into a p-i-n modulator diode that was monolithically integrated in a VCSEL. Y. Zou et al of the Xerox Palo Alto Research Center [Palo Alto, CA] showed that a 4 element VCSEL operating at 850 nm could be fabricated with minimal crosstalk, and that electrical isolation between devices could be as high as 850 kohm for device spacings of only 30 µm. P. Dowd and coworkers from the University of Bath [Bath, United Kingdom], reported on modelocking a VCSEL by placing it in an external cavity, and obtaining 36 ps pulses at a repetition rate of 1.46 GHz.

Visible Semiconductor Lasers

The next generation of optical data systems will be based upon visible AlGaInP laser diodes operating from 630-680 nm. For the read head of an optical storage system, the most important criteria of operation is that of maintaining low noise - measured as relative intensity noise (RIN) - which can be achieved by making the laser diode self-pulsate.

J. Major and coworkers of SDL Inc. [San Jose, CA] described the use of a distributed saturable absorber to achieve self-pulsation. An RIN as low as -137 dB/Hz with output powers as high as 25 mW were obtained using this structure. By using a strain-compensated AlGaInP-based MQW laser diode, Y. Bessho and coworkers of Sanyo Electric [Osaka, Japan], were able to reduce threshold currents to 48 mA using the strain compensated approach (a reduction of 40% as compared to a strained device), while obtaining self-pulsating operation up to 8 mW. Another application for AlGaInP-based laser diodes is extremely high power applications in the areas of solid state laser pumping, printing, and medicine. Using a compressively stained GaInP QW surrounded by AlGaInP waveguiding layers, R.S. Geels and coworkers at SDL Inc. [San Jose, CA] fabricated 1 cm wide monolithic array laser diode bars which produced 140 W output power, while a six-bar stack produced 500 W. These laser diodes exhibited threshold currents densities of 200-300 A/cm^2 and achieved power conversion efficiencies greater than 40%. And progress continues to be made in the area of II-VI-based blue-green laser diodes, with lifetime improvements being reported by P.F. Baude and coworkers of 3M Company [St. Paul, MN]. Laser lifetimes of up to 3.5 hours were reported for CW room temperature MgZnSSe-based lasers grown on GaAs by MBE, exhibiting threshold current densities of 500 A/cm^2 and operating voltages of 3.7-5 V, while at power levels of 10 mW/facet, these lasers would operate for up to 1.2 hr. These improvements in lifetimes (the previous record was approximately 1 hour) are attributed to a reduction in stacking fault densities from $1x10^6$ to $1x10^4$ cm^{-2}. Using a similar MgSnSSe-based structure, H. Okuyama of Sony [Yokohama, Japan] reported lifetimes of 4.3 hours.

1.3-1.55 mm Lasers

Semiconductor lasers emitting at 1.3-1.55 µm are important light sources for optical communication and optical interconnection systems. Using InGaAsP MQWs, H. Yoon and coworkers at the University of Michigan [Ann Arbor, MI] demonstrated a modulation bandwidth of 23 GHz for a ridge waveguide laser operating at 1.55 µm - the highest value reported to date for any InP-based ridge waveguide laser, while for a buried heterostructure device they obtained a very low threshold current of 3.5 mA and a modulation bandwidth of 24 GHz. Using strain compensated AlGaInAs MQWs and AlInAs/GaInAs graded-index-separate-confinement-heterostructures layers as the transverse waveguide, M.C. Wang et al of the Ministry of Transportation and Communications [Taoyuan, Taiwan, ROC] reported on 1.3 µm operation which had an estimated bandwidth of 23 GHz, and exhibited a maximum CW operating temperature above 170° C. Using tensile-strained GaInAsP MQWs and unstrained GaInAsP barriers, N. Yokouchi and coworkers at Furukawa Electric Co. [Yokohama, Japan] achieved a buried heterostructure laser exhibiting a very low threshold current of 16 mA, corresponding to a threshold current density of 530 mA/cm^2. Using a constricted blocking layer on a p-substrate coupled with a buried heterostructure approach, K. Uomi et al of Hitachi [Tokyo, Japan] reported on an InGaAsP/InP-based MQW-CBPBH laser in which the strain effects in the QWs resulted in a record-low threshold current of 1.33 mA for operation at 1.3 µm.

Growing Interest in Nitrides

The First International Symposium on Gallium Nitride and Related Materials sheds light on the epitaxial growth of nitrides.

In the early 1990's there was only modest interest in III-V nitride materials, but since then the field has been revolutionized by success in fabricating blue LEDs from GaN/InGaN. At present, nitrides probably qualify as the hottest topic in compound semiconductor research, especially among epi growers. In recognition of this fact, the Materials Research Society (MRS) added a major symposium on the topic to their annual fall meeting, held November 27 - December 1, 1995, in Boston, MA. The "First International Symposium on Gallium Nitride and Related Materials" drew 250 abstract submissions, 190 of which were accepted for presentations. More than 500 delegates attended the five-day event.

Epitaxial Growth Techniques

The majority of the presentations at the symposium involved growth-related issues. Whenever a large number of epi growers congregate, one topic of discussion is sure to arise - what's the best growth technique? In the area of nitrides it is difficult to argue with the success demonstrated by MOCVD. Leading the field is Nichia Chemical which uses its own proprietary "two-flow" MOCVD reactors to fabricate production quantities of blue and green LEDs (1-2 million units per month). The results presented by Nichia's Shuji Nakamura are extremely impressive: blue LEDs (450 nm) with 2 cd output and very narrow emission spectra (20 nm linewidths); green LEDs (520 nm) with output up to 12 cd and 30 nm linewidths. Toyoda Gosei and CREE Research also reported the successful "mass production" of high brightness blue LEDs grown by MOCVD.

MOCVD growth of the nitrides typically occurs at high temperatures (over 1000°C), an advantage for crystallization of high melting point materials like the nitrides. The high growth temperature is, however, a double-edged sword. Worsening of other problems, like phase separation of alloys such as AlInN and interdiffusion, may occur at elevated growth temperatures. Industrial labs see the scaleability to high throughput as an important advantage of MOCVD. Another reason for the popularity of MOCVD is that the group V hydride source gas for nitride growth, ammonia, is not as toxic as those used in MOCVD growth of conventional III-V's, arsine and phosphine. A minor disadvantage of MOCVD is the necessity of post growth annealing to activate magnesium, the standard the p-type dopant.

Nevertheless, there are still many groups growing nitrides by MBE. It is on the opposite side of the growth temperature issue from MOCVD, using lower growth temperatures in the range of 700°C. This may be an advantage for controlling interdiffusion and phase separation. Unlike MOCVD, MBE does not require post-growth annealing for dopant activation. Additionally, MBE has the advantage of well developed *in situ* diagnostics. Most of the MOCVD nitride activity is located in industrial facilities, while MBE seems to be primarily the tool of the academic research groups. Nitride growers on both sides usually concede to MOCVD the business of growing billions of LED units per month, since MOCVD seems to be the more scaleable technique. Only time will tell if MBE can gain a role in the nitride laser field.

Quietly lurking in third place is hydride vapor phase epitaxy, a technique that pre-dates both MOCVD and MBE. HVPE's primary advantages are high quality material and growth rates of several tens of microns per hour that enable the growth of up to a few hundreds microns of material. Maki and co-workers of Lincoln Labs reported the HVPE growth of a 10 μm thick GaN buffer layer, grown at 70 μm/hr. on a sapphire substrate. The buffer is very high quality material, as indicated by the high room temperature electron mobility of 600 cm^2/Vs and dislocation density of 5×10^8 cm^2. The HVPE buffer improves the morphology of the MBE-grown laser structure, lowers the laser's series resistance and facilitates the cleaving of laser mirrors along GaN cleavage planes. The high quality cleaves were crucial in enableing Maki to observe lasing modes in the output spectrum of the optically pumped device.

The Materials

The keystone of the material system, GaN, is the most straightforward nitride to grow, and a constituent of all the other nitrides of interest. AlN's main use, at present, is as a buffer layer to assist in the correct nucleation of epitaxial growth. The alloy formed from these two binaries, AlGaN, is widely employed as a high bandgap, quasi-lattice-matched partner to GaN for the construction of heterojunctions. The third binary, InN, has not enjoyed as much attention as the others. It does not lattice match GaN or AlGaN, and its 2 eV bandgap, the lowest of the nitrides, is comparable to that of other, better developed III-V's. The gallium rich alloys of InN and GaN, however, are extremely important. These InGaN alloys are the materials with bandgap wavelengths in the green, blue and violet region of the spectrum, and are the materials usually employed for the active layers of short wavelength LEDs. The group III nitrides can crystallize in either the wurzite (hexagonal) or zincblende (cubic) structures. The two crystal structures have small, but perhaps significant, differences in all the materials' properties, most importantly, bandgap, lattice constant, and electron mobility. Most researchers are producing the wurzite structure, although not necessarily by choice. In certain cases, there may be advantages to use the zincblende structure, if it can be controllably produced.

Substrate Options

A good indication of the relative immaturity of nitride technology is the number of substrate materials being investigated. ***Thirteen*** different substrates options were discussed at the Symposium. They are, in approximate order of current popularity: (1) sapphire, commonly used because it is readily available, moderately inexpensive and produces acceptable quality material, despite a large 14% lattice mismatch with GaN; (2) silicon carbide, which provides a closer lattice match than sapphire and better cleavability, but is very expensive; (3) gallium nitride, which would be ideal if it were available in inch-sized wafers;

(4) zinc oxide, an isomorphic material (elements from the same rows of the periodic table) with GaN, that has a 2% lattice mismatch; (5) & (6) silicon and gallium arsenide which are cheap, readily available high quality materials; (7)-(12) the oxides: lithium gallate, aluminum gallate, spinel, magnesium oxide, $ScAlMgO_4$, and $NdGaO_3$, most of which are reasonably closely lattice matched to GaN; and (13) hafnium, a metal that has a close lattice and thermal match to GaN.

Sapphire's position atop the ladder may be tenuous. Both Nichia and Toyoda Gosei use sapphire for their production of nitride LEDs; however, CREE is using SiC substrates. Sapphire does have advantages over SiC in cost, and presently nitride LEDs on SiC do not demonstrate the same brightness and color purity as those grown on sapphire. But because SiC is a conductor, it is possible for CREE to do 100% on the wafer testing prior to packaging, and they can also sell the devices in chip form to manufacturers who prefer to do their own packaging. Furthermore, in laser applications, the device construction is made much simpler if high quality cleaved planes can be made through the substrate and epitaxial structure, something that is possible with SiC substrates, but not sapphire.

Other than the homo-epitaxial growth on GaN substrates, the growth on nitrides on "foreign" substrates produces material that has approximately a billion defects per square centimeter. Such large defect densities in the more conventional III-V's would create huge non-radiative recombination rates and large trap densities, making useful devices impossible Nature is kind to the nitrides, however - although only defect-ridden nitride materials can be grown, the defects seem to be fairly benign.

GaN substrates are the great hope of the nitride community. There is some work already in progress on this front, mainly by Unipress in Poland, which reports the growth of GaN platelets of sizes up to 5 mm. But there is still a long way to go before inch diameter GaN substrates are available.

The Future

Nichia, Toyoda Gosei, and CREE are currently enjoying the highest profile positions in the field, but it is likely that other manufacturers will be joining in the near future. Estimates provided by Hewlett-Packard suggest that the current market for blue LEDs is around 20 million units per year, but it is obviously poised to grow quickly, perhaps reaching the billion dollar/year level in ten years. Evidence that the manufacturers are "gearing up" for large-scale production is provided by the manufacturers of MOCVD systems, who report that more than a dozen multi-wafer reactors have been sold recently to companies interested in manufacturing nitride LEDs.

In addition to the flurry of industry-funded nitride activity, the US Department of Defense is a significant sponsor of nitride research. At present DoD nitride funding exceeds $40 million annually, with a good likelihood for sizable increases in the near future. The great majority of these DoD research funds are handled by the Advanced Research Projects Agency (ARPA). Federal funding, such as that from the DoD, has enabled the entrance of American academic research groups into the nitride field.

Short wavelength LEDs are certainly nitrides' main market, but not the only one. With LEDs moving out of the research labs into production, researchers are increasingly turning their attentions toward short wavelength (blue, violet and UV) diode lasers. The primarily application of these devices is optical data storage. The robustness of the materials has created interest in the use of nitrides for high temperature and high power electronics. The DoD is interested in nitrides for solar-blind UV detectors. A more speculative possible application of nitrides, especially AlN, is negative electron affinity cathodes for flat panel displays and electron multipliers. In fact, at times it seems as if there is no end to the list of potential applications being considered for nitrides. APA Optics [Blaine, MN] reported the fabrication of nitride transistors and UV detectors, and Nichia's Nakamura even presented a demonstration of nitride light emitters covering the whole visible spectrum.

The progress in the field of nitrides has already produced very impressive results in high brightness LEDs. Other devices such as lasers, UV photodetectors and high power/high temperature transistors seem on pace to become practical products over the next decade. These already good results would be immediately be pushed forward in one large step if high quality GaN substrates were to become available. Defect densities would drop four or five orders of magnitude. This dramatic improvement in an already booming field is a cause for great optimism.

One thing which can be said definitively about the future of III-V nitrides: it will engender more conferences in the future. The "Second International Symposium" in this series is expected to be held in Japan in 1997. In the meantime, the MRS will continue to cover nitride issues in its annual spring (San Francisco) and fall (Boston) meetings. And an international conference on "Blue Lasers and LEDs" will be held in Chiba, Japan, in March, 1996.

G.W. WICKS
THE INSTITUTE OF OPTICS
UNIVERSITY OF ROCHESTER
ROCHESTER, NEW YORK

23rd International Symposium on Compound Semiconductors
St. Petersburg, Russia

September 23-27, 1996

ISCS•23

Successor to the International Symposium on GaAs and Related Compounds

Organized by the Ioffe Physico-Technical Institute
and the St. Petersburg Scientific Center of the Russian Academy of Sciences

ISCS•23

First Announcement and Call for Papers

The 23rd International Symposium on Compound Semiconductors (ISCS-23)will be held in St Petersburg, Russia - a city which has a long history of excellence in sciences and, specifically, in physics of semiconductors. This Symposium continues a series started in 1966. The first 20 events bore another name, the Symposium on GaAs and Related Compounds. The present name reflects the emergence of many other compound semiconductors as vital materials for modern electronic and optoelectronic devices. ISCS-23 will be held on September 23-27, 1996 at the Astoria Hotel where the majority of participants will be accommodated. The Hotel is located in the downtown, near St.Isaak's Cathedral and Mariinskii Palace. The opening session is scheduled to be held in the building of the Russian Academy of Sciences, founded in St.Petersburg in the mid-18th century.

Scope and Format

In the spirit of the preceding meetings, the Symposium is to be a forum for papers on all aspects of compound semiconductors, including growth, processing, devices, and ICs. The main materials are III-V compounds, SiC and wide band gap II-VI compounds such as ZnSe, ZnS, etc. Specific areas will include, but not be limited to:

1. Nanoelectronics and Nanophotonics
2. Epitaxy and in-situ Processing
3. Visible Emitters
4. Heterostructure Photocells
5. Heterostructure Transistors
6. OEICs
7. High Power, High Temperature Devices
8. Simulation and Modeling
9. Quantum Effects
10. Quantum Dots
11. Characterization

The Symposium program will be comprised of invited and contributed papers. The contributed papers will be refereed by the members of the Program Committee on the basis of submitted abstracts. The authors will be given 30-40 and 20 minutes for oral presentations of invited and contributed papers, respectively. A part of contributed papers will be presented in poster sessions. The list of invited speakers will be announced in due time.

Submission of Contributions

Authors are requested to submit their contributions by April 30, 1996. The papers should be submitted in both forms listed below. The forms should include: title, authors' names (capitalize the name of a principal author who will present the paper), authors' affiliations, body text, and the number(s) of related area(s) (listed above in "Scope and Format") in priority order.

Extended Abstract Form

The Extended Abstract may consist of one-page text and, if necessary, one optional page with up to 4 figures, and should be submitted on paper (6 copies). It should be clear on the originality and the rélevancy to the scope of the Symposium. The Extended Abstract will be only a subject for consideration of the Program Committee and will not be published.

Short Summary Form

The Short Summary (text only, no more than 100 words) should be submitted both on paper (6 copies) and electronically as an ASCII file. Electronic files may be sent to the Secretary of the Organizing Committee by e-mail (Subject: ISCS-23, <name of the principal author >) or on IBM PC compatible disk. The first way is preferable. The Short Summary will be published in the program booklet prior to the Symposium.

The decision of the Program Committee will be notified to the principal author by early June 1996. A limited number of papers reporting very recent results of special importance will be accepted as Late News Papers. The abstract may be submitted before June 30, 1996. The acceptance of papers will be notified prior to the Symposium.

Submissions should be sent to:

Secretary of the Organizing Committee

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As in the past, the Proceedings of the Symposium will be published as part of the long-standing series of these meetings. For accepted papers, authors will be asked to submit the manuscripts to facilitate refereeing. The format and instructions will be forwarded at the time of acceptance notification.

For More Information

Anyone requiring more information about ISCS-22 is encouraged to visit our WWW site at http://www.ioffe.rssi.ru/ISCS-23/ or contact one of the following:

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Exhibits

The Symposium will again feature a table top exhibition. This is an opportunity for companies to display their latest products, technologies, and services. If interested in exhibiting, please contact:

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1995 GaAs IC Symposium

OCTOBER 29-NOVEMBER 1, 1995
SAN DIEGO, CA
500 ATTENDING, 143 PAPERS

From A/D converters to high speed communication systems, digital GaAs continues to make progress

The consensus at the 1995 GaAs IC Symposium was that GaAs has truly turned a corner, and firmly established itself in several commercial markets - the foremost of which is wireless communications, where GaAs' ability to produce low noise, superior linearity, and outstanding PAEs, have made it a natural for RF applications. However, despite the fact that RF/wireless continues to generate GaAs-MMIC headlines, and at times appears to be the GaAs success story, there is another GaAs-based capability that also deserves a few headlines - digital GaAs. Despite stiff competition from ever improving Si-based devices, represented by bipolar, CMOS and BiCMOS, digital GaAs' capabilities also continue to improve, finding applications in A/D converters and in the rapidly growing high speed communications market. This year, 20% of the papers presented at the GaAs IC symposium covered digital and time domain topics. That portion of the program will be covered in this report. Analog-related topics will be covered in out next issue.

Digital Capabilities

More than just reporting on the particular details of a specific GaAs digital circuit, several groups reported on the wide range of digital GaAs capabilities that they have developed. Presented in the opening plenary session, B. Bernhardt et al of Motorola [Tempe, AZ] described their Complementary GaAs (CGaAs) process. This digital technology, analogous to CMOS in Si, contains NFETs with threshold voltages of +0.55V and PFETs with threshold voltages of -0.55V. Circuits with 5-7K gate complexity were demonstrated in both a 4K SRAM as well as a high speed digital processor. They have also demonstrated that 1.0 μm CGaAs is faster than both 0.5 μm CMOS or Thin-Film Silicon-on-Insulator (TFSOI) technologies. Furthermore, 0.5 μm CGaAs shows delay times below 100 ps at a supply voltage of only 1.2 V. In addition, Motorola's CGaAs requires 13 mask layers (all the way through 3rd level metal interconnects), as compared to Si-CMOS/BiCMOS processes which can require up to 25 mask layers. Motorola's digital GaAs processes can support complementary circuits operating from DC to 500 MHz, DCFL circuits operating from 100 to 1000 MHz and SCFL circuits operating from 500 to 5000 MHz - making SCFL suitable for fast communications circuits required in ATM/SONET applications. The complementary process exhibits a speed power product of 0.01-0.1 microwatt/MHz/Gate, while that of the SCFL is at 0.4 microwatt/MHz/Gate when operating at over 1 GHz. In addition, the CGaAs process can also support RF capabilities, with the NFET exhibiting an f_t and f_{max} of 20 and 30 GHz, respectively, and the PFET exhibiting an f_t and f_{max} of 5 and 10 GHz, respectively.

In an invited talk, W.E. Stanchina and coworkers of the Hughes Research Labs [Malibu, CA] described an InP-based HBT technology which is capable of producing digital, analog, mixed signal, and optoelectronic ICs within the same process. Depending on the base/collector structure (both SHBT and DHBTs utilizing GaInAs bases with either GaInAs or InP collectors), the f_t for these HBTs ranges from 60-170 GHz. Several high speed accumulators chips have been demonstrated in this technology, including a 15 bit accumulator which is the largest reported InP IC to date, with over 1500 transistors. In addition, a 12 bit low-side accumulator occupying a 1.4x1.4 mm^2 die was described, which was fully functional for clock rates over 7 GHz, at which speed it dissipated 1W This accumulator performance, makes it suitable for application in direct digital synthesis, being capable of generating waveforms having frequencies up to 2.5 GHz. Delta-Sigma modulators (components for high speed, high resolution A/D converters) were also demonstrated exhibiting a 12-bit dynamic range for an oversampling ratio of 32 and a sampling rate of 3.2 GHz.

Using the OEIC capabilities of the Hughes Research Labs InP HBT process, J. Sitch of BNR [Ottawa, Canada] described in an invited talk the efforts of the Optical Networks Technology Consortium [Bellcore, Columbia University, Hughes Research Labs, Nortel/BNR, Rockwell Science Center, United Technologies Photonics, United Technologies Research Center, Case Western Reserve University and Lawrence Livermore National Labs] in using III-V ICs in wave division multiplexing (WDM) optical network access module. The OEIC input segment of the WDM network access module utilized a Hughes p-i-n/HBT detector array. Clock recovery array ICs and laser driver arrays were fabricated with Rockwell's AlGaAs/GaAs HBT process, while the most complex chip in the module is a cross-point chip designed and fabricated by TriQuint (see R. Savara below) using their E/D MESFET process. Bellcore fabricated the multi-wavelength DFB laser array for the output transmitter. The resulting multiwavelength SONET Network Access Module constructed from these components is able to receive, regenerate, switch and transmit signals on eight different wavelengths - each of which operates at 2.5 Gb/s, for an aggregate throughput of 20 Gb/s.

Digital Circuits

In addition to the presentations focusing on digital capabilities, and system applications, a wide range of digital GaAs ICs were also presented - those including advanced A/D converter circuits, as well as a broad spectrum of high speed communications circuits.

K.R. Nary and coworkers of Rockwell [Newbury Park, CA] reported on an 8-bit, 2 Gsample/s A/D converter fabricated with an AlGaAs/GaAs HBT process. The process features non self-aligned emitter-up npn AlGaAs HBTs, Schottky diodes, NiCr and WSiN thin film resistors, MIM capacitors and three layers of gold based interconnect. The HBTs exhibit and f_t and f_{max} of 55 GHz when biased at a collector current of 2 mA. Using a folding and interpolation architecture to provide wide bandwidth with a moderate device count (2500 HBTs), the A/D exhibits a single tone spurious free dynamic range of 48 dB at Nyquist rates along with a 6.5 effective bit performance when sampling a full scale 12.2 KHz input. The A/D requires a 5.0 and -5.2 V supplies and dissipates 5.3 W. Also reporting new A/D results were R.M. Hickling and coworkers of TechnoConcepts Inc. [Newbury Park, CA], describing a GaAs Multibit Delta-Sigma A/D which uses a new comparator design which eliminates the need for comparator threshold terminals, thereby allowing each of the individual latched comparators to operate upon the same differential input signal. The 4-bit delta-sigma modulator test chip represents the first efforts in implementing this type of architecture in GaAs MESFETs, and was fabricated using Vitesse's 0.6 µm HGaAs-III MESFET process. The modulator functioned at speeds up to 1.6 GHz.

In the area of digital communication circuits, R. Savara et al of TriQuint [Beaverton, OR] described a 16x16 Crosspoint Switch which can be used for data communications, telecommunications, digital video and computer networking - all of which have needs for high speed switching, including the WDM system as described above by J. Sitch of BNR. The architecture for the switch uses 16 fully independent 16:1 multiplexers, allowing each output to be arbitrarily programmed to any input port. Using a 0.6 µm E/D GaAs MESFET process that utilizes a fully differential Source Coupled FET Logic (SCFL) circuit design, and 4 layers of metalized interconnects, the crosspoint switch operated at 2.5 Gb/s while consuming 8 W.

J. Jakobsen of Tele Danmark Jyudsk Telefon R&D [Tranbjerg, Denmark] described a GaAs multiplexer chip suitable for ATM switching, which utilized a mixed logic design approach, including: direct coupled FET Logic (DCFL), Source-Follower Direct Coupled FET Logic (SDCFL) and Super Buffer FET LOGIC (SBFL). This circuit was fabricated by Vitesse using their 0.8 µm H-GaAs-II MESFET process. With a chip area of 19.2 mm^2, the chip contains 29,307 transistors and is able to hold a total of 2K bits of data stored in on-chip FIFO registers. The maximum frequency of operation for this multiplexer chip was 1.15 GHz, corresponding to a total throughput of 10 Gb/s, with a power consumption of 1.2 W.

Optical fiber communication systems require MUX/DMUX circuitry. K. Numata et of NEC [Ibaraki, Japan] demonstrated an ultra-low power consumption Heterojunction FET 8:1MUX/1:8 DEMUX. Using DCFL, these circuits operated at over 2.4 Gbps at a supply voltage of 0.7 V, with the MUX consuming 150 mW and the DEMUX consuming 170 mW. The devices utilized for these circuits were 0.35 µm n-AlGaAs/i-InGaAs HJFETs. At a supply voltage of 0.8 V, a maximum operating speed og 6.5 Gbps for the MUX and 5.2 Gbps for the DEMUX was obtained. The power consumption of these circuits has been reduced by a factor of 10 as compared to earlier 8:1MUX/1:8 DEMUX designs.

Lastly, illustrating the high levels of integration which GaAs is being implemented in, M. Venkataraman and coworkers of Vitesse Semiconductor Corporation [Camarillo, CA], described a 256 entry by 14 bit dual compare content addressable memory (CAM), which can be utilized as a support chip for high speed microprocessors (100 MHz). Using Vitesse's H-GaAs III E/D MESFET process the CAM utilizes 123,766 transistors, exhibits a fast hit detect access time of 5.5 ns for a clock time of 7 ns, and consumes 8.8 W. It uses DCFL, in which a typical two-input NOR gate has a propagation delay of 133 ps. The CAM flags multiple hits and outputs the hit address when a single hit has occurred. The CAM achieves a high throughput due to its pipelined architecture, parallel organization of its primary blocks, and the inherent speed of the processing technology. When implemented in Vitesse's new H-GaAs IV technology, it is expected that the CAM will operate at the same, or higher speed, with a 50% reduction in power dissipation.

The Compound Semiconductor Portfolio

Seven stocks that represent the compound semiconductor industry on Wall Street - are they good investments?

Despite a little year-end profit taking, and a bit of waffling on individual companies, Wall Street investment analysts have been very bullish on technology stocks lately. And we here at Compound Semiconductor are, not surprisingly, very bullish on compound semiconductors. Therefore we've decided to jump on the technology stock bandwagon by instituting this column. We'll use it to track the share price performance of a handful of compound semiconductor-related companies. We've also created a "Compound Semiconductor Portfolio", consisting of a hypothetical investment in these shares. Our readers can use the Portfolio to judge the performance of this segment of the industry, or to take a vicarious foray into the stock market, or, perhaps, just to learn if you are better at picking stocks than we are.

The Companies

We selected the stocks by looking for publicly traded companies engaged in compound semiconductor-related activities. We then reduced the list to only those companies whose share price is likely to be impacted by those activities. As a result, industry giants such as Fujitsu, Motorola and Siemens didn't make the cut, because their share prices are dominated by performance in other sectors, such as silicon semiconductors or consumer goods.

We were left with five obvious choices: semiconductor laser manufacturer SDL, silicon carbide & blue LED manufacturer CREE Research, and GaAs IC foundries Anadigics, TriQuint and Vitesse. They are all small capitalization companies that derive virtually all of their revenue from compound semiconductors. We've also chosen to include two other companies: Advanced Technology Materials International (ATMI) and Alpha Industries. Although similar in size to the others, these companies are not so clearly driven by compound semiconductors. ATMI is active in the SiC field, and is expanding into III-V's (see page 12), but it currently derives most of its revenue from other parts of the company. Alpha is a rapidly growing presence in the GaAs MMIC field, but it's bottom line is still dominated by silicon semiconductors. Nevertheless, both companies made our final cut because we believe that compound semiconductors will be an important part of their futures. All seven are based in the US, and all but Alpha are traded on the Nasdaq exchange. (it trades on AMEX). We did not intended to restrict our list to only American companies, but we were unable to identify any qualified candidates on foreign exchanges.

The Portfolio

In each issue we will provided updated share price information and news and financial results from these companies. Also, beginning with our next issue, we'll provide a more detailed profile of each.

We've also created a "Portfolio" in order to provide a quick and easy snapshot of the performance of the group as a whole. Our hypothetical investment is 100 shares of common stock in each of the seven companies. Our "buy in" price is the close on the first day of trading in 1996 (see below). We will update the value of the portfolio in each subsequent issue. Some historical information on share prices is provided on page 47.

The Compound Semiconductor Portfolio

Company	Symbol*	Products	Share Price 1/2/96
Alpha Industries	AHA	MMICs, both GaAs and Si. Ceramic filters, other microwave & MM-wave components.	13.625
Anadigics, Inc.	ANAD	GaAs ICs for RF and microwave frequencies in CATV, DBS, wireless and fiber optic systems.	21.25
Advanced Technology Materials International	ATMI	Diamond and SiC semiconductors, III-V epi (through recent acquisition of Epitronics), point-of-use semiconductor environmental equipment.	10.375
Cree Research	CREE	SiC materials and devices, including blue LEDs. Subsidiary manufacturers full color displays.	14.75
SDL Inc.	SDLI	High power semiconductor lasers (esp. high power) and optoelectronic ICs.	25.375
TriQuint Semiconductor	TQNT	Analog and mixed signal GaAs ICs for wireless, telecommunications and computing markets.	14.25
Vitesse Semiconductor	VTSS	GaAs ICs for computer, communications, defense, aerospace, test and instrument systems.	13.125
		Portfolio Value, 1/2/96 (100 shares of each)	**$11,275**

**AHA traded on AMEX, all others on Nasdaq exchange.*

But Are They Good Investments?

It is not surprising that we are bullish on compound semiconductors - as the trade magazine for the industry, that is part of our job. One might well wonder whether there is any justification for our interest in these stocks, beyond partisan loyalty. *Smart Money*, a monthly magazine published by the *Wall Street Journal*, recently offered a guide to selecting technology stocks as long term investments. They identified five important characteristics that many current stars in the technology sector shared before they began their ascent. Here is how our selections fare according to the *Smart Money* criteria:

#1. The company should show some history of earnings. It is not uncommon to find brokers touting technology companies with no history of earnings or even revenue, claiming that the "breakthrough" product which will make them a stock market superstar is just around the corner. *Smart Money* advises leaving these offerings to venture capitalists and other professional risk-takers. Instead, one should invest in companies that have at least some history of profitability.

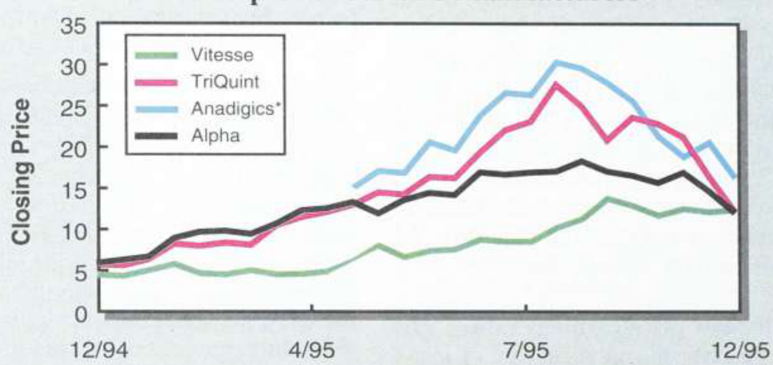
The road has not been smooth for all of our stocks. Most of them have recorded loss-making years, and three of them (Cree, TriQuint, and Vitesse) recorded a loss as recently as 1994. However, 1995 will likely go down in the books as a "breakthrough" year for many or all of our picks. All seven are currently profitable, with many reporting strong growth in both revenue and income in the past 6-12 months. For example, SDL's income was up 204% in the third quarter of 1995. Another piece of good news is that the GaAs companies appear to have successfully completed the transition from low volume/military applications to high volume commercial markets. So, although we may not be looking as far back as the professionals would like, we will score this one as **Yes**.

#2. Pick companies which have demonstrated solid sales growth. *Smart Money* advocates companies with at least 15% annual growth rates. Our seven companies as a group increased sales by around 10% per year from 1992 to 1994, but should report an increase of 20-25% for 1995, which would bring the average for the past four years up to 15%. In fact, 1995 year-end results (not available as this issue went to press) may be even better. For example, Anadigics and TriQuint's results for the first nine months of 1995 showed a 48% increase in revenue. Therefore, this item is also scored as **Yes**.

Hindsight

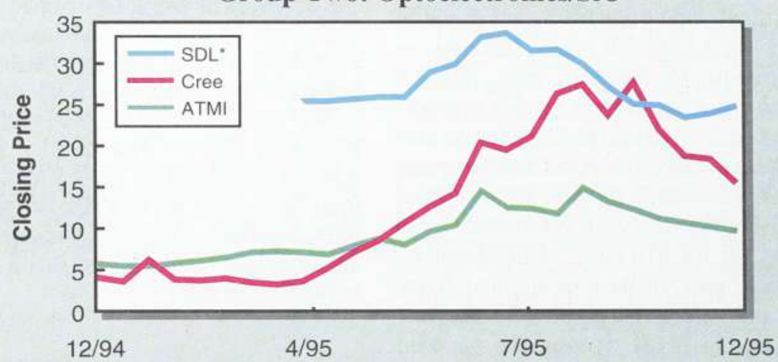
Share price performance for the seven stocks in our portfolio over the past 13 months. Charts based on biweekly closing prices.

Group One: GaAs IC Manufacturers



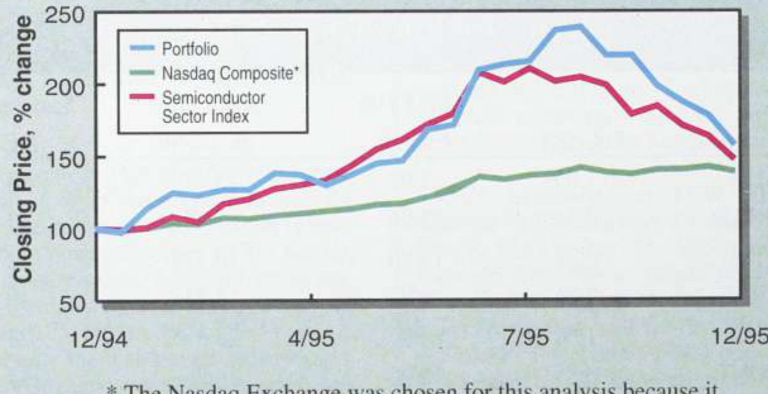
* Anadigics made its initial public offering of stock in April, 1995.

Group Two: Optoelectronics/SiC



* SDL made its initial public offering of stock in March, 1995.

Compound Semiconductor Portfolio vs. Nasdaq Composite & Semiconductor Sector Index



* The Nasdaq Exchange was chosen for this analysis because it contains a larger proportion of technology companies than the other American exchanges. Six of the seven companies in our portfolio are traded on the Nasdaq.

#3. No dividends. Companies in an R&D intensive industry should have better uses for their cash than paying out dividends. Of our seven picks, only Alpha Industries has paid a dividend, and that was one-time only. Another result of **Yes**.

#4. Relatively small market capitalization. "Small is beautiful" - the best stock tips are supposed to relate to companies that the rest of the stock market hasn't heard of. *Smart Money* recommends companies with market capitalizations (number of shares outstanding times the share price) of less than $1 billion. We can do much better: the top of our group is Vitesse at just $187 million. The low is ATMI at $82 million. According to Standard & Poors our stocks all rank around the 50th percentile for market capitalization. Score: **Yes**.

#5. Look for low price/earnings ratios. The "P/E" ratio, a favorite analytical tool of many investors, is determined by dividing the current price of the stock by its earnings per share (EPS) for the last 12 months. *Smart Money* likes stocks that are close to the market average of 15. Conventional wisdom says that a low P/E means that market has little confidence in the stock, while a high P/E means that you are paying a premium for the stock, especially if it is more than twice the current market average.

On the face of it, our picks falter on this criteria. The published P/E ratios for our group are all over the board, ranging from several "zero" or meaningless reports all the way up to a whopping 80 for TriQuint. Unfortunately, this analytical tool, in its conventional form, doesn't fit our selections very well. For one thing, the timing is all wrong. As we said above, many of the companies listed above turned the corner on profitability in 1995, but that fact isn't visible yet in public reports.

Therefore, we've decided to fudge a bit and modify the analysis. Instead of calculating the current P/E based on 1994/1995 earnings, we've projected P/E ratios based on current prices and estimated EPS for the 1996 fiscal year. The estimates are averages of various professional forecasts, complied by Zacks Investment Research. The result? P/E ratios around 15-20, with only ATMIand SDL straying into the possibly premium range. See chart below. Are we cheating? Perhaps. Nevertheless, we will score this one as (**a qualified**) **Yes**.

Which brings us to our grand total: 4.5 out of a possible 5. There might be some that object to our treatment of the P/E ratios and they may have a point, but we'd like to offset it with some subjective input regarding the widespread increase in demand for high frequency microelectronics, optoelectronics, and, perhaps someday, high temperature electronics. As the old saying goes, "a rising tide lifts all boats". We aren't the only bullish party: According to Zacks the stocks in our group have recently received a total of 19 "Strong Buy" and 4 "Moderate Buy" recommendations (compared to just 3 "Holds" and no "Sells".)

There will likely be ups and downs along the way. Technology investors can be extremely fickle, and prone to some odd behavior. For example, it is not unusual for the entire sector to track the performance of Microsoft shares. That is why *Smart Money* advises their readers to buy and hold for at least five years. We will also be taking the long term approach. Whether you are an actual or an "armchair" investor, we invite you to come along for the ride.

Marie Meyer

In our next issue: year-end results; profiles of Alpha Industries and ATMI, the first update on the value of our portfolio.

Estimated Price/Earnings Ratios

Company	Est. EPS*...	...for FY96 Ending	Share Price on 1/2/96	Estimated P/E
AHA	1.05	3/97	13.625	13
ANAD	0.91	12/96	21.25	23
ATMI	0.32	12/96	10.375	32
CREE	0.76	6/97	14.75	19
SDLI	1.00	12/96	25.375	25
TQNT	0.85	12/96	14.25	17
VTSS	0.83	9/97	13.125	16

**Source: Zacks Investment Research, 12/27/95*

Financial Reports

Alpha Public Offering

In late November Alpha Industries announced the public offering of 1,600,000 shares of its common stock, with a grant of an option to the underwriters to purchase up to 240,000 additional shares for the purpose of covering over allotments. The company plans to use the net proceeds from the offering for repayment of indebtedness, capital expenditures, working capital, potential acquisitions and general corporate purposes.

Cree First Quarter Results

Cree Research financial results for the first quarter of fiscal year 1996, ended September 30, show revenues of $3,359,000 for the period, and increase of 60% over the same period in FY95. The company posted a net profit of $194,000 for the quarter, compared with a loss of $197,000 for the first quarter in FY95. The company reports that it is actively expanding its production capabilities to meet increasing demand for its LEDs. Neal Hunter, Cree's president, commented "the value of LED sales in the first quarter equaled 76% of all LED sales for the entire fiscal year 1995. In addition, we are confident about our ability to show substantial revenue and earnings growth in the second quarter." In commenting on the company's increasing production capabilities, Mr. Hunter noted that the company spent $2.0 million in the first quarter and had committed an additional $1.3 million to bring on line a new production facility and renovate its existing facilitate. The new facility began shipping completed products at the end of the first quarter.

SDL Reports Record Setting 3rd Quarter

SDL announced sharply increased sales and revenue figures for the third quarter of 1995, ended September 30. Revenues of $14.1 million and net income of $1.6 million were recorded, compared to revenues of $8.3 million and net income of $0.5 million in the third quarter of 1994. This represents a 71% increase in revenues and a 204% increase in net income as compared to the prior year. For the first nine months of 1995 SDL reported revenues of $37.1 million and net income of $3.9 million, compared to revenues of $23.6 million and net income of $1.4 million in the first nine months of 1994. This represents a 57% increase in revenues and a 177% increase in net income as compared to the prior year.

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.

Electronic Circuits and Devices

12 GHz, 12-W HJFET Amplifier with 48% PAE

Demands for high power amplifiers are increasing for microwave communication applications. GaAs-based heterojunction FETs (HJFETs), which have the capacity for high output power, gain, and PAE, along with high gate breakdown voltages, have emerged as viable candidates for solid state power amplifiers (SSPAs). An MBE-grown HJFET is described which consists of a 130 Å undoped $In_{0.20}Ga_{0.8}As$ channel layer sandwiched between two Si-doped $Al_{0.22}Ga_{0.78}As$ donor layers. The HJFET exhibits a maximum transconductance of 370 mS/mm, an f_{max} of 158 GHz and a gate-drain breakdown voltage of 12 V for a 0.45 µm gate-length. Utilizing a 16.8 mm gate width and operating at 12 GHz with a V_d of 8 V, it delivered 40.9 dBm (12.3 W) with 10.1 dB linear gain at a PAE of 48%. This is the highest output power reported to date from a single FET power amplifier at this frequency. Work performed at Kansai Electronics Research Laboratories, NEC Corporation [Shiga, Japan]. See "A 12-GHz, 12-W HJFET Amplifier with 48% PAE Peak Power-Added Efficiency," K. Matsunaga et al, IEEE Microwave and Guided Wave Letters, 5(11), 402 [November 1995].

SiGe Power Amplifiers

The power capability of devices at microwave frequencies is determined mainly by f_{max}, which requires low base sheet resistances in order to obtain high f_{max} values. Base resistances in Si-based BJTs can be reduced by the introduction of Ge into the base, thereby increasing emitter injection efficiency at the emitter-base junction, and permitting high base dopings without serious degradation to the transistors dc gain. An all MBE-grown SiGe HBT is described for power amplifier applications, in which a 25 nm $1x10^{20}$ cm^{-3} B-doped $Si_{0.7}Ge_{0.3}$ base is used. This HBT exhibits an f_t and f_{max} of 24 and 48 GHz, respectively, with dc base-collector and collector-emitter breakdown voltages of 6 and 5 V, respectively. For 5.7 GHz operation, a common-emitter and common-base class A amplifier were fabricated, exhibiting output powers of 18 and 20 dBm, respectively. The HBT-based amplifier operated with a PAE of 30% and an output power density of 1 mW/µm^2 at a V_{CB} of 4V. Work performed at University of Ulm [Ulm, Germany] and Daimler-Benz Research Centre [Ulm, Germany]. See "Class-A SiGe HBT Power Amplifiers at C-Band Frequencies," U. Erben at al, IEEE Microwave and Guided Wave Letters, 5(12), 435 [December 1995].

1 W Ku-Band Power HBT's with 72% PAE

AlGaAs/GaAs-based power HBTs were developed for 12 GHz operation. In order to realize high power and high efficiency HBTs, both parasitic resistance and capacitance have been reduced by optimization of the emitter ballasting resistor in order to achieve uniform collector current distribution among a 10-finger structure, as well as using air bridge interconnection of each collector electrode and a gold plated heat sink. Grown by MOCVD, and utilizing base widths of 100 nm which were C-doped at $4x10^{19}$ cm^{-3}, the transistor exhibits f_t and f_{max} of 40 and 42 GHz, respectively. Output power of 1 W with a PAE of 72% was achieved from a 10 finger HBT with a total emitter size of 300 µm^2, resulting in a output power density of 5.0 W/mm - the best reported values for solid-state power devices with output powers of more than 1 W at Ku-band. Work performed at Mitsubishi Electric Corporation [Hogo, Japan]. See "1 W Ku-Band AlGaAs/GaAs Power HBT's with 72% Peak Power-Added Efficiency," T. Shimura et al, IEEE Transactions on Electron Devices, 42(11), 1890 [November 1995].

Comparison of SiC, GaAs and Si RF MESFETs

With the recent advances in SiC-based devices, and the material's excellent high electric field breakdown capabilities, it becomes important to compare the RF capabilities of SiC-based devices with the more conventional devices based on Si and GaAs, in order to evaluate which material system is optimum for a given RF power requirement. A comparison of maximum power densities of Si-, GaAs-, and 4H-SiC-based MESFET's was modeled using material parameters, a planar MESFET cross section, and a piecewise linear MESFET drain characteristic. It was calculated that the maximum power density for the Si, GaAs, and 4H-SiC MESFET's were 0.45 W/mm, 0.78 W/mm and 17.37 W/mm at drain voltages of 8.4 V, 8.3 V, and 105 V, respectively. However, despite the high power density capabilities of 4H - SiC, it was determined that the GaAs MESFET has the highest power density under low voltage operation, due to its high electron mobility and very low channel resistance. Work performed at Motorola, Inc. [Tempe, AZ]. See "Comparison of SiC, GaAs, and Si RF MESFET Power Densities," C.E. Weitzel, IEEE Electron Device Letters, Vol 16(10), 451 [October 1995].

HEMT-HBT Monolithic Integration

TRW continues to exploit their capability to monolithically integrate both HEMTs and HBTs in the same microwave circuit (see CS 1(2), pg. 4), by fabricating a wideband HEMT cascode low-noise amplifier with HBT bias regulation, and an LNA which integrates a common-source HEMT with an HBT Darlington amplifier. This selective-MBE based technology integrates 0.2 µm gate-length pseudomorphic InGaAs-GaAs HEMT's with 2 µm emitter-width GaAs-AlGaAs HBT's. The HEMT devices achieve g_m > 500 mS/mm with f_t of 60 GHz, while the HBT devices achieve $\beta = 60$, with f_t and f_{max} of 23 and 50 GHz, respectively, at a current density J_c = 20 kA/cm^2.

By utilizing the HEMT-HBT monolithic approach, a wideband HEMT cascode low-noise amplifier with HBT bias regulation was fabricated, resulting in a 25:1 reduction in size and a 30:1 reduction in part count as compared to an LNA fabricated with the more typical hybrid integration approach. The self-biased MMIC (with an area of 0.9x1.0 mm^2) achieved greater than 13 dB gain across a band of 1-8 GHz, with a minimum noise figure of 1.6 dB from 1-4 GHz, and less than 1.9 dB from 1-8 GHz. The MMIC consists of a HEMT cascode first stage and a source-follower output stage, with shunt feedback between the stages used to obtain good broadband noise figure and gain performance. An HBT current regulator is monolithically integrated with the cascode stage of the LNA because the low-noise performance of the cascode input stage is more sensitive to bias than the source-follower output stage. The performance of this circuit is comparable to single-technology HEMT self-biased LNA's. A second LNA circuit was also fabricated - integrating a common-source HEMT with an HBT Darlington amplifier. This MMIC (with an area of 0.9x0.7 mm^2) functioned over a 1-8 GHz bandwidth, exhibiting greater than 17.5 dB gain, and a minimum noise figure of 2.5 dB, while obtaining a maximum IP3 of 18 dBm with a saturated output power (P_{sat}) greater than 12 dBm. This HEMT-HBT amplifier achieves comparable P_{sat} to the conventional HBT-only Darlington amplifier, while achieving over 2 dB reduction in noise figure across the band.

Work performed at TRW Electronics Systems and Technology Division [Redondo Beach, CA]. See "A Wideband HEMT Cascode Low-Noise Amplifier with HBT Bias Regulation," K.W. Kobayashi et al, IEEE Microwave and Guided Wave Letters, 5(12), 457 [December 1995] and "A Novel Monolithic LNA Integrating a Common-Source HEMT with an HBT Darlington Amplifier," K.W. Kobayashi et al, IEEE Microwave and Guided Wave Letters, 5(12), 442 [December 1995].

Optoelectronic Devices

Strain Compensated Multiple Quantum Well Lasers at 1.3 µm Wavelengths

For good high temperature, high gain and low threshold performance, a quantum well laser should have a large conduction band offset between the material of the quantum well and that of the barrier. The traditional materials for 1.3 µm lasers suffer somewhat in this respect. To improve this situation, InAsP has been considered for the well material. However, because InAsP has about 1.5% strain at 1.3 µm bandgap wavelengths, the number of wells in the laser structure is typically limited to one or two, due to pseudomorphic critical thickness limitations. Many of the benefits of large conduction band offsets are compromised by the large carrier densities per well that is required with such a small number of wells. The solution to this problem is the introduction of strain into the barriers that is equal in magnitude, but opposite in sign, to that in the InAsP wells. InGaP was recently tried for the strain-compensated barriers in such structures, allowing three InAsP wells to be used. Very low threshold current densities, 300 A/cm^2, were obtained with this structure at 1 mm long cavity lengths. This is a 25% improvement over the thresholds that resulted from structures with two InAsP wells with lattice matched barriers. Work performed at Furukawa Electric Co. [Yokohama, Japan]. See "Very low threshold current density 1.3 µm InAsP/InP/InGaP/InP/GaInAsP strain-compensated multiple quantum well lasers", A. Kasukawa, et al, Electron. Lett. 31(20), 1749 [28 September 1995].

Solar-Blind UV Photodetectors Based on GaN p-n Junctions

UV detectors that do not sense visible light have important potential applications for missile guidance systems and UV radiometry. Previous solar-blind UV detectors have been based on photocathodes, however these are expensive, inconvenient, bulky and fragile. GaN-based devices offer great potential for these applications, and have been tried with intrinsic photoconductors and Schottky barriers. Recently unbiased GaN p-n junctions were demonstrated for this purpose. The responsivity of these photodiodes was essentially zero for wavelengths longer than 370 nm. At shorter wavelengths the responsivity was 0.09 A/W. At these UV wavelengths the responsivity is comparable to that of a UV-enhanced silicon p-n detector, however the silicon detector is not solar-blind. The response time of the unbiased GaN device was 0.4 ms. The device became slightly faster at 10 volts of reverse bias, but still much slower than its RC time constant. The factors that determine the device speed are not well understood yet. Work performed at APA Optics, Inc. [Blaine, MN USA]. See "Visible-blind ultraviolet photodetectors based on GaN p-n junctions", Q. Chen, et al, Electron. Lett. 31(20), 1781 [28 September 1995].

High Speed Polarization-independent Modulator for 1.55 µm Wavelengths

High speed, low voltage modulators of 1.55 µm wavelengths could be very useful components in optical communication systems. A leading candidate for such a modulator is a p-n junction combined with waveguide structure that has a multi-quantum well core. Since polarization control is difficult in long haul fiber systems, it would be very convenient if the modulators were polarization insensitive. Since light and heavy holes absorb polarizations differently, and the size effect of quantum wells separates the energies of light and heavy holes, the absorption of quantum wells is, unfortunately, polarization sensitive. The separation of light and heavy holes by the size effect can, however, be counteracted by the use of tensile strain in the quantum well. Such quantum wells were recently incorporated with great success into waveguide modulators. The quantum wells consisted of 0.38% tensile-strained GaInAsP with unstrained GaInAsP barriers. Low polarization sensitivity (0.4 dB at 1.55 µm) of insertion loss, extinction ratio and output phase was demonstrated. A high bandwidth of 42 GHz with a low drive voltage of 1.8 V was achieved. Work performed at Alcatel Corporate Research Centre [Stuttgart, Germany]. See "Ultrahigh-bandwidth (42 GHz) polarisation-independent ridge waveguide electroabsorption modulator based on tensile strained InGaAsP MQW", K. Satzke, et al, Electron. Lett. 31(23), 2030 [9 November 1995].

Normal Incidence Infrared Detector Using Electron Intersubband Transitions In Multiple Quantum Wells

The use of intersubband transitions for 8-12 µm IR detector applications has been a very active area of research over the last decade. There have been two main approaches, neither of which is ideal. Intersubband transitions in the conduction band of GaAs/AlGaAs structures have produced high responsivity detectors, but the optical selection rules do not allow this approach to be used at normal incidence. Gratings and other techniques to couple light into the plane of the quantum well have been used, but these complicate fabrication and can cause cross talk between pixels of focal plane arrays. Normal incidence intersubband absorption works in the valence band, but the high mass of the holes causes such detectors to have low responsivities. Recently, the best of both approaches was combined by using strained GaInAs/GaAs multiple quantum wells to absorb normal incidence IR in the conduction band. It is suspected that the device works on spin-flip intersubband transitions that can occur due to the narrow bandgap of GaInAs and the strong spin-orbit interaction. The reported responsivity is 0.2 A/W for 9.5 µm radiation. Work performed at Alpha Photonics [El Monte, CA USA] and Wright Laboratory [WPAFB, OH USA]. See "Normal incident InGaAs/GaAs multiple quantum well infrared detector using electron intersubband transitions", G. Karunasiri, et al, Appl. Phys. Lett. 67, 2600 [30 October, 1995].

Tunable Micromachined Vertical Cavity Surface Emitting Laser

Vertical cavity surface emitting lasers (VCSELs) have created much enthusiasm for optical communication and optical interconnects. They have circular beams and low thresholds, are amenable to 2-D integration and on-wafer testing. Wavelength tunability would enable VCSELs to be used in wavelength division multiplexing for increased throughput and flexibility of communication and interconnect systems. In the past, however, tunability has not been one of the strong points of VCSELs. There have been several attempts to tune VCSELs. The largest tuning range that has previously been demonstrated relies on a heating-based red shift, which is undesirable.

Researchers at Stanford University recently reported an innovative approach utilizing a micromachined, electrically movable top mirror. The lower part of the VCSEL was grown with a conventional structure - n-type GaAs substrate, lower n-type reflector stack, active region. The upper reflector was started with a few layers of a conventional p-type reflector stack, but then a 1.3 micron sacrificial GaAs layer was inserted, followed by an n-type reflector stack. The sacrificial GaAs layer was etched away, leaving a cantilever n-type reflector separated from the rest of the structure by an air gap. The structure is an n-p-n structure. The drive current to the laser is supplied by forward biasing the lower p-n junction. Movement of the cantilever mirror is accomplished by electrostatic forces that result from reverse biasing the upper p-n junction. As the cantilever voltage was increased from 0 to 5 volts, the VCSEL continuously tuned from 935 to 925 nm. It then hopped to an adjacent Fabry-Perot mode at 943 nm. Further increases in cantilever voltage continuously tuned the VCSEL from 943 to 938 nm. Thus the total tuning range was 15 nm, including both red shifts and blue shifts. This represents the largest VSCEL tunability yet reported.

See "Tunable micromachined vertical cavity surface emitting laser", M.S. Wu et al, Electron. Lett. 31(19), 1671 [14 September 1995].

Compound Semiconductor Materials

Growth of Ge-Doped $Al_xGa_{1-x}N$

Direct energy gaps from 3.4 eV to 6.2 eV can be achieved by varying the Al mole fraction in the $Al_xGa_{1-x}N$ alloy. This work reports the growth and doping of $Al_xGa_{1-x}N$ alloys over the composition range $0 < x < 1$ by low-pressure MOCVD. Photoluminescence data for $x < 0.2$ samples displayed sharp band edge emissions and a broad deep-level emission near 2.4 eV. Hall measurements on un-doped AlGaN films showed that the free electron concentration decreases linearly for increasing Al mole fractions while the measured resistivity increases exponentially. Layers with compositions of $x > 0.2$ displayed a resistivity that was too high to be characterized. Ge doping eliminated the deep level emission feature observed in un-doped AlGaN samples, suggesting that this deep level emission may be related to Ga vacancies that could be filled by Ge donor impurities. Work performed at Northwestern University [Evanston, IL USA]. See "Growth of $Al_xGa_{1-x}N$:Ge on Sapphire and Silicon Substrates", X. Zhang et al, Appl. Phys. Lett. 67(12), 1745 [18 September 1995].

Analysis of AlAs-like Barriers in InAs/AlSb/GaSb RIT Structures

Interest in the nearly lattice-matched InAs/AlSb/GaSb material system has been stimulated by the realization of promising resonant interband tunnelling (RIT) diodes that may have applications in analog devices and multiple-valued logic circuits. The RIT diodes display a marked reduction in valley current density when AlAs interfacial layers are introduced between the AlSb barriers and the GaSb and InAs layers. Because both the cation and anion change across the InAs/AlSb interface, both AlAs-like and InSb-like bonding configurations are possible at such interfaces. There currently exists some controversy on whether complete AlAs bonding layers can be formed at InAs/AlSb interfaces grown by MBE. This work reports that vibrational mode Raman spectroscopy measurements show that the introduction of AlAs-like interfaces at InAs/AlSb and GaSb/AlSb interfaces results in the formation of ternary AlSb(As) interfaces. The authors infer that the arsenic content in the AlSb(As) interfacial layer is approximately 10%. Work performed at the Fraunhofer IAF [Freiburg, Germany]. See "Compositional and structural analysis of AlSb(As) tunneling barriers in InAs/AlSb(As)/GaSb resonant interband-tunneling structures", J. Wagner, et al, Appl. Phys. Lett. 67(20), 2963 [13 November 1995].

GaAs HBTs Mounted on Natural Diamond Substrates

GaAs substrates suffer from a notoriously poor thermal conductivity, and HBTs are particularly subject to thermal limitations because of their high current densities. Diamond offers more favorable thermal properties making it interesting as a potential heat-sink material. In this work AlGaAs/GaAs HBTs were separated from their parent GaAs substrate using an $Al_{0.8}Ga_{0.2}As$ etch stop layer inserted 1.3 μm below the collector-base junction. The HBTs were then mounted on type IIA natural diamonds cut and polished on the (110) face. Small, medium and large emitter size HBTs were studied with respective areas of 4.2, 175.95, and 4489 μm^2. The measured I-V characteristics for the large transistor sizes exhibited a marked improvement by showing no NDR nor gain compression in their collector characteristics in contrast to the devices on the original GaAs substrates. Small and medium sized HBTs benefited less from the mounting on the diamond substrates: the diamond heat sink played only a minor role since for smaller devices the heat dissipation process is dominated by the 1.3 μm thick sub-collector layer. Work performed at University of California [Los Angeles, CA USA] and Rockwell International Science Center [Thousand Oaks, CA USA]. See "Flexible, Thin-Film, GaAs Hetero-Junction Bipolar Transistors Mounted on Natural Diamond Substrates", V. Albert-Engels et al, Solid State Electron., 38(11), p. 1972 [November, 1995].

Room Temperature Optical Memory Based on InAs Quantum Dots

Low-dimensional (1-D, 0-D) structures generally require cryogenic environments in order to display their trademark quantum behavior. However, a new work has demonstrated the room temperature operation of a new wavelength-selective optical memory structure based on self-assembled InAs quantum dots grown into a GaAs substrate. The retention time for the quantum dot optical memory was measured to be equal to 0.48 ms at 300K. Upon a "WRITE" illumination with a properly selected wavelength, electron-hole pairs are created in quantum dots characterized by a corresponding ground state energy (thus implementing the wavelength selectivity). The photogenerated electrons tunnel out of the dots to be collected in the buffer layers and read as a photocurrent. On the other hand, photogenerated holes are blocked by an appropriate barrier: the blocked holes bleach further absorption and reduce the photocurrent magnitude in subsequent "READ" light pulses, thus implementing the desired optical memory effect. The memory contents as a whole can be erased by positively biasing the Schottky gate metal electrode. Work done at Fujitsu Laboratories [Atsugi, Japan] and Hokkaido University [Sapporo, Japan]. See "New Optical Memory Structure Using Self-Assembled InAs Quantum Dots", K. Imamura et al., Jpn. J. Appl. Phys., 34(11A), L1445 [1 November 1995].

Characterization of Very High Purity InAs

Interest in InAs has rekindled because of its very high electron mobility and because its narrow energy gap makes it suitable for application in mid-infrared optoelectronic components. However, surprisingly little is known about the optical properties of this increasingly significant binary compound, due to the fact that its very light electron and hole effective masses places severe restrictions on the purity of the material required to observe excitonic processes in InAs.

Researchers at Simon Fraser University [Burnaby, BC Canada] recently reported the growth of high-mobility, high-purity InAs bulk layers by MOCVD, and the resolution of excitonic and impurity band emission bands. InAs epilayers were grown in a low-pressure vertical MOCVD reactor using TMI and TBA sources under a variety of growth conditions at a pressure of 50 Torr. Hall effect samples were grown on (100) and 2° vicinal [toward (110)] GaAs semi-insulating substrates. The best photoluminescence samples were grown on un-doped LEC (100) InAs substrates. Average Hall effect electron mobilities as high as 120,000 cm^2/Vs were observed at 50K in 10 micron thick samples grown at 540°C. Fitted mobilities from field-dependent measurements reached values as high as 180,000 cm^2/Vs. AFM measurements of samples grown side-by-side on GaAs and InAs substrates reveal that samples grown on InAs display very smooth surfaces with well-defined terraces characteristic of step flow growth while samples grown on GaAs show significantly rougher surfaces. SIMS analysis revealed that samples grown with a higher TBA partial pressure (0.12 Torr) were characterized by low carbon ($2x10^{16}$ cm^{-3}) and sulfur ($3x10^{15}$ cm^{-3}) background concentrations, while samples grown with a TBA partial pressure of 0.028 Torr showed significantly higher background concentrations.

PL measurements on samples grown on high-purity InAs substrates revealed excitonic features that have been identified as a i) donor-acceptor pair band (based on the blue shift observed with increasing pumping laser power excitation), and ii) a very sharp acceptor bound exciton band at 413 meV. Two distinct acceptor levels of unknown chemical origin were observed through their two-hole transitions demonstrating that chemical central cell shifts between different acceptors are clearly observable in high-purity InAs epilayers despite the small energy gap and the light effective masses.

See "Characterization of very high purity InAs grown using Trimethylindium and Tertiarybutylarsine", S. P. Watkins, et al, J. Electron. Matls., 24(11), 1583 [November, 1995].

Crystal Puller from CVD

CVD Equipment Corporation [Ronkonkoma, NY] has introduced a CZ Crystal Growing System specifically designed for growing semi-insulating undoped GaAs crystals. The system may also be used for the production of a variety of other materials. Crucible sizes from 4" to 8" dia. can be accommodated. Other features include stainless steel water cooled construction, vacuum through 30 PSIG integrity, balanced seed lift/rotation assembly with seed lift cable wound on a traveling horizontal reel, and viewport designs allowing clear sight of the crystal during growth. ***Circle 148 on Reader Service Card.***

Metalorganic Level Monitor

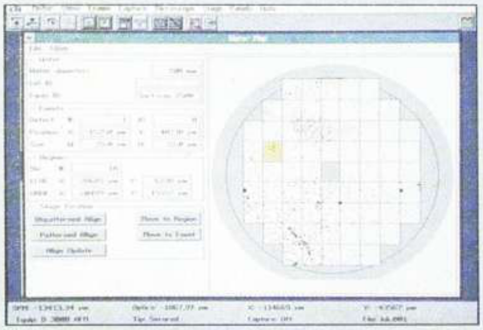
Advanced Process Technology [Plano, TX] has developed a liquid level sensor for fluids used in CVD and MOCVD epitaxy. Levels of heated or refrigerated liquids are measured from 0 to 20 inches in increments of 0.010 inches. Both high and low pressure systems are accommodated, and the sensor is placed externally to the bubbler, which eliminates the possibility of interference with source temperature control. Applications include reactor monitoring to prevent unexpected depletion of source material as well as diagnostics. ***Circle 45 on Reader Service Card.***

Ion Beam System from Oxford Plasma Technology

Ionfab 300 Plus is a new compact ion beam processing system from Oxford Plasma Technology [Yatton, Bristol, UK] for use in inert or reactive ion etching, ion beam sputter deposition, and ion assisted deposition. RF powered ion sources and filamentless beam neutralizers provide extended up-time, reduced source cleaning requirements, and improved process stability, especially when using "aggressive" process gases such as chlorine or oxygen. Wafer handling facilities include a simple automatic load-lock, multi-way automatic load-locks, and a robotic wafer handler with optional vacuum cassette loading. ***Circle 32 on Reader Service Card.***

Time of Flight SIMS + ESCA from VG Scientific

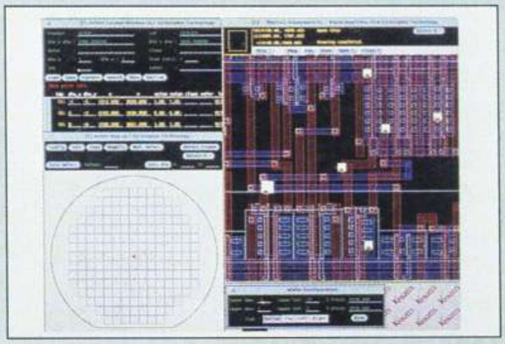
VG Scientific [East Grinstead, W. Sussex, UK] have added time of flight (ToF) SIMS capability to their ESCALAB 220i-XL system. The "ESCA ToF" provides chemical information and quantification from ESCA and molecular structural information and sensitivity from ToF SIMS for completely unambiguous and complementary analysis. Data can by acquired by both techniques without moving the sample. The ESCALAB 220i-XL also includes unique parallel XPS imaging which provides state-of-the-art spatial resolution for ESCA while the monofocusing monochromator provides excellent energy resolution. ***Circle 99 on Reader Service Card.***



Wafer Defect Map Import for AFMs

Digital Instruments [Santa Barbara, CA] has announced that their Dimension™ 5000 and 7000 Atomic Force/Scanning Probe Microscopes (AFM/SPMs) now support optional Navigator™ Software for importing wafer defect maps generated by KLA and Tencor defect inspection systems. The software allows for fast, non-destructive review of defects which are too small for optical analysis or measurement. The operator selects the defect to be analyzed from the defect map or through filters and the unit drives to the selected site(s) for scanning and measurement. ***Circle 127 on Reader Service Card.***

Software for Linking Defect Mapping, Failure Analysis Tools, and CAD

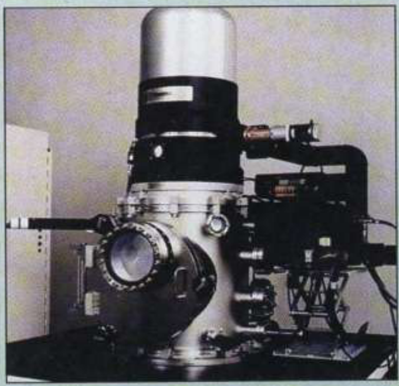


The new Defect Wafer Map™ software from Knights Technology, Inc. [Sunnyvale, CA] provides a direct link between defect data and failure analysis tools and CAD software, allowing engineers to directly correlate defect coordinate data from inspection equipment with the IC design. By combining defect and design data and overlaying defect locations on the chip design, users can view the defect locations relative to the physical layout or schematic of the chip for better evaluation of defect sources and their potential contribution to yield loss. ***Circle 151 on Reader Service Card.***

New RGA from Hiden

Hiden Analytical Ltd. [Warrington, UK] has announced the HAL-RC Series of residual gas analyzers for fast, precise and easy to use vacuum diagnostics. They operate under Windows™ software with an integral "Scan Gallery" which provides easy access to the primary RGA operations including vacuum fingerprinting, leak detection and multiple ion detection for real time trend analysis of complex gas mixtures. A selection of ion source options are available for specific applications including a platinum version for minimal outgassing and reduced electron stimulated desorption in UHV. ***Circle 59 on Reader Service Card.***

Large Area ECR Plasma Source

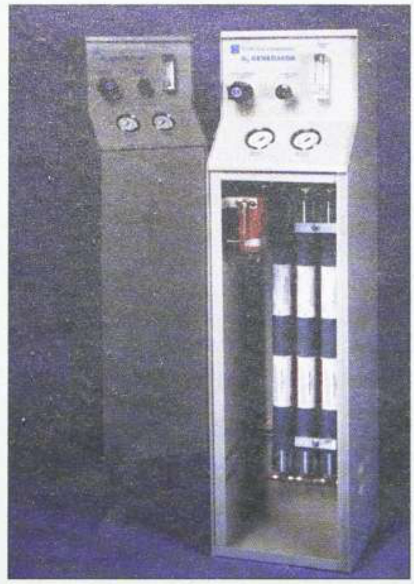


Wavemat, Inc. [Plymouth, MI] has introduced the MPDR 325i Electron Cyclotron Resonance (ECR) microwave plasma source with automatic closed-loop tuning for production processing of large substrates. This advanced ECR plasma source generates a stream of low energy ions, atomic neutrals and activated species that can be used to obtain exceptional thin film properties in a wide variety of applications such as etching of sub-0.25 micron insulating and semiconducting thin films as well as high-rate ECR enhanced CVD of dielectrics and diamond-like carbon, boron nitride and other hard films. ***Circle 114 on Reader Service Card.***

Angle Resolved Electron Spectrometer

A new analyzer, model AR65, has been released by Omicron. It has been designed for dedicated angle-resolved electron spectroscopy (ARUPS) in laboratory and synchrotron environments. Features include a 65mm mean radius 180° hemispherical analyzer with a 4-element lens, featuring uniform magnification throughout the fixed ratio (FRR) range and ± 1° typical angular acceptance. It is offered with a dedicated, um-metal shielded UHV chamber or as part of a complete multi-technique ARUPS/surface science system. ***Circle 92 on Reader Service Card.***

Nitrogen Generators from Scott Specialty Gases



Scott Specialty Gases [Plumsteadville, PA] has announced the formation of Scott Gas Generators, a new division that manufacturers nitrogen generators for purging and blanketing operations. Scott nitrogen generators offer users a convenient, safe and cost-effective method of producing a continuous supply of nitrogen on-demand. They are capable of producing dry nitrogen up to 99.9% pure, with flowrates up to 500 scfm. Customized configurations that are matched to individual application requirements are also available. ***Circle 38 on Reader Service Card.***

RF Connectors for High Voltage Applications

Tru-Connector Corporation [Peabody, MA] has introduced a line of HN series of RF connectors that can be supplied in a wide variety of configurations for use with etching, sputtering, and other wafer processing systems and instrumentation. They are capable of handling up to 5,000 volts, have an impedance of 50 ohms, and a 0 to 4 GHz frequency range. They are fabricated from brass with a silver or nickel finish and silver or gold plated brass, phosphor-bronze, or beryllium-copper center conductors. ***Circle 149 on Reader Service Card.***

Permanent Magnet ECR Plasma Source from PlasmaQuest

PlasmaQuest, Inc. [Richardson, TX] has introduced the PQ 2000 Series permanent magnet electron cyclotron resonance (ECR) plasma source and multipolar confinement process chamber. Features include a permanent magnet with a steep magnetic field gradient allowing a locally-generated ECR plasma zone to diffuse into a plasma confinement process chamber. This offers great flexibility for CVD and etch processes where plasma reactants and workpieces each require optimized conditions. In addition, the permanent magnet creates a virtually zero magnetic field at the wafer. ***Circle 142 on Reader Service Card.***

Crystals for III-V Epitaxial Films

New oxide and semiconductor crystals specifically developed for depositing epitaxial films are now available from MarkeTech International [Pittsburgh, PA]. These include the newest crystal, lithium aluminate, which has been used to produce blue GaN LEDs. Other oxides include $MgAlO_3$ spinel up to 32 mm diameter, MgO up to 50 mm diameter, and sapphire. Non-oxide and semiconductor wafers are also available. All wafers are available with standard or custom orientations, edge orientation, one or two side epitaxial polish, and in custom sizes. ***Circle 102 on Reader Service Card.***

UPCOMING EVENTS

1996 IEEE Int'l Solid State Circuits Conference
February 8-10, 1996 at San Francisco, CA.
Contact: Diane Suiters, Courtesy Associates
655 Fifteenth St., NW, Suite 300
Washington, DC 20005 USA
TEL [1] 202 639 4255 FAX [1] 202 347 6109
Net or Web:
diane+la+rcourtesy_associates@mcimail.com

Int'l Symp. on Blue Laser and Light Emitting Diodes
March 5-7, 1996 at Chiba, Japan.
Contact: Prof. M. Kobayashi, Secretary, ISBLLED
Chiba Univ., E&EE Dept.
1-33 Yayoi-cho, Inage-ku, Chiba, Japan 263
TEL [81] 43 290 3330
FAX [81] 43 290 3360
E mail isblled@semi.te.chiba-u.ac.jp

3rd Int'l Conf. on the Physics of X-Ray Multilayer Structures
March 3-7, 1996 at Breckenridge, CO, USA.
Contact: Ms. Marty Benson, Admin. Asst.
Univ. of Arizona, Dept. of Physcis
PAS #81, Tucson, AZ USA 85721
TEL [1] 520 621 2878 FAX [1] 520 621 4356
E mail pxrms-info@nanook.div111.att.com

1996 Spring Meeting of the Materials Research Society
April 7-11, 1996 in San Francisco, CA, USA.
Contact: M. Geil, Dir., Meering Activities
Materials Research Society
9800 McKnight Road
Pittsburgh, PA 15237 USA
TEL [1] 412 367 3004 FAX [1] 412 367 4373
E mail info@mrs.org

8th Int'l Conf. on Indium Phosphide and Related Materials
April 22-25, 1996 at Schwabisch-Gmund, Germany.
Contact: Volker Schanz
ITG/VDE
Stresemannaliee 15
60590 Frankfurt Main, Germany
TEL [49] 69 6308 360
FAX [49] 69 9631 5217

1996 Int'l Conf. on GaAs Manufacturing Technology
April 28 to May 2, 1996 in San Diego, CA.
Contact: Neal Mellen, Conf. Chair
Motorola
4800 Alameda NE
Albuquerque, NM 87113 USA
TEL [1] 505 822 8801x236
FAX [1] 505 822 8812
Net or Web: gaas@ee.eustl.edu or
http://www.ee.wustl.edu/GaAs/

3rd Int'l Workshop on Expert Evaluation and Control of Compound Semiconductor Materials and Technologies
May 12-15, 1996 at Freiburg, Germany.
Contact: Dr. W. Jantz
Fraunhofer IAF
Tullastr. 72
D-79108 Freiburg I. Br., Germany
TEL [49] 761 5159 510
FAX [49] 761 5159 423

1996 European GaAs and Related III-V Compounds Applications Symposium
June 5-7, 1996 in Paris, France.
Contact: GAAS 96
ENSEA, 6 avenue du Ponceau
95014 Cergy Cedex, France
FAX [1] 33 1 30 73 66 27

8th Int'l Conf. on MOVPE
June 9-13, 1996 in Cardiff, Wales.
Contact: Glenda Bland
Global Meeting Planning, GMP 22 Plas Taliesin
Portway Village Marina, Penarth,
South Glamorgan CF64 1TN, Wales
TEL [44] 1222 700 053 FAX [44] 1222 700 685
E mail 100416.1402@compuserve.com

CALL FOR PAPERS

20th Workshop on Compound Semiconductor Devices and Integrated Circuits

WOCSDICE '96 will be held May 19-22, 1996 in Vilnius, Lithuania. This annual European workshop is an important milestone in research activity directed toward applications where silicon devices seem to be inferior as compared to the performance offered by compound semiconductors and heterostructures with a wider spectrum of fundamental properties. Devices and circuits operating at high ambient temperatures, in microwave and terahertz frequency range, fast optoelectronic and low noise devices and circuits together with the related physical and technological backgrounds are the scope. The number of particpants will be limited to around 80.
Abstract Submission Deadline: March 1, 1996
Contact: Ilona Matulioniene
Semiconductor Physics Institute
A. Gostauto 11
LT-2600 Vilnius, Lithuania
TEL [370] 2 618 101 FAX [370] 2 627 123
Net or Web: matulionis@uj.pfi.LT or
http://uj.pfi.LT/conf/wocsdice/wocs96.htm

1st European GaN Workshop

The 1st European GaN Workshop will be held June 2-4, 1996 at Rigi, Switzerland. It will encompass all areas of research relating to the physical properties and device applications of the Group III-Nitride semiconductors. The workshop will be formatted in 5-10 minute presentations followed by a longer open discussion period. In addition, a few distinguished people from outside of Europe will be invited to present their research in depth. It is the intention of the organizers that the GaN Workshop be as open as possible to permit maximum interaction amongst the participants.
Abstract Submission Deadline: March 1, 1996
Contact: Dr. Toby Strite
IBM Zurich Research Laboratory
Saumerstrasse 4
Ruschilkon CH-8803 Switzerland
TEL [41] 01 724 83 55 FAX [41] 01 724 17 89
Net or Web: srt@zurich.ibm.com

1996 Device Research Conference

DRC '96 will be held June 24-26, 1996 at Santa Barbara, CA, in conjunction with the Electronic Materials Conference (see below). The DRC is intended to bring together scientists, engineers, and students to discuss new and exciting breakthoughs and advances in the field of device research. Papers are solicited on a wide variety of novel device work.
Abstract Submission Deadline: March 1, 1996
Contact: Jim Sturm, Princeton Univ., EE Dept.
Olten Street.
Princton, NJ 08544 USA
TEL [1] 609 258 5610 FAX [1] 609 258 6279
Net or Web: sturm@ee.princeton.edu or
http://www. ee.princeton.edu/~sturm/drc.html

1996 Electronic Materials Conference

EMC '96 will be held June 26-28, 1996 at Santa Barbara, CA, in conjunction with the Device Research Conference (see above). The conference is intended to provide a forum for topics of current interest and significance in the area of preparation and characterization of electronic materials. Individuals actively engaged or interested in electronic materials research and development are encouraged to attend this meeting, and papers in this general subject area are solicited.
Abstract Submission Deadline: Feb. 15, 1996
Contact: Customer Service, TMS
420 Commonwealth Dr.
Warrendale, PA 15086 USA
TEL [1] 412 776 9000 x241
FAX [1] 412 776 3770

23rd Int'l Conf. on the Physics of Semiconductors

ICPS-23 will be held July 21-26, 1996 at Berlin, Germany. All aspects of semiconductor physics including organic and inorganic materials and devices will be covered and highlighted by plenary and invited talks as well as contributed papers.
Abstract Submission Deadline: Feb. 19, 1996
Contact: Dr. Axel Hoffmann, Secretary
Institut fur Festkorperphysik
PN 5-1, TU Berlin
Hardenbergstr. 36
10623 Berlin, Germany

Ninth Int'l Conf. on Superlattices, Microstructures, and Microdevices

ICSMM-9 will be held July 14-19, 1996 at Liege, Belgium. The scope of this conference includes novel phenomena in semiconductor superlattices and quantum wells based on IV-IV, III-V, & II-VI compounds, as well as microstructures and superlattices based on other materials such as porous silicon, nitrides, metal/magnetic/semimagnetic materials, and semiconductor/metal microstructures. Also of interest are: nanostructures and low dimensional systems with strong emphasis on novel phenomena in quantum wires and quantum dots including dot-dot interaction; novel fabrication and probing techniques of quantum structures, including self-organized systems, ordered granular systems, and chemistry of nanoscale systems; STM, ATM, and novel technologies; photonic band gap materials and microcavities; and novel nanoscale devices including Si, SiGe, and SiC devices.
Abstract Submission Deadline: March 15, 1996
Contact: Prof. Jean-Pierre Leburton
Univ. of Illinois
Beckman Institute, Urbana, IL 61801 USA
TEL 217 333 6813 FAX 217 244 4333
Net or Web: leburton@ceg.uius.edu

Ninth International Conf. on Molecular Beam Epitaxy

MBE-IX will be held August 5-9, 1996 at Malibu, CA. This conference will cover the full spectrum of MBE-related topics. Subjects covered will include MBE growth of semiconductors, metals, insulators, and superconductors, as well as novel growth techniques , in situ control and characterization, and device applications of MBE technology.
Abstract Submission Deadline: March 15, 1996
Contact: Dwight Streit
TRW
R6-2373, One Space Park, Redondo Beach,
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

TWHM '96 will be held August 19-21, 1996 in Sapporo, Hokkaido, Japan. The objective of this conference is address critical technical issues in the development and application of heterostructure microelectronic technologies by providing a forum for international collaboration. This year's workshop will focus on HBT and HEMT technologies based upon a range of heterostructure materials systems including III-V's, IV-IV's and wide bandgap materials such as GaN and SiC. Papers are solicited in areas of heterostructure materials and device development and circuit demonstration, as well as the application of heterostructure microelectronic technologies to wireless, telecommunications, and signal/data processing systems.
Abstract Submission Deadline: April 8, 1996
Contact: Dr. Takyiu Liu
Hughes Research Laboratories
Malibu, CA 90265-4799 USA
FAX [1] 310 317 5450 E mail tliu@msmail4.hac.com

23rd Int'l Symposium on Compound Semiconductors

ISCS-23 will be held September 23-27, 1996 in St. Petersburg, Russia. This conference is a premier forum on all aspects of compound semiconductors, including growth, processing, devices, and ICs. Materials covered include GaAs, InP, GaN, ZnSe, and SiC. ISCS is the successor to the "Gallium Arsenide and Related Compounds" conference series.
Abstract Submission Deadline: TBA
Contact: See ad on page 43 for more information.

Int'l 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

2nd Int'l Symp. 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

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 by February 15 to appear in our next issue.

The Last Semiconductor?

Looking back some years from now, we may well identify the invention of the GaN laser as the moment in which we began contributing to technologies as opposed to founding them.

TOBY STRITE
Research Staff Member
IBM Zurich Research Laboratory
Ruschlikon, Switzerland

As you've read in this issue (page 7), Shuji Nakamura and coworkers at the Nichia Chemical Company have announced the successful fabrication of the first GaN-based diode laser. For many of us who have been active in the GaN field, this is the Holy Grail of nitride semiconductor research. Not only does its 410 nm wavelength enable further increases in optical storage density, but it gives the community the collective satisfaction that GaN has been brought to heel. It also should cause us to reflect that the GaN laser was the final semiconductor device known to be of major technological and economic importance which had not yet been demonstrated.

Semiconductor materials and device research has enjoyed a well deserved golden age reflecting the economic impact of semiconductor and derivative technologies. Academic and industrial researchers collaborated to usher an unprecedented rapidity of development. In less than fifty years we have seen the invention of the transistor blossom into the Information Age. During this entire period, there were always clear-cut next challenges; devices like the semiconductor laser which had not yet been realized or new material systems which promised to extend our reach to higher frequencies or new wavelengths.

When Si became a technology, few universities could support the infrastructure needed for frontier research. This period coincided fortuitously with the development of advanced epitaxial techniques which opened compound semiconductors to fruitful academic research. Materials of unprecedented quality were grown with atomic layer thickness control, and universities pioneered whole new materials and device concepts. GaAs, and later InGaAlAs/InP, have since moved out of the laboratory. No longer able to make the world's fastest transistors, university research shifted again to lesser developed semiconductor materials.

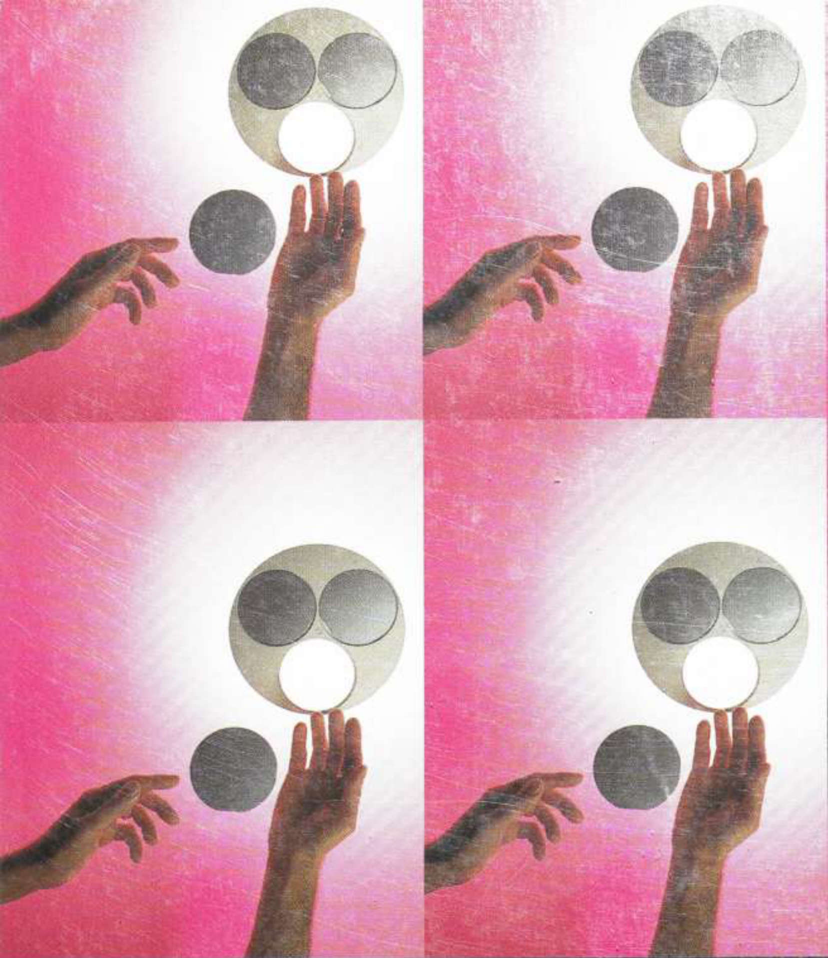
GaN is the final semiconductor whose exploitation was known to be of profound economic importance, and thereby justified the type of research effort to which the semiconductor community has grown accustomed. Therefore, when GaN funding subsides, it cannot simply reappear as before with the group III or V element changed. On the other hand, the invention of the GaN laser certainly does not decrease our need for further progress in this or other material systems. It simply means that future tasks will be a little more mundane, the goals no longer so grand.

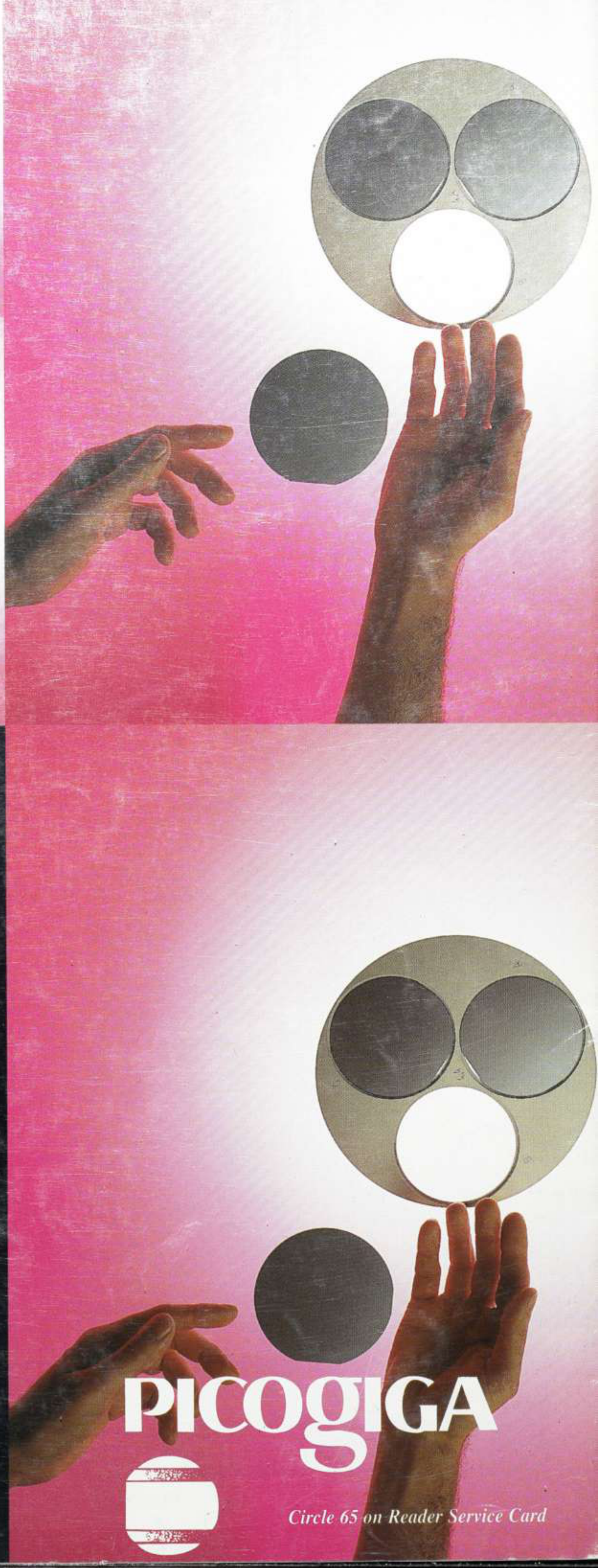
Nichia's work has completed the hegemony of semiconductor LEDs and lasers of the full visible spectrum. Meanwhile, leadership in InGaAlP, SiGe, SiC, HgCdTe, and now GaN devices has been largely ceded to industry as development and production begin in earnest. GaN is the final semiconductor whose exploitation was known to be of profound economic importance, and thereby justified the type of research effort to which the semiconductor community has grown accustomed. Therefore, when GaN funding subsides, it cannot simply reappear as before with the group III or V element changed.

On the other hand, the semiconductor industry, and therefore funding and demand for skilled graduates, will only increase in size and influence as a result of these new materials. The invention of the GaN laser certainly does not decrease our need for further progress in this or other material systems. It simply means that future tasks will be a little more mundane, the goals no longer so grand. Looking back some years from now, we may well identify the invention of the GaN laser as the moment in which we began contributing to technologies as opposed to founding them.

Dr. Strite has been working on GaN and other compound semiconductors for nearly 10 years. He is currently a member of the optoelectronics department of the IBM Zurich Research Laboratories where he works on LED display applications. He holds a B.S. in physics from Bucknell University and a PhD. in physics from the University of Illinois in Urbana-Champaign. Dr. Strite is an editor of the Materials Research Society Internet Journal of Nitride Semiconductor Research and Co-chairman of the first European GaN Workshop.


FROM SUBSTRATES TO SUPERLATTICE OUR QUALITY IS CRYSTAL CLEAR
Single & Poly Crystal
GaAs • InP • InSb
GaSb • InAs
Epitaxy
VPE • LPE • MBE • OMVPE
Sumitomo Electric has been supplying a full range of III-V materials for more than 20 years. During this period we have developed a repertoire of epitaxial processes that include LPE, VPE & MBE. One of our latest substrate advances has been growth of super-long LEC ingots with the most electrically consistent properties available. Our proprietary InP VCZ material has crystal uniformity that is unmatched.





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