COMPOUND SEMICONDUCTOR

September/October 1996 *Volume 2 Number 5*

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COMPOUND SEMICONDUCTOR

COVER STORY

OTHER FEATURES

DEPARTMENTS

NEWS

On the Cover: Vitesse's 16:1 mux/demux for 10Gb/s SONET telecommunications links. Currently available in microwave modules, with lower cost packaging in development.

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UPCOMING EVENTS

1st European Conference on SiC and Related Materials
October 6-9, in Heraklion, Crete, Greece.
Contact: Georgia Papadaki
FORTH/IESL, PO Box 1527
GR-711 10 Heraklion, Crete Greece
TEL [30] 81 239 779 FAX [30] 81 239 735
Net or Web: georgia@iesl.forth.gr

Int'l Workshop on Novel Index Surfaces
October 7-9 in Lyon, France.
Contact: Prof. G. Guillot
INSA Lyon, LPM, Bat 502
69621 Villeurbanne Cedex France
TEL [33] 72 438 161 FAX [33] 72 438 531

Symp. On Novel Device Structures
190th Meeting of the Electrochemical Society
October 6-11 in San Antonio, TX, USA.
Contacts: April Brown or Kevin Brennan
Georgia Institute of Technology
ECE Dept., Atlanta, GA 30332-0250 USA
TEL [1] 404 894 5161 FAX [1] 404 894 0222

43rd Nat'l Symp. Of the American Vacuum Society
October 14-16 in Philadelphia, PA.
Contact: AVS
120 Wall Street, 2nd Floor
New York, NY 10005 USA
TEL [1] 212 248 0200 FAX [1] 212 248 0245
Net or Web: avs96@vacuum.org or
http://www.vacuum.org

2nd Int'l Symp. On Control of Semiconductor Interfaces
October 28 - November 1 in Karuizawa, Japan.
Contact: Prof. T. Ito, Osaka Univ., EE Dept.
2-1 Yamada-oka, Suita
Osaka 565 Japan
TEL [81] 6 879 7702 FAX [81] 6 879 7704

1996 IEEE GaAs IC Symposium
November 3-6, 1996 in Orlando, FL.
Contact: Phil Wallace, Anadigics
Box 4915, 35 Technology Drive
Warren, NJ 07060 USA
TEL [1] 908 412 5985 FAX [1] 908 412 5986
Net or Web: wallacepw@aol.com

4th IEEE Int'l Wkshp on High Performance Devices for Microwave and Optoelectronic Applications
November 24-26, 1996 at Leeds, UK
TEL [44] 113 233 2032 FAX [44] 113 233 2032
Net or Web: z.iezekiel@elec-eng.leeds.ac.uk

Advertiser Index

CALL FOR PAPERS

Gallium Arsenide VLSI '96
A course entitled "Gallium Arsenide VLSI '96: Circuits & Systems" will be offered by the Centro Microelectronica Aplicada on November 26-29, 1996 at Maspalomas, Gran Canaria, Spain.
Registration Deadline: October 1, 1996
Contact: Gallium Arsenide VLSI '96
Centro Microelectronica Aplicada
Universidad de Las Palmas de Gran Canaria
Campus Universitario de Tafira
E-35017 Las Palmas de Gran Canaria Spain
TEL [34] 28 45 12 32 FAX [34] 28 45 12 43
Net or Web: gaas96@cma.ulpgc.es or
http://www.cma.ulpgc.es/GaAsVLSI96/

1996 Conference on Optoelectronic and Microelectronic Materials and Devices
COMMAD '96 will be held December 9-11, 1996 at Canberra, Australia. The aim of this conference is to bring together industrial collaborators, scientists, engineers and students to discuss new and exciting advances in the fields of optoelectronic and microelectronic materials and devices.
Contact: C. Jagadish
Dept. Of Electron. Matls Eng.
RSPhysSE, Australian Nat'l Univ.
Canberra, ACT 0200 Australia
TEL [61] 6 249 0363
FAX [61] 6 249 0511
Net or Web: cxj109@phys.anu.edu.au

1997 IEEE International Solid-State Circuits Conference
ISSCC '97 will be held February 6-8, 1997 in San Fransico, CA USA. The theme for the 1997 conference is "Multimedia".
Abstract Submission Deadline: September 6, 1996
Contact: Ms. Diane Suiters
655 - 15th Street, N.W., Suite #300
Washington, DC 20005 USA
TEL [1] 202 639 4255 FAX [1] 202 347 6109
Net or Web: isscc@mcimail.com

Photonics West 1997
Photonics West 1997 will be held February 8-14, 1997 in San Jose, CA USA. This meeting encompases more than 80 conferences on Lasers & Applications, Integrated Optoelectronics, Biomedical Optics, and Electronic Imagaing.
Abstract Submission Deadline: July 15, 1996
Contact: SPIE
TEL [1] 360 676 3290 FAX [1] 360 647 1445
Net or Web: PW97@spie.org

1997 Spring Meeting of the Materials Research Society
The Spring '97 Meeting of the MRS will be held March 31- April 4, 1997 in San Francisco, CA. Symposia topics include: Epitaxial Growth - Principles and Applications; Processing of Compound Semiconductors for High-Speed Devices; and GaN and Related Materials.
Abstract Submission Deadline: November 1, 1996
Contact: Materials Research Society
9800 McKnight Road
Pittsburgh, PA 15237-6006 USA
TEL [1] 412 367 3004; FAX [1] 367 4373
Net or Web: http:/www.mrs.org

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

Eighth Biennial Workshop on Organometallic Vapor Phase Epitaxy
The 8th OMVPE workshop will be held April 13-17, 1997 in Dana Point, CA, USA. This workshop is intended to provide an setting for the informal scientific and technical exchange of recent progress in OMVPE.
Abstract Submission Deadline: October 15, 1996
Contact: TMS Customer Service
420 Commonwealth Drive
Warrendale, PA 15086 USA
TEL [1] 412 776 9000
FAX [1] 412 776 3770
Net or Web: csc@tms.org

Ninth International Conference on Indium Phosphide and Related Materials
IPRM'97 will be held May 11-15, 1997 on Cape Cod, MA USA. Papers are requested in the following areas: Optoelectronics, Electronic Devices, Processing, Epitaxy, Bulk Growth, and Characterization. The conference will include invited and contributed oral and poster presentations. Short Courses and an Industrial Exhibit will also be offered.
Abstract Submission Deadline: November 11, 1996
Contact: Stephen Forrest
Princeton University
EE Dept.
E-Quad, Room 00301
Princeton, NJ 08544 USA
TEL [1] 609 258 3000
FAX [1] 609 258 1954
Net or Web: forrest@ee.princeton.edu

7th European Workshop on Metal-Organic Vapor Phase Epitaxy
EW MOVPE will be held June 8-11, 1997 in Berlin, Germany. This conferences aims to bring together scientists and engineers actively engaged in MOVPE, VPE and CBE/MOMBE growth of compound semiconductor materials.
Abstract Submission Deadline: February 28, 1997
Contact: Dr. Wolfgang Richter
Technishe Universitat Berlin
Hardenbergstr. 36
D-10623 Berlin Germany
TEL [49] 30 3142 2078
FAX [49] 30 3142 1769
Net or Web: richter@gift.physik.tu-berlin.de or
http:\\www.hhi.de

International Conference on Gallium Arsenide Manufacturing Technology
GaAs MANTECH '97 will be held June 2-5, 1997 in San Francisco, CA. The theme for this year is GaAs Manufacturing Challenges & Solutions - Cheaper, Better and Faster! Abstracts on processing, devices, manufacturing, reliability, materials and applications are solicited.
Abstract Submission Deadline: November 1, 1996
Contact: Terri Lockhart
Connections Plus
12 Lincoln Circle East
Red Bank, NJ 07701-5815 USA
TEL [1] 908 747 3075
FAX [1] 908 741 1009
Net or Web: gaas@ee.wustl.edu or
http://www.ee.wustl.edu/GaAs/

Eight International Conference on II-VI Compounds and Devices
II-VI '97 will be held August 25 - 29, 1997 in Grenoble, France. The conference will focus on fundamental aspects and on recent perspectives for applications of narrow and wide bandgap II-VI semiconductors. Areas of interest include: materials science, where many long-standing problems (particularly compensation) are still to be solved, low dimensional physics including semimagnetic heterostructures, and optoelectronic applications.
Abstract Submission Deadline: March 15, 1997
Contact: Le Si Dang
II-VI Conference Secretariat
Laboratoire de Spectrometrie Physique
Universite J. Fourier - Grenoble 1, BP 87
F-38402, Saint Martin d'Heres Cedex France
FAX: [33] 76 51 45 44
Net or Web: lesidang@spectro.grenet.fr

24th International Symposium on Compound Semiconductors
ISCS '97 will be held September 7- 11, 1997 in San Diego, CA. This meeting is a forum for papers on all aspects of compound semiconductors including growth, processing, devices, and ICs. Materials of interest include III-V compounds including nitrides; SiC; wide bandgap II-VI compounds such as ZnSe, ZnS; IV-IV materials such as SiGe; and others.
Abstract Submission Deadline: April 14, 1997
Contact: ISCS '97
IEEE/LEOS
445 Hoes Lane
Piscataway, NJ 08854 USA
TEL [1] 908 981 0060
FAX [1] 908 981 0027
Net or Web: http://luciano.stanford.edu/ISCS/

6th International Conference on Chemical Beam Epitaxy and Related Growth Techniques
ICCBE 6 will be held September 8-10, 1997 in Montreux, Switzerland. The scope of this meeting is the entire spectrum of CBE, MOMBE, GSMBE, as well as related growth technologies. Mechanisms and processes of growth and film properties directly related to the growth process are the main focal points, but relevant characterization techniques, physical properties and the relation between materials and device properties are equally addressed.
Abstract Submission Deadline: April 1, 1997
Contact: Dr. Alok Rudra
Swiss Federal Institute of Technology
Institute for Micro and Optoelectronics
CH-1015 Lausanne Switzerland
FAX [41] 21 693 54 90
Net or Web: rudra@eldp.epfl.ch

International Conference on Secondary Ion Mass Spectrometry
SIMS XI will be held September 7-12, 1997 at Disney World (Orlando, FL) of all places.
Abstract Submission Deadline: June 1, 1997
Contact: Judith Sjoberg
SIMS XI
1201 Don Diego Avenue
Sante Fe, NM 87505 USA
TEL [1] 505 989 4735
FAX [1] 505 989 1073

16th North American Conference on Molecular Beam Epitaxy
NAMBE 16 will be held October 5-8, 1997 at the University of Michigan in Ann Arbor. Topics will include but are not limited to: advances in MBE, CBE, etc. growth techniques; in-situ measurment and control; deposition of new materials; heterostructures; patterned and selective area growth; devices and novel concepts; production MBE technology.
Abstract Submission Deadline: TBA
Contact: Pallab K. Bhattacharya
University of Michigan
Dept. Of EE & CS
1301 Beale Ave.
Ann Arbor, MI 48109 USA
TEL [1] 313 763 6678
FAX [1] 313 763 9324
Net or Web: pkb@eecs.umich.edu

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 October 21 to appear in our next issue.

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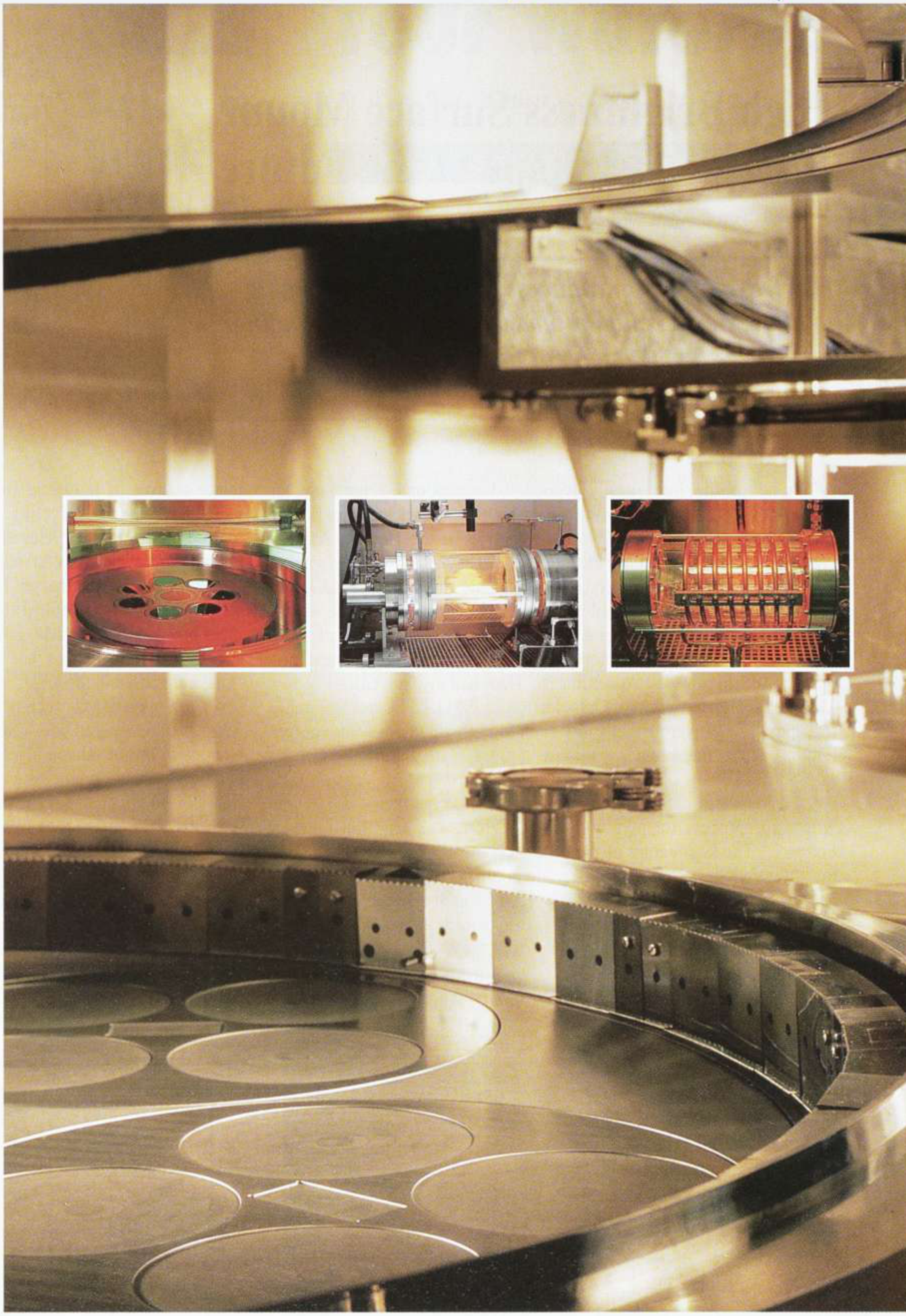

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High Brightness Surface Mount LEDs: The Shape of the Future

Hewlett-Packard introduces "Flip-Chip" packaging to allow surface mount models without wire-bonding; introduces a new family of high brightness AlInGaP LEDs

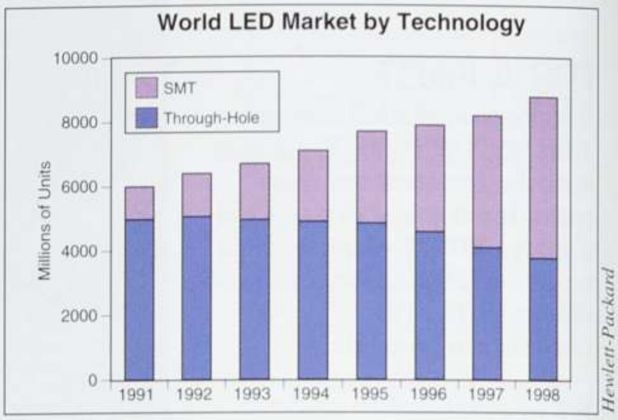


Figure 1: Hewlett-Packard's quantification of the demand for LEDs.

One of the most easily recognized compound semiconductor devices is the LED, with its familiar domed package. But not for long, according to the market analysts at the Hewlett-Packard Optoelectronics Division in Palo Alto, CA. They report that the market is moving away from traditional through-hole mounting for LEDs in favor of surface mount technology (SMT). HP predicts that the world-wide LED market will reach 8 billion units this year, and that SMT LEDs will constitute the majority of that market within the next two years. See Figure 1. According to Dan Kolody, an LED Product Manager at Hewlett Packard Optoelectronics, SMT LEDs are preferable for many fast-growing applications such as portable phones, automotive lighting, and office products because of their small footprint and easy assembly.

HP hopes to capture a major portion of that market with its new "flip-chip" process for packaging SMT LEDs, which is illustrated in Figure 2. The key feature of the process is the elimination of the need for a wire bond, because the LED chip is turned on its side ("flipped") and the wire bond is replaced with solder. This technique reduces the cost of manufacturing the LEDs, because wire bonding is one of the most demanding - and therefore expensive - steps in conventional SMT processes. It also improves the reliability of the product, by eliminating the possibility of wire breakage, and allows for a slimmer profile, down to 0.6mm in some models. HP believes that broken bond wires are a major sources of failure in LEDs, especially where the device is subjected to temperature cycling. These new flip chip LEDs are qualified to 1,000 temperature cycles at full operating power, as opposed to 100 temperature cycles for conventional wire-bonded units.

Kolody reports that at least four new processing developments were required to implement the flip-chip LED. The first was development of a proprietary pick-and-place SMT die handling system, because standard equipment was not available which could pick up the very small chips used in the LEDs and then turn them on their sides. The second development was techniques for metalizing both sides of the epi wafer. Also required was a new high-temperature soldering process to work with the metalized layers. And the final new requirement was a batch encapsulation process capable of whole-board encapsulation. This final development also helps to reduce the cost of the flip-chip LEDs, as previous SMT techniques relied on encapsulating the devices one at a time. Kolody reports that this step is also interesting in that the new process allows use of a wide range of epoxy types, and in the future HP plans to create lenses through epoxy alone, which will allow models with highly focused output.

The flip-chip process is currently being applied to HP's GaAsP/GaP LEDs in the red, orange, yellow and yellowish-green (what HP calls "GaP green") colors. This technology provides luminous intensities ranging from 9 mcd for red to 5 mcd for orange and GaP green to

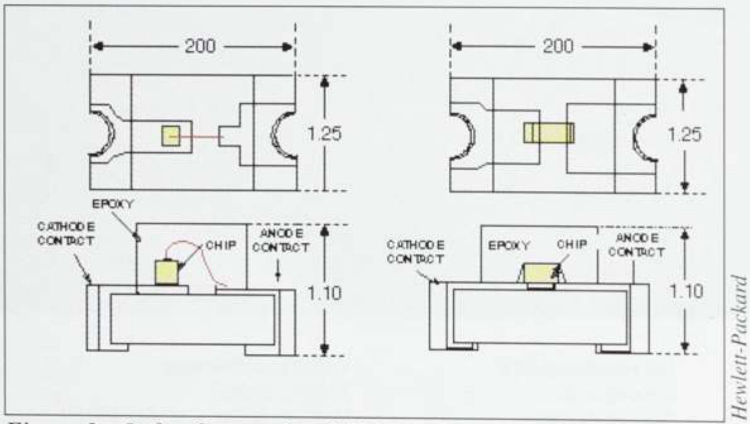


Figure 2: Left - Conventional SMT LED with die attach and wire bond assembly. Right - HP's SMT LED with flip chip die attach and solder assembly.

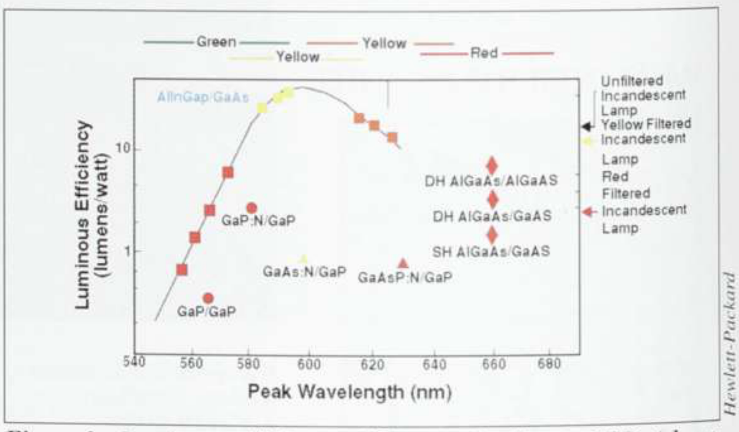


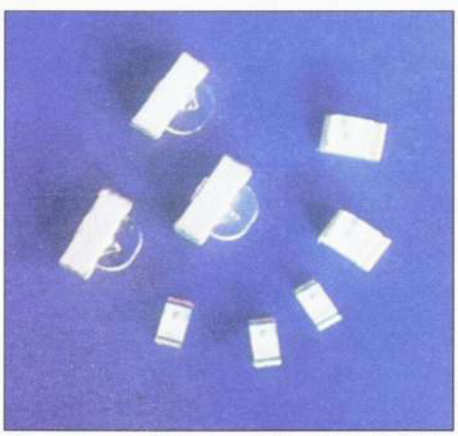
Figure 3: Luminous efficiency of the new SunPower LEDs (shown as squares) compared to competing materials.

4 for yellow (all @ 20 mA). HP plans to introduce higher brightness, quaternary-based LEDs in the flip-chip package sometime later this year or early next year. The current flip-chip LEDs are priced at \$0.17 each in low volumes.

"Sun Power" LEDs

Hewlett-Packard has also introduced a new family of high brightness MOVPE-grown AlInGaP LEDs in amber, orange and reddish-orange. At 20 mA the new LEDs have luminous intensities of 65 mcd for amber and orange and 50 mcd for reddish-orange. These new devices, called the "Sun Power Chip" series (an HP trademark for AlInGaP), are priced at ~\$0.26 each in low volumes, which is about twice the price of conventional surface-mount LEDs. However, HP calculates that, because of their extremely high brightness, the total cost to provide equivalent illumination will be approximately one-third less. For example, only four of the new LEDs are needed instead of twelve GaP LEDs to achieve the same or brighter illumination in a typical backlighting application, such as cellular telephones. Also, the power consumption is reduced by a factor of three (120 vs. 40 mA).

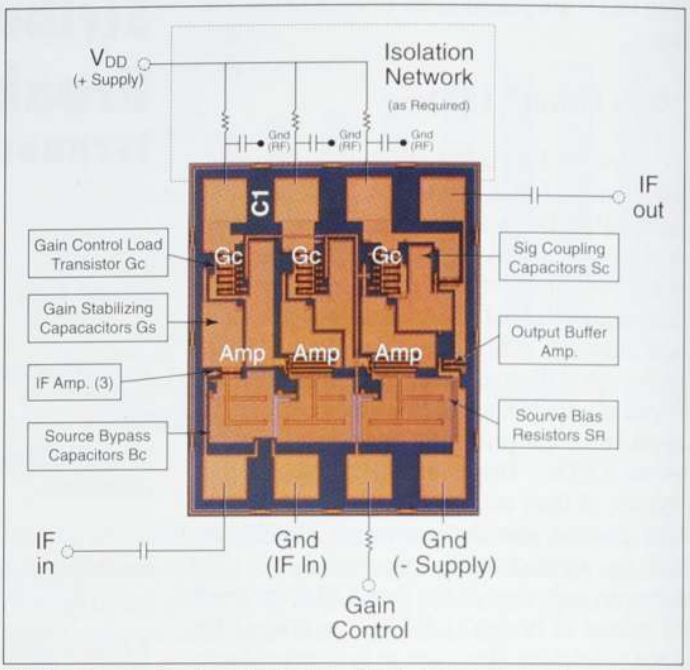
The SunPower Chip technology provides a significant improvement in luminous efficiency over competing materials, as is shown in Figure 3. And new models are on their way. The current SunPower Chip structure is grown on GaAs, which means that a portion of the emitted light is absorbed by the substrate. But HP will soon be introducing commercial models which utilize its transparent substrate (TS) technology, wherein the GaAs substrate is removed and replaced with a GaP substrate (see *CS* 2(1), p. 22). The light emitted into the larger bandgap GaP substrate is transmitted through it, making the LED more efficient - and even brighter than the already impressive models currently on the market.



Examples of HP's new "Flip-Chip" LEDs.

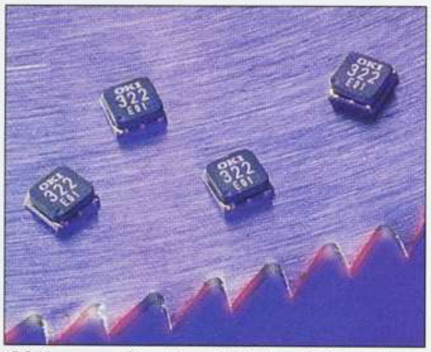
Oki Continues to Roll GaAs Products for Wireless

Oki Semiconductor has continued its recent roll out of new GaAs devices with three new offerings. First is an **adjustable gain control (AGC) 5-V intermeddiate frequency (IF) amplifier** capable of amplifying and attenuating a wide range of signals for CDMA radios, cellular phones, Persconal Comunications Services (PCS) and spread spectrum applications. Specified for 130 MHz, its usable range extends 70 MHz to 260 MHz. The company claims that the new device offers a dynamic gain/attenuation range greater than 90 dB, whereas most AGC amplifiers can only achieve a dynamic gain/attenuation range of <45 dB. This is due, at least in part, to the low distortion characteristics of GaAs. The company also points out that many AGC amplifiers require both a negative and a positive power supply voltage to attain a wide dynamic range, whereas the new device uses a single, positive 5V supply of 5 mA. The small size of the device (8 pin plastic SOP, 5mm x 6.8 mm) eliminates additional gain stages and can expand the number of users in a WLAN or wireless systems. The low distortion level permits a single device to be used in both the transmitter and receiver. No critical imedance matching is required on inputs or outputs. The device is fabricated using OKI's 0.5 µm high implant density process, and is currently in full production. Pricing begins at $4.45 each for orders in excess of 1,000 pieces.



Die functions for the KGF2441, Oki's new adjustable gain control IF amplifer circuit. There are three adjustable gain control stages of two layer metal, GaAs MESFET amplifiers, followed by a fixed gain buffer output stage. GaAs is used to achieve the best noise figure, with widest, non-distortng dynamic range.

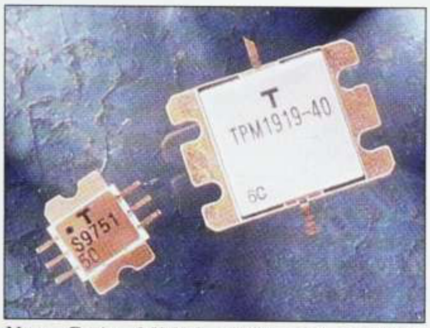
Also new from Oki is a family of **low-distortion RF driver and power amplifiers** for cellular, PCS and ISM Voice/Data Communications. These new devices are part of Oki's product line aimed at 850 MHz to 2.4 GHz digital communications systems operating at 3V. Target applications include wireless industrial, scientific & medical (ISM) band communications, as well as spread spectrum and microwave cellular voice/data systems. The new products include a power amplifier in a ceramic SMT package and two driver amplifiers in plastic packages, one providing 24 dBm @ 21 dB gain and the other providing 27 dBm @ 19 dB gain. All three are manufactured using OKI's 0.5 µm high-efficiency implant technology, permitting peak curents over 5.5 A at GHz frequencies, according to Dr. Moni Mathew, Oki's RF product manager. "The latest digital communications systems require very low distorition to prevent interference between phone channels'" said Mathew. "For the two major U.S. digital pone standards, IS-54/IS-136 (TDMA) and IS-95 (CDMA), Oki has developed a low-distortion, ion-implanted, epitaxial GaAs process to meet digital cellular and PCS power amplifier requirements. With Oki's new low-distortion power amplifier, for example, no system over-design is necessary, because the added epitaxial layer linearizes the gain vs. gate voltage curve, reducing channel leakage power and simplifying amplifier and system design." The new devices are currently in full production, with pricing for the power amplifier begining at $14.50 each, while the driver amplfiers are priced in the $6 - 8 range.



Oki's new family of GaAs RF surface acoustical wave (SAW) filters.

Oki has also recently launched a family of **GaAs RF surface acoustical wave (SAW) filters**. They are targeted toward wireless handsets, PCMCIA cards and wireless LANs. Operating at frequencies from 750 MHz to 2.0 GHz, the new filters come in a new, ultra-thin plastic/ceramic package (3.8 mm x 3.8 mm x 1.6 mm). The new family comprises two transmitting filters and three receiving filters. They have input and otuput impedances of 50 ohms. They exhibit insertion loss of < 3.5 dB for a STOP band > 20 dB and < 4.0 dB for a STOP band > 30 dB. Maximum input power rating is > 100 mW. The band pass ripple ranges from < 1.5 dB to < 2 dB, depending on frequency and bandwidth. The new SAW filters are priced at $4.00 each.

New Products from Toshiba



New GaAs MMIC (left) and partially matched L/S-band GaAs FET from Toshiba America Electronic Components, offered at a frequency of 1.9 GHz.

Toshiba has announced a handful of new GaAs products for wireless and satellite applications. The new products include a **low distortion 15 W, 14.0 - 14.5 GHz Ku-band GaAs FET** for very small aperture terminals and satellite communications. Also available is a new **partially matched L/S-band GaAs FET operating at 1.9 GHz**. The new device is offered at 40 W, which Toshiba believes is the first L/S band GaAs FET to achieve shuch a high output of power. According to a company spokesperson, achieving this level of output usually requires the use of a MMIC, but this new device will give designers an option in the 1.9 GHz frequency range to use a discrete device instead. The new product is targeted toward base stations used in cellular phone transmissions. Toshiba has also introduced a companion device, a **1.9 GHz GaAs MMIC**, for use as an LNA in wireless handsets. The Ku-Band FETs are priced at $1,100 each. The L/S-Band FETs are priced at $490 each. The new MMICs are priced at $150 each.

Two New Catalog Items from Motorola

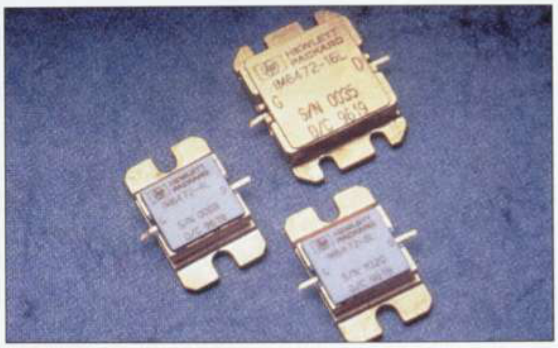
Motorola has announced the addition of a **new GaAs FET power amplifier** to its RF device portfolio. The new device offers new biasing and control techniques that provide dynamic range and control circuit bandwidth ideal for applications in the Personal Communication Network System (PCN). Designed specifically for a digital, 1 W hand-held radio, this device operates froma 6 V supply in the frequency range of 1710-1785 MHz and requires only 1.0 mW of RF input power. It produces an average RF output power of 33.2 dBm, and a minimum gain of 33.2 dB. Pricing begins at $64.35. Also new from Motorola is a **GaAs IC two-stage driver amplifier** designed for class A/B operation in applications in the 800 MHz to 1.0 GHz range. Using Motorola's advanced GaAs FET process (which the company calls "MAFET"), the new IC was designed with depletion mode GaAs MESFETs to perform at high efficiency at battery voltages of 3.6 and 4.8 volts. It can be used in a number of ways, including as a drive amplifier for analog phones using the AMPS standard and digital cellular phones using the GSM, NADC and PDC standards, or as a power amplifier for ISM band handsets. The IC comes in a plastic package and is priced at $4.72 each.

New GaAs FET power amp for Personal Communication Network (PCN) System applications from Motorola.

Motorola's new two-stage driver amplifier for 800 MHz to 1.o GHz frequencies.

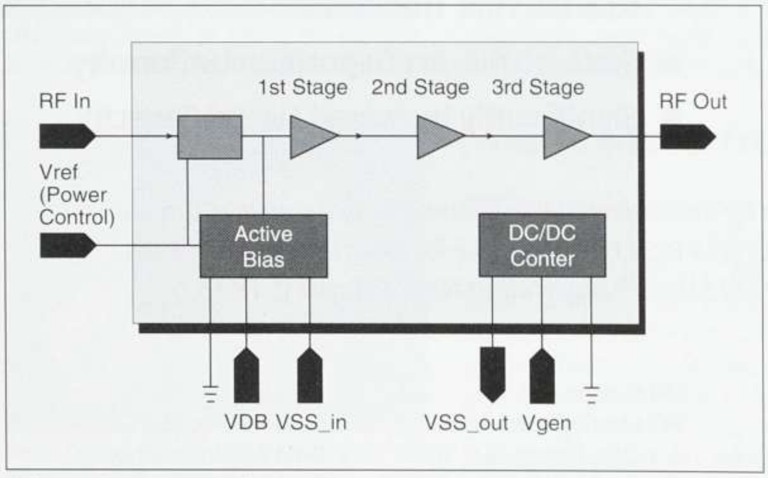
HP Satellite FETs

Hewlett-Packard has introduced a new family of **internally matched power GaAs FETs** that are optimized for use in solid-state power amplifiers for 6.4 GHz to 7.2 GHz C-band satellite earth-station and microwave point-to-point and point-to-multipoint communications transmitters. Class-A, linear operation makes these devices suitable for digital signals. They offer a combination of high output power combined with high power added efficiency - + 0.3 dB gain flatness and high linearity (-45 dBc third-order intermodulation distortion at specified single carrier level). All performance specifications are ensured at +25°C. The new devices range in output from 4.5 to 9.0 to 18.0 W output and are priced at $194, $366 and $720 each, respectively.



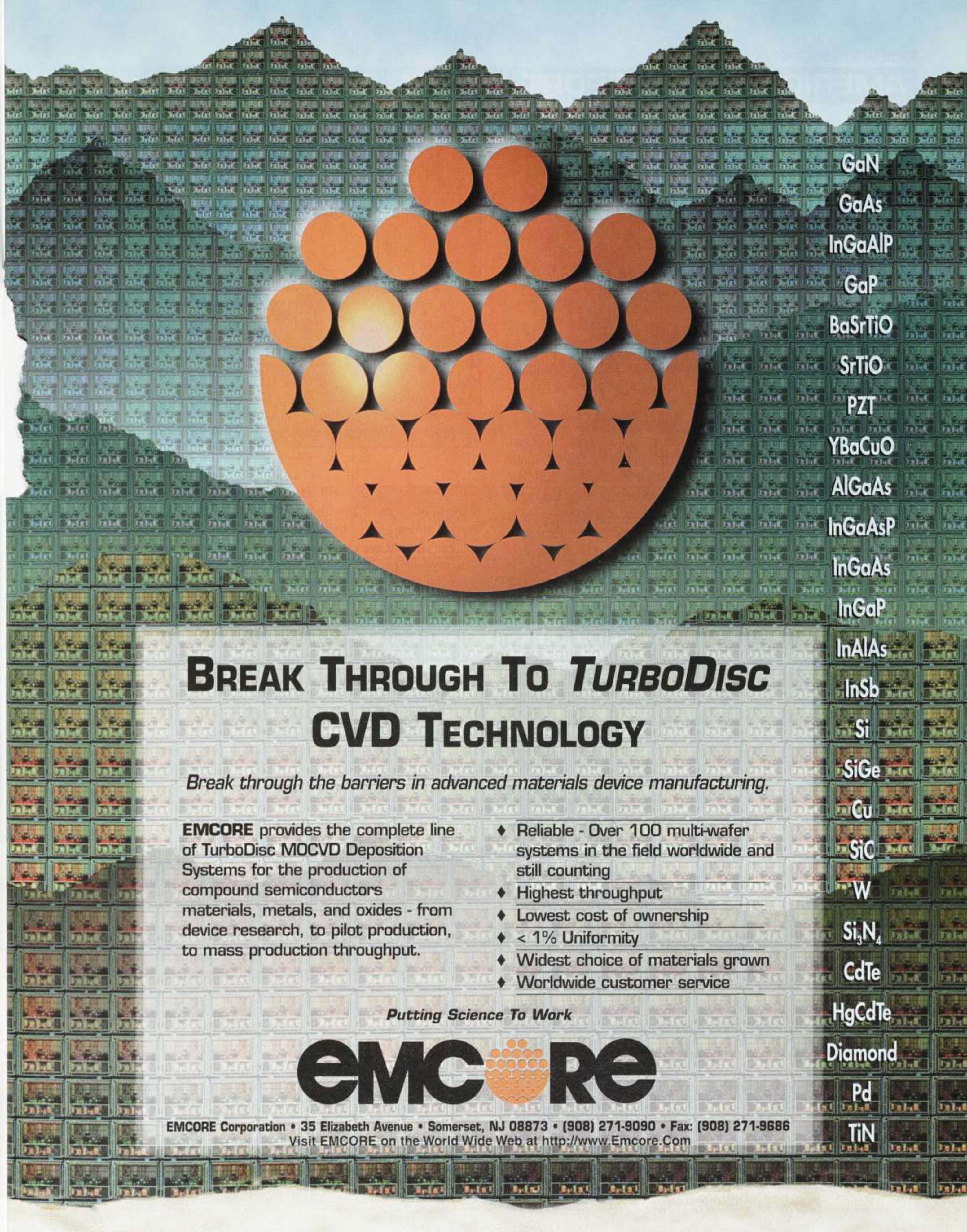
A new family of internally matched GaAs power FETs for 6.4 - 7.2 GHz, from Hewlett-Packard.

Anadigics Amplifier for DCS & PCS



Schematic diagram of Anadigics' new single supply power amplifier for DCS 1800 and PCS 1900 applications.

As part of it continuing efforts to address all cellular and personal communications standards, Anadigics has introduced a new, **low cost single power supply amplifier** for DCS1800 and PCS1900 applications. The product is being manufacutred in two versions, one for 6V and one for 4.8V operations. They offer the highest power level available at a very high efficieny, in a low cost IC package. The amplifiers use three stages, allowing them to operate with +7 dBm input power. The output power and efficiency are determined with a single external capacitor matching the amplifier output. Typical efficeincy at 32 dNm power out its 45%. According to Joseph de Moura, Anadigics senior design engineer, the company estimates that these transmitter amplifiers will offer a greater power added efficiency than typical solutions in use today, and, he says, "we would expect this to translate into a comparable increase in talk time for the subscriber." Both chips are manufacturered using Anadigics' 0.5 µm high volume GaAs MESFET technology. They are priced at $4 each in quantities of 100,000.



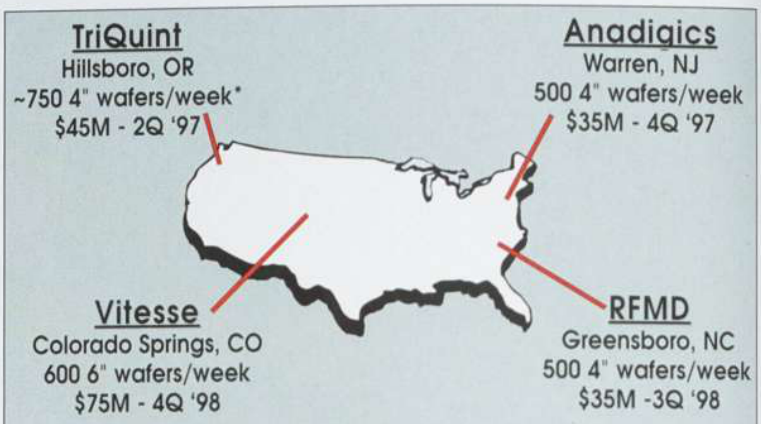
Circle 10 on Reader Service Card

Absolutely Fab-ulous

Four new GaAs fabs are planned in the U.S.A.

Consider it a measure of confidence in the future prospects for GaAs: there is a "boomlet' in fab building activity, as Anadigics, RFMD, TriQuint and Vitesse are all building or planning to build new facilities.

TriQuint Semiconductor has already begun construction of its new semiconductor manufacturing and office complex in Hillsboro, Oregon. When completed, the complex will consist of a 36,000 square foot IC fab and a 122,500 square foot office/test/development building. The new site will house all of the company's manufacturing, engineering, marketing and administration functions that are currently located in two facilities in Beaverton, Oregon. Completion of construction is planned for early 1997. The company expects this new facility to provide sufficient production capacity until the year 2000.



Covering the USA with GaAs: Four new fabs currently under construction. The Anadigics and Vitesse sites will supplement existing facilities in Warren, NJ and Camarillo, CA respectively.

*estimate

The new facility will be commissioned for 4" wafer processing, but will be compatible with conversion to 6". Total output capacity will be 2-3 times greater than TriQuint's current levels, which are ~100 wafers per shift per week (see page 11).

Anadigics is expanding its facilities in Warren, New Jersey. A lease has been signed for a site adjacent to the company's existing headquarters which will provide 131,000 square feet of new office and manufacturing space. Approximately 70,000 square feet is expected to be devoted to manufacturing, including a 10,000 square feet clean room. The company has also leased the facility next door to its headquarters for its administrative offices.

This expansion will double Anadigics' wafer production capacity to ~500 wafers/week. The fab is expected to begin operation in the fourth quarter of 1997. The company's intent is to run 4" wafers, but the new equipment being purchased will be upgradable to 6".

Vitesse is building what is likely to be the first high-volume 6" GaAs processing facility in Colorado Springs, Colorado. The new fab, which is scheduled for completion in late 1998, will be a second manufacturing site for the company, which will continue to operate its existing production facility in Camarillo, CA. The decision to locate the new plant in Colorado was motivated, in part, by input from customers expressing a desire for back-up manufacturing capability away from earthquake-prone California. Vitesse President Lou Tomasetta also cites the excellent infrastructure in the area, which will provide the skilled work force needed to run the facility.

RF Micro-Devices (RFMD) is building the industry's most unique facility in Greensboro, North Carolina. The new plant will be dedicated to HBT processing, and will have capacity for 25,000 4" wafers a year. It is the centerpiece of the strategic alliance between RFMD and TRW which is aimed at developing the latter's HBT technology for high-volume applications in the wireless market. (See *CS* 2(2), 13). Under that agreement, TRW will continue to produce HBT products for its own use and for its own customers, while RFMD will manufacture HBT circuits, under an exclusive license, for wireless applications below 10 GHz. When the new facility is operational in 1998, TRW and RFMD will also provide second source production backup for each other. In late August RFMD announced that it had received a half million dollar incentive package to build the new plant in Greensboro, which is also home to RFMD's "fabless" semiconductor operation.

A Survey of U.S. GaAs Foundries

A report on the growth of capacity at 14 American GaAs manufacturers

Acknowledgment

The data presented in the following tables was compiled by the editors of *Microwave Journal*, and originally appeared in the August, 1996 issue of that magazine, and is used here by permission. *Microwave Journal*, which is published by Horizon House Publications, Inc., can be reached at TEL [1] 617 769 9750, FAX [1] 617 762 9230, or via e-mail at mwj@mwjournal.com.

GaAs wafer processing capacity in America has risen more than 300% since 1993, according to the editors of *Microwave Journal*, which publishes a bi-annual survey of GaAs foundry activities. Fourteen companies responded to requests for information - See Table One. This is not a complete roster of American GaAs device manufacturers (for that list, see *CS* 2(2) p. 30); rather, it is comprised of only those companies which offer foundry services to their merchant customers (thus companies such as Hewlett-Packard and Motorola are not included) and which agreed to participate in the survey (some foundries declined - notably Alpha Industries). Although it is not a complete survey of the industry, it is nonetheless a useful indicator of the current status of GaAs manufacturing capability in the U.S. We examine here three aspects of the survey: wafer capacity; capacity utilization; and processes and services available.

Table One
Wafer Processing Capacity
(# of Wafers per Single Shift per Week)

	2" GaAs			3" GaAs			4" GaAs			6" GaAs		
Foundry	**'93**	**'96**	**'99**	**'93**	**'96**	**'99**	**'93**	**'96**	**'99**	**'93**	**'96**	**'99**
Anadigigics				125				180	500			
Celeritek				50				250				1000
Hughes				125	200	300						
ITT GTC	30	10	5	60				100	400			
Litton					50	100						
M/A-COM				40	50	50		150	200			50
Northrop Gr.				190	200			50	500			
Raytheon				40				53	120			
Rockwell							100	300	400			
Samsung				150				400	4000			
Sanders					80				200			
Texas Inst.				30	50			75	100			
TriQuint							35	100	250			
TRW				30	90	90						
Total	**30**	**10**	**5**	**840**	**720**	**540**	**135**	**1658**	**6670**			**1050**

Totals in Sq. In: 1993 = 7,725; 1996 = 25,940; 1999 = 117,280

Table Two
Capacity Utilization
(Percentage of Capacity Used by Major Product or Market Type)

	In-House			Merchant			Analog			Digital			Discrete			IC's			Commercial			Military		
Foundry	**'93**	**'96**	**'99**	**'93**	**'96**	**'99**	**'93**	**'96**	**'99**	**'93**	**'96**	**'99**	**'93**	**'96**	**'99**	**'93**	**'96**	**'99**	**'93**	**'96**	**'99**	**'93**	**'96**	**'99**
Anadigics	0	0	0	100	100	100	100	100	100	0	0	0	0	0	0	100	100	100	100	100	100	0	0	0
Celeritek	90	50	20	10	50	80	100	100	100	0	0	0	90	50	30	10	50	70	10	80	95	90	20	50
Hughes	90	90	90	10	10	10	100	100	100	0	0	0	0	0	20	100	100	80	10	60	70	90	40	30
ITT GTC	80	80	80	20	20	20	95	100	100	5	0	0	0	0	0	100	100	100	20	70	80	80	30	20
Litton	2	5	10	98	95	90	100	100	100	0	0	0	90	80	60	10	20	40	20	50	65	80	50	35
M/A-COM	40	85	80	60	15	20							10	5	10	90	95	90	15	80	90	85	20	10
Northrop Gr.	100	80	60	0	20	40	100	100	100	0	0	0	0	0	0	100	100	100	10	30	50	90	70	50
Raytheon	90	60	30	10	40	70	100	90	80	0	10	20	30	20	20	70	80	80	20	60	70	80	40	30
Rockwell													0	0	0	100	100	100	0	100	100	100	0	0
Samsung	40	20	5	60	80	95	100	100	100	0	0	0	70	50	25	30	50	75	10	80	100	90	20	0
Sanders		90	50		10	50		100	100		0	0		20	20		80	80		15	50		85	50
Texas Inst.	80	70	40	20	30	60	95	95	80	5	5	20	2	2	5	98	98	95	25	25	60	75	75	40
TriQuint	0	0	0	100	100	100	40	60	75	60	40	25	0	0	0	100	100	100	90	95	95	10	5	5
TRW	90	40	20	10	60	80	90	95	95	10	5	5	0	0	0	100	100	100	10	30	20	90	70	80
Average	**59**	**52**	**37**	**42**	**48**	**63**	**93**	**95**	**94**	**7**	**5**	**14**	**22**	**16**	**14**	**78**	**84**	**86**	**26**	**63**	**75**	**74**	**37**	**25**

Capacities

Table One lists the processing capabilities of the responding foundries by wafer diameter, in terms of number of wafers which can be processed per week, using a single shift. (In reality, many of the companies are currently running two or three shifts to meet demand, but a detailed accounting of this point is not available.) In addition to current capacity, historical data from 1993 and forecast data for 1999 are presented.

Only one respondent - ITT - indicated that it was still using some 2" wafers, and only two respondents - Celeritek and M/A-COM - were brave enough to offer a forecast for usage of 6" wafers.[1] The tabulation of the results from Table One shows that since 1993 capacity has risen from around 7725 sq. in. per shift/per week to slightly less than 26,00- sq. in - an increase of 335%. Table One also shows a forecasted increase by 1999 of more than 450%! However, the history of this survey, which dates back to 1985, indicates that these forecasts are usually over-optimistic, by around 50%.

Capacity Utilization

Survey respondents were asked to classify usage of their GaAs processing capacity into four major categories:

- in-house vs. merchant
- analog vs. digital
- discretes vs. ICs; and
- commercial vs. military.

[1] *Vitesse Semiconductor is, at present, the only company which has publicly announced firm plans for high volume processing of 6" GaAs - see page 10. They were not included in this survey.*

The results are given in Table Two, which shows that, for the 14 responding companies, capacity is utilized as follows:

- 52% in-house;
- 95% analog;
- 84% ICs; and
- 63% commercial.

The biggest shift was in the commercial/military category, where the ratio has almost completely flip-flopped over the past three years (74% military/26% commercial in 1993 to 37% military/63% commercial in 1996). Another surprise, perhaps, is the tenacity of the discrete sector. Though its percentage of total activity continues to decline, the forecasted decrease was much greater. The forecast data which was given in 1993 (not shown) shows that respondents anticipated that discretes would comprise only 4% of the total by 1996 - but Table Two shows that it is higher, by a factor of four.

The two remaining categories, in-house/merchant and analog/digital, showed little change from 1993, and were consistent with the historical forecast data.

Processes & Services

Table Three lists the device types and minimum line widths which are available from the foundries. All 14 respondents offer the MESFET process, and 10 of the 14 offer PHEMT processes. Only 4 companies offer HBTs, and 3 companies offer HEMTs.

Regarding line widths, it appears that process capabilities at the foundries are substantially unchanged from 1993. Apparently, the current product mix is served adequately by the available capabilities and there is little incentive to offer finer line widths. For MESFET processing, 0.5 µm dominates, with only 5 of the 14 respondents offering 0.25 µm.

Table Four lists the merchant services available from each responding company. Mask making is the task most frequently left to the customer, but, with some exceptions, most other services are available from each foundry.

Table Four
Services Offered

	Circuit Design	Mask Making	Layout	Fab
Anadigics				
Celeritek	x			
Hughes	x		x	x
ITT GTC	x		x	x
Litton	x	x	x	x
M/A-COM	x		x	x
Northrop Gr.	x	x	x	x
Raytheon	x		x	x
Rockwell		x		x
Samsung	x			x
Sanders	x	x	x	x
Texas Inst.	x	x	x	x
TriQuint		x		x
TRW	x	x	x	x

	On-Wafer Test	Wafer Die Convert	Carrier/ Pkg. Mount	Test
Anadigics				
Celeritek				
Hughes	x	x	x	x
ITT GTC	x	x	x	x
Litton	x	x	x	x
M/A-COM	x	x	x	x
Northrop Gr.	x	x		
Raytheon	x	x	x	x
Rockwell		x		
Samsung	x			x
Sanders	x	x	x	x
Texas Inst.	x	x	x	x
TriQuint	x	x	x	x
TRW	x	x	x	x

Table Three
Processes Offered
and Minimum Line Widths (µm)

	MESFET						HEMT					
	Low Noise			Power			Low Noise			Power		
Foundry	'93	'96	'99	'93	'96	'99	'93	'96	'99	'93	'96	'99
Anadigics	0.4	0.4	0.4	0.4	0.4	0.4						
Celeritek	0.3	0.25	0.1	0.5	0.5	0.5						
Hughes	0.5	0.25	0.25	0.5	0.5	0.5						
ITT GTC	0.5	0.5	0.5	0.5	0.5	0.5						
Litton	0.5	0.25	0.25	0.5	0.35	0.3	0.25					
M/A-COM	0.5	0.5	0.5	0.5	0.5	0.5						
Northrop Gr.				0.5								
Raytheon	0.5	0.5	0.5	0.5	0.5	0.5						
Rockwell		0.5	0.5									
Samsung	0.5	0.5	0.25	0.5	0.5	0.25						
Sanders		0.25			0.5							
Texas Inst.	0.25	0.25	0.25	0.5	0.5	0.5		0.5	0.25	0.5	0.5	0.5
TriQuint	0.5	0.5	0.5	0.5	0.5	0.5						
TRW	0.5	0.5					0.2	0.15	0.1	0.15	0.1	

	HBT						PHEMT					
	Low Noise			Power			Low Noise			Other*		
Foundry	'93	'96	'99	'93	'96	'99	'93	'96	'99	'93	'96	'99
Anadigics								0.4	0.4		0.4	0.4
Celeritek							0.3	0.25	0.1			
Hughes			1				0.25	0.25	0.25			0.25P
ITT GTC												
Litton								0.25	0.25		0.25P	0.25P
M/A-COM								0.18	0.1		0.18P	0.1P
Northrop Gr.	1.5									0.25P		
Raytheon			1			1		0.25	0.15		0.15P	0.15P
Rockwell		2	1		2	1						
Samsung								0.5	0.25			
Sanders								0.1			0.15P	
Texas Inst.		2	1			2	0.25	0.25	0.25	0.5	0.5	0.5
TriQuint												
TRW	3	2	1	3	2	1						

* P=Power

Japanese Wafer Vendors Report Shipments Up 15.4% in 1995

Japanese materials companies currently account for ~75% of the worldwide market for compound semiconductor wafers, which makes their sales statistics a useful measure of current activity in the compound semiconductor industry. The most recent bi-annual report from the Japan Manufacturers' Society of Compound Semiconductor Materials (JAMS-CS) provides further evidence of buoyant demand for compound semiconductor devices, led primarily by visible LEDs.

The report covers shipments made by Japan's nine largest compound semiconductor materials manufacturers during the 1995 fiscal year (ended March 31, 1996). In that period Japanese substrate manufacturers shipped more than Y40 billion (US$ 376 million) worth of compound semiconductor wafers, a 15% increase over FY 1994. GaAs wafers accounted for half of the shipments, followed by GaP (42%), InP (6%) and other materials (2%). See Figure One. Domestic consumption accounted for 65% of the shipments.

The report also provides segmentation of shipments according to application and destination. See Figure Two, which shows that materials for LED manufacturing account for 66% of the JAMS-CS market. The very high percentage of wafers exported in this area (over 45%) reflects the fact that much of the world's LED manufacturing is done in Taiwan and other "Asian Tiger" countries, where labor costs are lower. But for non-LED applications, the JAMS-CS members report that nearly 85% of their sales come from within Japan.

This is the third consecutive year that the JAMS-CS has reported double-digit growth in the value of compound semiconductor wafer shipments. Over that three-year period shipments have risen by 65%. The organization declines to speculate about the forecast for next year, but there is some evidence that a slowdown may be on the horizon, consistent with the historical pattern revealed in Figure Three. The 15% growth rate posted in FY 1995, while impressive, is still only half the figure posted in FY 1994. Also, the value of shipments in the second half of FY 1995 actually declined by 6% compared to the first half. This may be a sign that inventories are building up at the device manufacturers. However, it should be noted that the JAMS-Cs statistics concern the value of compound semiconductor wafer shipments, not the surface area. (Statistics for surface area are not available.) One of the fundamental rules of the semiconductor industry is that when volume increases, prices decrease. Thus the apparent slowdown is likely driven more by price pressure than an actual decline in the consumption of compound semiconductor materials.

The nine members of the JAMS-CS are: Dowa Mining, Furukawa Electric, Hitachi Cable, Japan Energy, Mitsubishi Chemical, Shin-Etsu Handotai, Showa Denko, Sumitomo Electric Industries, and Sumitomo Metal Mining.

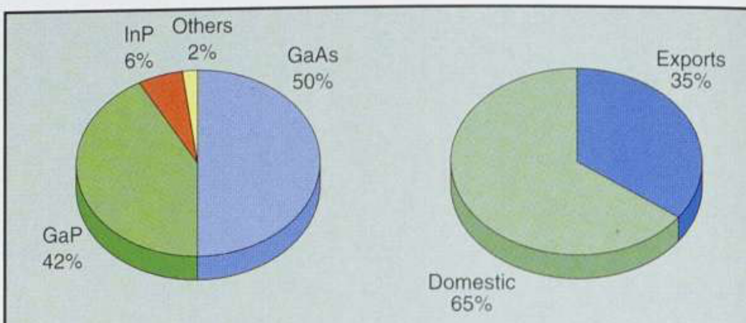


Figure One. The value of shipments made by the nine members of the JAMS-CS during FY 1995, segmented according to material type (left) and destination (right).

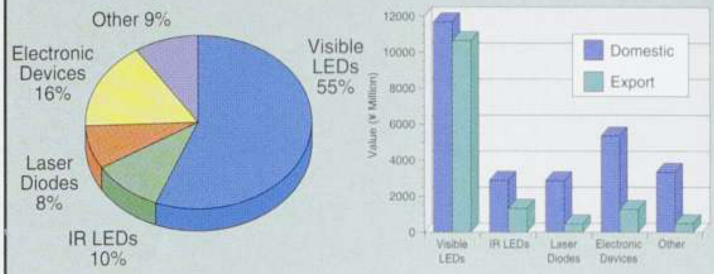


Figure Two. Value of shipments by JAMS-Cs members in FY 1995 according to application (left) and application plus destination (right).

Figure Three. Growth in the value of compound semiconductor wafer shipments reported by members of the JAMS-CS from 1984 to 1995. CAGR for the past 10 years = 10.5%; for past 5 years = 13%.

Source: JAMS-CS

Shipments by Japanese manufacturers of compound semiconductor wafers in the 1995 fiscal year (ended March 31, 1996)

	Domestic Shipments			Export Shipments			Total		
Material	¥M	US$M	%	¥M	US$M	%	¥M	US$M	Increase*
GaAs	15,246	142.50	76%	4,739	44.30	24%	19,985	186.80	24%
GaP	8,565	80.06	50%	8,485	79.31	50%	17,050	159.37	3%
InP	1,749	16.35	68%	819	7.66	32%	2,586	24.17	41%
Other	526	4.92	82%	112	1.05	18%	638	5.96	68%
Total	26,086	243.83	65%	14,155	132.21	35%	40,241	376.13	15%

*Compared to FY 94
Source: JAM-CS

DVD News

With the launch of the first DVD[1] players scheduled for this fall, much of the compound semiconductor news from Japan this summer is related to laser diodes for optical pick-ups. The DVD standard will require 635 - 650 nm AlGaInP diodes as compared to 780 nm AlGaAs diodes which are used in the current generation of CD players. Typical output power for the read-only versions will be ~5 mW. Interestingly, the roadmap for developing the DVD standard calls for an erasable version to be available in 1 - 2 years time. It is known that such a product would require much higher power diodes (around 35 mW), but many other details regarding it have not yet been worked out.

Another, rather important, detail which remains unknown is the size of the market for DVDs. The current market for the CD-format is around 100 million units, ± 20%, depending upon your source. As we reported in our last issue (*CS* 2(4) 18), the experts disagree about the forecast for DVD players. The low estimate is 50 million units/year by the year 2000, while the high estimate is twice that.

Between the two of them, Sony and Sanyo are believed to control around 70% of the market for optical pickups for these applications. Last month **Sanyo** announced it was **expanding its annual optical pick-up business** to 55 million units by 1998, up from 45 million scheduled for 1996. The company estimates that they hold a 30% market share. Production of DVD lasers at Sanyo, which was launched in June, is currently around 200,000 units a month, and is expected to more than double to 500,000 units a month by March. Current production consists of a 645 nm, 5 mW read-only model, and the company is sampling a 635 nm, 30 mW read/write model.

Not to be outdone, **Sony** has announced that it is **raising semiconductor laser production**. The company is spending around $100 million to install a new assembly line at its subsidiary Sony Shiraishi Semiconductor, which will allow it to raise output by 40% to 5 million units/month. The company says that it hopes to have 60% of the market for optical pickups by the end of fiscal 1997.

Four other companies also announced new DVD laser developments. **Matsushita** reported that it has **launched production of read-only DVD lasers** and that it is **developing a high temperature read/write DVD laser**. While its relative position in the optical pick-up market is not clear, Matsushita is likely to the be a leading manufacturer of complete DVD systems. The production model is a 650 nm, 5 mW self-pulsating laser that will be used in players produced by Matsushita and will also be sold to other manufacturers. Production is currently "tens of thousands" units per month, and is expected to reach 200,000 units per month by the end of the year. The new read/write model, which is described as being "close to development", is said to be capable of operating at over 30 mW for 1,000 hours at 60°C, and is expected to have a life span of 5,000 - 10,000 hours. According to a Matsushita press release, the high temperature, long life operation is made possible by coating the laser's edge with silicon hydride film which absorbs less light.

NEC has announced that it has **developed and started sample-shipping a DVD-ROM semiconductor laser that operates at 70°C.** NEC Kansai's Otsu plant will produce 50,000 units monthly from October. NEC, which unveiled in February a 635 nm laser that operated at 60°C, reports that it has optimized the MQW active layer structure to develop a 650 nm, 5 mW laser that operates as higher temperatures, targeting PC-use DVD-ROM drives and DVD-based car navigation systems. An 85°C model will be brought to market one year from now. NEC plans to produce 200,000 DVD lasers per month late this year and expand output to 950,000 units in fiscal 1997.

Rohm announced in July that it has **begun sample-shipping DVD read-only lasers**. The company has developed a single-mode 650 nm AlGaAs laser with an output of 5 mW based on its CD/CD-ROM laser technology that uses MBE to grow the epitaxial layers. The current device can operate at up to 60°C, and the company plans to raise the operating temperature to 75°C by early next year in order to develop the DVD-ROM market. Rohm also plans to unveil a multi-mode, 5 mW, 650 nm AlGaInP MQW semiconductor laser by November.

And, rounding-out the new announcements, **Sharp** reports that it is **ready to mass-produce both 650- and 635-nm DVD lasers**. The company says that its DVD lasers are guaranteed to operate for 10,000 hours and withstand high temperatures of up to 60-70°C. The company is currently sample-shipping 5 mW lasers for DVD-ROM and 30 mW lasers for DVD-RAM. Sharp now has a DVD laser production capacity of 500,000 units per month and will be able to produce 1 million units monthly from this fall. The company has spent about 2 billion yen ($18.5 million) on existing semiconductor laser lines to produce DVD lasers.

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[1] *DVD = digital "versatile" disk or digital "video" disk. The DVD format is the higher-data-density follow-up product to the CD format for both audio and ROM applications. See CS 2(3), p. 35.*

LED Update

Blue LED for Sanyo

Sanyo Electric has announced that it has developed a blue LED, and that its subsidiary Tottori Sanyo Electric will produce and market blue LEDs lamps from October 1996 and bring full-color (red-green-blue) LED displays to market in the spring of 1997. This would make Sanyo the fourth company to enter the blue LED market, behind Cree Research, Nichia Chemical, and Matsushita/Panasonic. No details, such as active layer materials and performance specifications, are available at this time, but the company says that the newly-developed blue LED is brighter than those from Cree and Nichia, and has a comparable life span. A company spokesperson also reports that Sanyo will now focus on the development of a blue semiconductor laser.

Matsushita To Enter LED Display Market

Matsushita Electric has begun marketing LED displays through its Panasonic Division. The company will bring to market the ADVISION, a low-cost, standard-configuration display which measures 1.9x2.5m and can display full-color motion pictures. Matsushita, which expects the LED display market to grow 5-10% per annum, is aiming to increase LED display sales to 18 billion yen ($165.1 million) and grab a 30% share by 2000. The company manufactures its own blue, red and green LEDs. Kagoshima Matsushita Electronics, in collaboratioon with Toyoda Gosei, has been producing blue LEDs for one year, and currently produces 1 million units per month. Depending upon the model, brightness ranges from 1400 to 500 to 280 mcd (typical). The full color displays which will be offered by Panasonic are said to be sufficiently bright and rugged to allow outdoor use.

Sharp Goes Into Pachinko Parlors

Sharp has developed a full color LED display that it will start marketing in early 1997, promoting it to pachinko parlors and other entertainment outfits. Three models will be available, ranging in size from 9.2x7.6m to 4.8 x 3.6m to 1.9 x 1.4m. The later is shown above - it utilizes just over 49,000 individual LEDs. The price is 4-8 million yen ($36,697-73,394) per square meter. Sharp intends to develop the LED display business around this product into a 10 billion yen ($91.7 mil) business by 2000.

Other Opto News

NEC Sets Optical Device Target at Y40 Billion/Year; Announces New Developments

NEC is aiming to double optical device sales to 40 billion yen ($370.4 mil) by 2000. The company, which provides various devices for optical communications and information systems including laser diodes, photo diodes and optical switches, says it plans to aggressively develop new products, lower costs and expand its distribution channels toward this goal. The company will produce DVD-related optical devices at NEC Kansai and Kyushu Electronics and also launch in October fully automated photo coupler production lines at a facility in Taiwan.

In new product news, NEC has announced the release of two new compact, low-priced 1.3 μm semiconductor laser modules. The new products are meant for optical-fiber networks between telephone offices and subscribers and adopt a new alignment method to reduce production costs. The laser is based on a proprietary DC-PBH structure, with a strained MQW structure used for the active layer. The 8-pin mini DIL package is about 1/10 the size of its DIP counterpart. The NDL7801P plastic mold package and the NDL7800P ceramic package modules are sample-priced at ¥5,500 ($50.93) and ¥6,500 ($60.19), respectively. NEC will produce a combined total of 10,000 units monthly.

Also new from NEC is a GaAs optical communications amplifier IC. A photoelectric converter converts 0.1-5 μA optical signals carrying data at 40 Gbps and coming in via an optical fiber to electric signals. The IC chip, which measures 0.69 x 0.94 x 0.08 mm, then amplifies the electric signals to 10-500 mV signals. Since it offers a large amplifying capacity, the company claims that the chip can be used to simplify parts for such devices as switches. NEC plans to use the IC for telephone, CATV, and optical fiber network switches.

NEC has also announced the development of an ultra-high-speed GaAs optical communications device capable of switching in 0.8 ps, fast enough to boost optical data communications fourfold over the fastest current system which supports 2.5 Gbps. The device can change its refractive index when exposed to light different from one carrying signals. The company has used two semiconductors to solve the problem of extra time it takes for an altered refractive index to return to the original rate and has succeeded in operating the device at room temperature. NEC plans to replace the GaAs with InP and conduct an experiment using wavelengths actually used in commercial service.

Matsushita Optical Module for Fiber-to-the-Home

Matsushita has developed a subscriber optical communications module which will be in demand as optical cable installation extends to the home. Integrating a 1.3-μm semiconductor laser, 1.3 and 1.55 μm photo detectors as well as the optical fiber, the module features a simple structure for emitting laser light into the optical fiber directly without using a lens. The company has devised the shape of the laser's active layer to reduce the angle of emission and efficiently enter the light in the fiber. Matsushita, which believes the module can be mass-produced at a cost below ¥10,000 ($92.59), plans to commercialize the module within a year.

20 GHz Optical Modulator from OKI

Oki Electric has prototyped a 20 GHz optical modulator for use in large-capacity optical communications systems. Eight times faster than conventional devices, the prototype has an InGaAsP waveguide, several microns wide, formed on an InP substrate. A non-reflection film with high transmissivity is created on one edge of the waveguide, and a total reflection film is created on the other edge so that light goes back and forth inside the waveguide. The structure helps double the distance over which light is absorbed inside the waveguide, achieving high-speed and low-voltage operations simultaneously. Running on 1 V, the prototype can generate 20 Gbps signals.

3" GaAs for Laser Diodes from Sumitomo

Sumitomo Electric has developed a semiconductor laser-quality 3" GaAs wafer fabrication process which yields less than 500 crystal defects/sq. centimeter. The company reports that it uses the vertical boat (VB) crystal growth method, instead of the horizontal Bridgeman (HB) method which is used for 2" GaAs wafers, and has optimized the crystal growth temperature control to reduce crystal defects. Sumitomo is aiming for first-year sales of 200 million yen ($1.9 mil), targeting DVD laser manufacturers.

Analgog Update

12 GHz HEMTWith 15W Output from NEC

NEC has developed a 12 GHz HEMT that can amplify satellite radio signal output to 15W. The new transistor has GaAs electron source layers and an InGaAs electron transit layer, and features a gate width of 150 microns, up from its predecessor's 100 microns, to achieve an output power of 15W. The company will work on the development of a 30W FET which will replace vacuum tubes which are currently used in satellites.

Mitsubishi FET for Digital Cellular

Mitsubishi Electric has developed and will sample-ship in September a digital cellular phone-use power amp module which uses a double-hetero-structure GaAs FET. For use in PDC (Pacific digital cellular) format cellular phones, the FA01216 generates 1.26W from 3.4V, offering an operation efficiency of 52%; conventional modules give 45%. The increased efficiency allows cellular phones to extend talk time by nearly 10%. The 11.3x4.2x2.7mm module, 45% smaller than the conventional units, runs at 925-956 MHz and is sample-priced at ¥2,000 ($18.52). Mitsubishi plans initially to make 200,000 units per month. Plans also call for developing such power amp modules as one which will be housed in a 0.2cc package and another which will support the GSM standard.

Power Amps from Taiyo Yuden

Taiyo Yuden has developed the world's smallest power amplifier for use in personal digital cellular (PDC) phones. The new high-frequency amplifier is 0.18cc in volume and measures 10x10x1.8mm. Based on a GaAs (gallium arsenide) FET and running on 3.5V, it features bare chip bonding based on the KGD (Known Good Die) technique and an array of high-frequency circuit technologies. The company plans to start volume production in August at the Takasaki plant in Gunma Prefecture, with an output capacity of 300,000 units per month. The sample price is ¥3,000 ($27.27).

Research Update

Nitrogen/GaInP Compound for Laser Didoes

Hitachi and the Real World Computing Program (RWCP), a MITI-initiated research organization, have jointly developed a new semiconductor material which mixes nitrogen with GaInP grown on a GaAs substrate. The joint research group has created a laser sample which uses the new material in the active layer and has had the laser continuously oscillate at 1.2 µm at room temperature. They report that the laser is relatively unaffected by temperature changes, and it can stably oscillate even at 85°C if current about 1.6 times stronger than at room temperature is supplied, eliminating the need of cooling systems and controller ICs and paving the way for the miniaturization of optical communications subscriber transmitters. According to a MITI spokesperson, adding nitrogren as a matrix material increases the energy gap between the active and cladding layers, making the laser more resistant to changes in temperature and enabling it to operate stably at higher temperatures.

While there is obviously much work to be done in this area, this work is intriguing not only because of the high operating temperatures, but also because it indicates a possibility that in the future the 1.3 µm wavelength, which is vital for fiber optic communications, might be accesible by lasers which are grown on GaAs substrates. Since GaAs is generally of higher quality and less expensive than InP, this would be a boon for laser manufacturers. It could also enable greater use of VCSELs in fiber optics, as they are currently much more successful in the GaAs-based systems than the InP-based materials. (See page 37 for more information.)

According to a MITI spokesperson, the next steps will include construction of VCSEL structures, and attempting to increase the wavelength to 1.3 µm.

NTT Develops Solar Cell with Storage Capability

NTT reports that it has developed a solar cell that can store electricity. The cell generates electricity on the surface using the solar energy and charges/discharges electricity on the back side using oxygen in the air. Charged for eight hours, the 20 x 20 x 5mm prototype cell was able to discharge 10 mA electric current at 1V for 10 hours. The cell uses a mix of GaP and cobalt for the surface side and a platinum electrode on the back side, between which an electrolyte is sandwiched. NTT will continue working to enhance the cell targeting cellular phone and PC applications.

NEC Develops Technique for Producing BH Lasers Without Etching

NEC has announced that it has developed a technique for producing high-quality buried-heterostructure (BH) semiconductor lasers without performing the etching and regrowth steps that are normally required to create the active layer in lasers of this type. The new technique uses selective epi in the MOVPE growth process to form the laser's active layer completely through crystal growth, eliminating the need for etching. NEC test-manufactured a 1.3 µm optical communications laser and confirmed that the test device had a threshold current of less than 2mA and more than twice the element uniformity of conventional lasers. NEC will use the technique to produce optical communications lasers.

SOI Single Electron Devices from University of Tokyo

Associate Professor Hiramoto's group at the Institute of Industrial Science, the University of Tokyo, has developed a silicon single-electron device. The group has used a silicon-on-insulator (SOI) substrate, applied an etching process twice, and formed a two lines which are less than 10nm wide. Experimenting with a device which had electrodes connected to the fine lines, the group observed Coulomb blockade vibration at room temperature. The group thinks the technique is applicable to the development of single-electron memory

Toshiba SOI Transistor

Toshiba has announced that it has developed a high-speed transistor for use in silicon-on-insulator (SOI) devices. The transistor takes advantage of the speed overshoot effect, a phenomenon typically associated with the SOI, and is supposed to run 10-20% faster than conventional transistors although operating speed has not been confirmed. Designed using a 0.08-micron rule, the transistor operates on 0.9V. The threshold voltage is 0.4V. The research group involved in development thinks that the transistor will pave the way for the development of a high-speed, low-power SOI transistor which can realize the effect at room temperature.

Have Compound Semiconductors Reached the Mainstream?

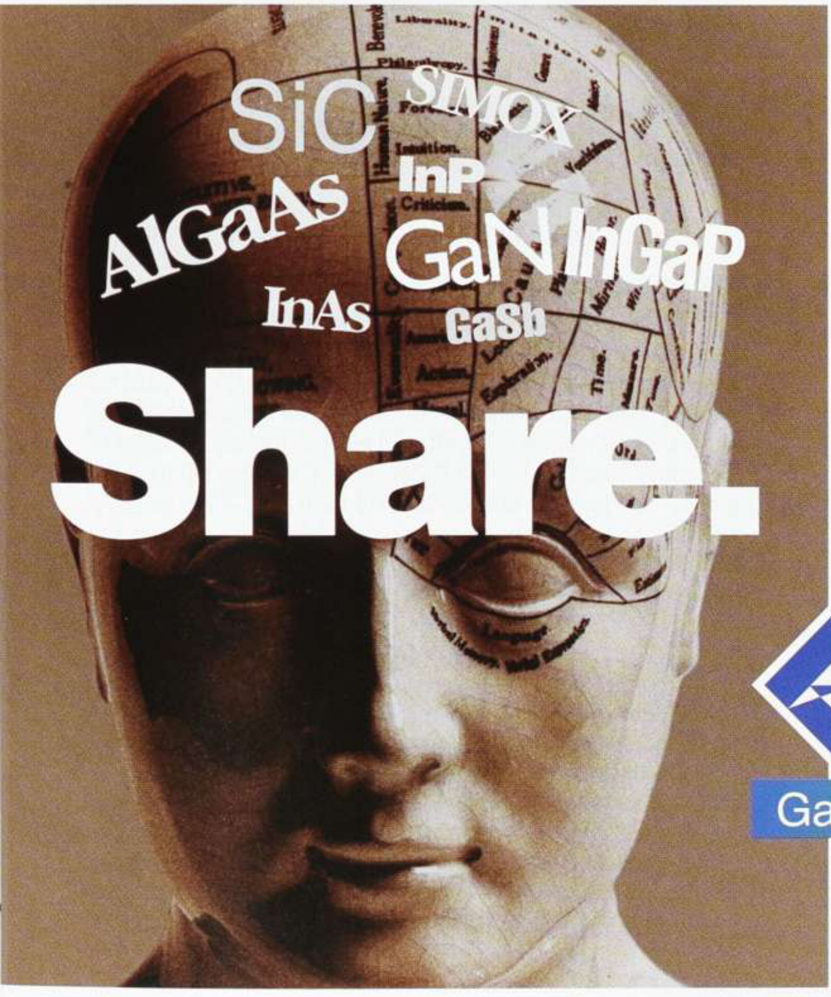
It is beginning to look as if compound semiconductors, led by GaAs, have reached the mainstream of hot technology topics, because there have been at least four compound semiconductor-related articles in large-circulation journals in the past three months. Either that, or it has been a slow summer for news, and editors are stretching to find stories to cover.

The most serious work is the July 1996 issue of *Scientific American*, which features a review of CD technology that includes a four page article on blue lasers by Robert Gunshor of Purdue University and Arto Nurmikko of Brown University. The funnest articles appeared in *Business Week*, a major American news magazine. The May 27 issue reviews a handful of "small, European and attractive" high-tech companies, and classifies epi-wafer vendor Picogiga as the kind of hot company "that makes investment bankers weak in the knees". The August 19 issue of that magazine includes a two-pager titled "GaAs Guzzlers on the Info Highway". While we here at this publication, as a matter of policy, tend to look askance at anything that uses such dreadful puns, it is nice to see some recognition of the fact that while the rest of the semiconductor industry has been flailing about this year, the GaAs chip makers, lead by Anadigics, TriQuint and Vitesse, have been posting some record numbers. The highlight of that piece is a forecast from a technology analyst at a major brokerage house that predicts that the market for GaAs chips, beginning next year, should grow at 50 - 60% a year.

The most surprising article appeared in the July 24 issue of *PC Week*. The subject being addressed was rumors circulating in Silicon Valley about the specifics of the P7 microprocessor, the second generation chip after the Pentiuim that is being developed in secrecy between Intel and Hewlett-Packard. The P7 is expected to debut in 1999, and by 2002 the 64-bit chip will reportedly be available in models which operate at a clock speed as high as 1400 MHz. In comparison, the fastest Intel chips that are currently available are around seven times slower. Such a roadmap is in keeping with the famous "Moore's Law" - the rule which says that microprocessor performance should double every 18 months. And while we hate to spread rumors, the reason this story is of interest is that unnamed sources in the article report that Intel is going to switch to GaAs to meet its goals, or perhaps SiGe. This story seems to good to be true, and of course it can't be verified, but nonetheless we couldn't resist the opportunity to pass it along. Such is the nature of gossip.

ABB Hafo Sold

Canadian electronics manufacturer Mitel has purchased ABB Hafo AB of Jarfalla, Stockholm, Sweden for $56 million. The company has been renamed Mitel Semiconductor AB and had been integrated into Mitel Semiconductor's operations. The sale provides Mitel with a European CMOS foundry. ABB has also been active in the GaAs and InP fields, and is particularly well known in Europe for work related to SiC semiconductors for high temperature applications.



Contracts for Spire

Spire Corporation [Bedford, MA] has announced the receipt of three new contracts for compound semiconductor development. The U.S. Naval Research Laboratory has awarded the company a contract for the continued development of complementary HBT (CHBT) push-pull power amplifiers and operational amplifiers. The power amps may find application in phased-array radar and wireless communications; the operational amps may find broad applications in analog electronics requiring high speed A/D and D/A converters. Spire reports that it will used selective MOCVD growth to integrate both n-p-n and p-n-p HBTs on a single wafer.

NASA Goddard Space Flight Center has awarded Spire a contract to develop 2 to 3 micron InGaAs detector arrays. The company reports that this program will adapt Spire's existing commercial InGaAs power converter technology to use in the development of new photodiodes and arrays. Spire plans to use compositional control over the InGaAs alloy to "tune" the photodiodes to various emission spectra in the 1.5 to 2.5 micron range, which is important for the differential absorption LIDAR measurements of various atmospheric gases

Spire has also announced the receipt of a grant from the National Science Foundation to develop a new wavelength-multiplexed monolithic semiconductor laser array for use in an IR-diode laser spectrometer. Potential commercial applications for such a device include trace gas detection and chemical process monitoring. The company reports that it plans to use a quantum cascade laser to develop a manufacturing-friendly semiconductor laser source which can be multiplexed over a large number of preselected wavelengths in the mid-IR range.

New Applications Updates

Our previous issue carried a cover story on new applications for compound semiconductors, focusing on power products and high temperature semiconductors. The past two months have produced some interesting developments in these areas.

In July, Motorola announced that Omnirel Corporation has selected Motorola's GaAs Schottky rectifier technology for a new series of military-qualified products. The GaAs wafers will be manufactured at Motorola's fab in Phoenix, and assembled, tested and qualified at Omnirel's facility in Leominster, Massachusetts. The unique characteristics of GaAs rectifiers are fast recovery time and low peak reverse current, resulting in low stored charge during the reverse recovery time. Unlike Si rectifiers, this characteristic varies little with increasing temperature, which enable operation at high frequency with minimum power loss over a broad temperature range. Ron Gantar of Motorola's Power Products Division said, "Motorola has developed a leading edge power semiconductor technology that is ideally suited for the high reliability power supply and motion control market. Omnirel's choice of Motorola's advanced GaAs rectifier technology enables us to offer the military and aerospace markets a competitive edge."

In high temperature news, HITEN, the European High Temperature Network, is reporting that General Electric has achieved the first insertion of a SiC flame sensor in a commercial product. A SiC flame sensor manufactured by GE Reuter Stokes [Twinsburg, OH] is currently being installed at a number of power plants. The sensor consists of SiC UV photodiodes and SiC signal diodes that capitalize on the fact that the UV emission spectrum of hydrocarbon flames is well matched to optical and electrical properties of SiC.

Vendor News

ATMI Reorganizes Epitronics, Diamond Electronics Division

ATMI [Danbury, CT] has folded its Diamond Electronics Division into the company's newly acquired subsidiary, Epitronics Corporation of Phoenix, AZ. Epitronics will retain its separate identity as a wholly owned subsidiary of ATMI, and now joins the ranks of ATMI's other subsidiaries, EcoSys and Novapure. Duncan Brown, Vice President of ATMI, will serve as the new President of Epitronics, replacing founder Robert Adams, who has left the company. The Epitronics product line will include III-V epi on GaAs and InP; SiC single crystal wafers; and GaN epi on sapphire and SiC. The company will also distribute III-V wafers from Wafer Technology Ltd. And SIMOX SOI from Nippon Steel.

Waterloo for Philips

Philips Analytical X-Ray [Almelo, The Netherlands] has acquired Waterloo Scientific [Ontario, Canada], a manufacturer of optical semiconductor characterization equipment. Included in Waterloo's product portfolio is a scanning PL system originally developed at Bell Northern, where it was affectionately known as SPAM - scanning photoluminescence and mapping. The company will be operated as a division of Philips Electronics of Canada, and its existing product lines will be offered under the Philips name.

Vendor News, Continued

EPI MBE Systems for Laser Production

The EPI MBE Products Group [Saint Paul, MN] has announced orders for two single wafer MBE systems to be used in semiconductor laser production. The Mod GEN II systems are for Pirelli Cavi S.p.a. [Milan, Italy] and Lasertron, Inc. [Bedford, MA]. Both companies are pursing 980 nm GaAs pump lasers. The Pirelli system has already been installed and is in operation at the recently formed Pirelli Laser Technology Division in Milan. The Lasertron system will be installed later this year.

Emcore Reactor #7 for Spectrolab

Emcore Corporation [Somerset, NJ] has announced the sale of three more production MOCVD reactors to solar-cell manufacturer Spectrolab Inc. [Sylamr, CA]. This brings the count of Emcore reactors at Spectrolab to seven, and boosts their capacity to more than 500,000 4" wafers/year. Emcore also recently announced the receipt of an order from Ericsson Components AB [Kista, Sweden] for a production reactor to be delivered in late summer.

Orders for Aixtron

Aixtron GmbH [Aachen, Germany] has announced three recent orders. First is a production reactor for ITT Night Vision [Roanoke, VA] capable of up to 5 x 4". The system will be used for the production of GaAs photocathodes for night vision equipment. Next is an order for two systems for Tecstar [City of Industry, CA] to be used in the manufacture of solar cells. This brings the number of Aixtron reactors at Tecstar to four. And the company also announced the sale of a reactor with a capacity of 35 x 2" wafers to United Epitaxy Company [Taipei, Taiwan] for the production of ultra-high brightness LEDs.

VG Semicon: 20th Multiwafer MBE

VG Semicon [East Grinstead] has announced that it recently secured 4 more orders for V100 multiwafer MBE systems, raising the total number sold to 20. The new systems will be used to produce microwave devices. The three previously reported (*CS* 2(2), p. 34) V100's configured for opto applications have now been installed, one in Europe and two in Japan. The company also reports a resurgence in GaAs R&D activity in Japan, with three orders for V80H single-wafer systems booked in the first half of September.

Europe's Status in Group III-Nitrides

Markus Kamp
University of Ulm
Ulm, Germany

The First European GaN Workshop (EGW-1), held in Rigi, Switzerland June 2-4, provided a unique opportunity to review the status of Group III-Nitride activities in Europe. The workshop, which was the first European meeting dedicated to Group III-Nitrides, attracted 140 attendees, 64 contributed presentations, and three invited talks.

The following statistics on the workshop can be used to help analyze Europe's relative position in this field. Seven categories (substrates, growth, characterization, alloys, doping, processing & devices) are used to describe activities in GaN research.

Attendees of EGW-1 enjoyed eight European talks (16%) on substrates and twelve talks on growth (24%). No talks from Europe were particularly on alloys. Twenty-one contributions (42%) were presented on characterization, two presentations (4%) dealt with doping issues. Five talks (10%) were given on processing and only two European contributions (4%) were on devices. The remaining 14 talks were contributed by non-European researchers. By way of comparison, it is interesting to note that the first MRS symposium on Group III-Nitrides (held last fall in Boston, MA - see *CS* 2(1), p. 41) had a significantly lower number of talks on substrates (3%), whereas there was a notably higher proportion (17%) of contributions on devices. All other topics at that meeting found comparable attention.

Europe, and especially Eastern Europe, has a strong background in crystal growth, and has produced powerful techniques such as the Czochralski method. Today, the group headed by Prof. S. Porowski at Unipress (Polish Academy of Sciences) is leading the field in GaN substrates (see box). As a further general trend concerning substrates, SiC seems to be less popular in Europe than in the USA. The exceptions to this rule are for obvious reasons: the Cree Eastern European Division and the Ioffe Institute (St. Petersburg, Russia).

The European device activities still suffer from the belated beginning of GaN research in Europe. Whereas the number of American and Japanese companies which are developing or offering GaN based devices (LEDs, FETs, detectors) is increasing, there is still very little real device activity in Europe. Serious efforts occur at many places, but only Siemens (Germany) and the University of Nottingham (UK) reported electroluminescence from GaN pn homojunctions. Both of these reports were based on MBE-grown material. Since the electroluminescence is still weak, these structures are not yet good enough to yield commercial products. At the University of Stuttgart (Germany), researchers have succeeded in optical pumping of a GaN/InGaN DFB laser. Although this is not a real device, it does prove the good quality of the underlying structure.

The two "real" device talks at EGW-1 were both contributed by the Ioffe-Institute/Cree EED collaboration. This group is active in GaN on SiC. Using HVPE they succeeded in the direct growth of GaN on SiC without the otherwise mandatory low temperature nucleation layer. Chlorine gas is assumed to play the key role in achieving the direct growth with reasonable quality. Since the GaN/SiC interface is conductive, they can employ vertical current transport through the substrate. Currently various heterosystems on SiC (AlGaN/GaN/SiC, AlGaN/SiC, GaN/SiC), where SiC acts partly as substrate, and partly as heteromaterial, are being reported.

The European contributions on characterization of GaN have been strong since Prof. B. Monemar of the University of Linkoping (Sweden) started optical characterization some 25 years ago. His well-regarded work on photoluminescence includes excitonic studies,

Progress in GaN Homoepitaxy

For a long time researchers struggled to grow high quality GaAs on Si substrates. Eventually, this work was all but abandoned because it was not possible to reduce the dislocation densities below 10^5-10^6 cm^{-2} due to the lattice mismatch of 4%. In GaN growth on sapphire substrates one has to cope with a 16% lattice mismatch, yielding dislocation densities as high as 10^9-10^{10} cm^{-2}. However, Shuji Nakamura of Nichia Chemical has certainly proved that LEDs and lasers can be produced nonetheless.

In spite of Nichia's outstanding results, there is a consensus that a better substrate material could improve the performance of most devices. The ideal substrate would be conductive (in contrast to sapphire), thereby allowing current injection through the substrate. It should also be highly heat conductive, to facilitate high power applications. Additionally, the crystal structure as well as the lattice constant and thermal expansion coefficient should be the same as the epitaxially grown layers, to allow the cleaving of laser facets and 2-dimensional epitaxial growth without dislocations.

Obviously, all of this can be achieved only in case of homoepitaxy, where GaN materials are grown on a GaN substrate. Happily, progress is being made toward that goal. With the outstanding work performed at the Polish Unipress Center in Warsaw, the group around Prof. Porowski for the first time has produced GaN substrates in useful sizes - up to 9 x 9 mm with thickness around 0.5 mm. Employing a high pressure (15000 bar), high temperature (1600°C) method they obtained GaN platelets from seeded or unseeded Ga melts under N_2 pressure. These crystals reveal dislocation densities in the 10^2 cm^{-2} range, whereas a high number of point defects still causes background carrier concentration of 10^{19} cm^{-3}.

The maximum achievable size is currently equipment limited, and Prof. Porowski presented an impressive plot at EGW-1 showing an strain dependence and time-resolved PL of undoped and doped GaN. Besides him, Prof. B. Meyer (formerly Univ. Munich, now Univ. Giessen) and Dr. U. Kaufmann (Fraunhofer IAF) performed well-respected studies on deep levels and excitonic transitions. Serious work on electrical and optical characterization is done at Ciudad University (Spain), within the cooperation of the European LAQUANI project.

So far, there are only a few companies in Europe which are interested in production of GaN-based devices. The major interest of European companies is a blue LED, where both Siemens and Temic (both German) have research projects. Temic, a subsidiary of Daimler-Benz, has publicly announced that it plans to enter the blue LED market with a GaN on SiC product - see *CS* 2(4), p. 25. Siemens, which is a major player in the worldwide LED market is also quite serious about GaN, and has invested heavily in a cooperation with Cree, giving Siemens access to their GaN/SiC LED technology. (See *CS* 2(1), p. 14.) Thompson-CSF (France) is working on photodetectors. Philips (Netherlands) has projects on lasers, but conducts research in the United States. One the other hand, several non-European companies have research activities in Europe, including Cree (mentioned earlier), IBM (IBM Zurich) and Sharp (Sharp Research in Oxford, England).

Beside companies interested in GaN-based devices, there are several European equipment manufactures. Certain companies produce general-purpose semiconductor equipment which can also be applied to GaN, such as x-ray diffractometers, PL & Hall systems, etc. Beyond that, there is equipment particularly dedicated to GaN. In Europe this includes systems from MOVPE manufacturers Aixtron (Germany) and Thomas Swan (UK) and MBE system manufacturers VG Semicon (UK) and Riber (France) and MBE component manufacturer Oxford Applied Research (UK). Vendor interest in the nitride field was revealed by the strong participation in the exhibit at EGW-1 - almost 20 companies, or roughly one for every eight attendees!

Today, almost every major European country has nation funding projects in the GaN field. However, most of these projects started very late. For example, the first significant German project on GaN was launched two years ago. Aside from the different national projects there is one single GaN project of the European Community - the ESSPRIT project LAQUANI, mentioned earlier, which is dedicated to laser quality material with one focus being the development of suitable substrates.

Europe has some 150 groups working on GaN, with efforts ranging from basic physical investigations to unconventional applications (e.g. carrier injectors to organic LEDs). It is impossible to make mention of every group. However, to complete the overview the theoretical work by V. Fiorentini of the University of Cagliari (Italy) and J. W. Orton of the University of Nottingham (UK) has to be mentioned, as well as the activities at universities in Montpellier (France), Stuttgart (Germany), Munich (Germany) and at CNRS Valbonne (France) and the Fraunhofer IAF and PDI Berlin (both German).

In summary, GaN activities in Europe started late (except for the area of characterization) and are still behind the status achieved in Japan and the United States. Up to now, Europe has achieved reasonable results on GaN growth and excellent research on characterization, and very notable work on GaN substrates from Unipress in Poland. But, there have been no commercial devices so far. However, at several European facilities GaN growth is succeeding to a point where the first devices can be expected soon.

The GaN activities in Europe will continue - and so will the European GaN Workshop. EGW-2 is being planned for June, 1997 by Prof. J.P. Faurie of CNRS-Valbonne. At that time we might expect some device work and will be able to see if Europe is managing to catch up with Japan and the US in the emerging field of GaN.

almost exponential increase in size with time (See Figure One.) So far the crystals, which usually have a rough N terminated and a smooth Ga terminated surface, have been used unpolished. With MOVPE excellent optical properties have been achieved on these substrates (Pakula et al.), where PL linewidths down to 0.6 meV have been reported at 4K. Recent results obtained at the University of Ulm (Germany) revealed record PL linewidths of 0.5 meV on MBE grown homoepitaxial layers (See Figure Two). This work, in which ammonia was used as the N source in an on-surface-cracking approach, revealed that MBE can deliver high quality GaN layers at fairly low growth temperatures (~ 750°C). However, so far it remains to be shown that homoepitaxial growth of ternary alloys will also be significantly improved in spite of the lattice mismatch or if stress compensated structures have to be employed. Nevertheless, it seems likely that if the GaN crystal size and availability can be further improved, it will have a major impact on many aspects of the development of GaN technology.

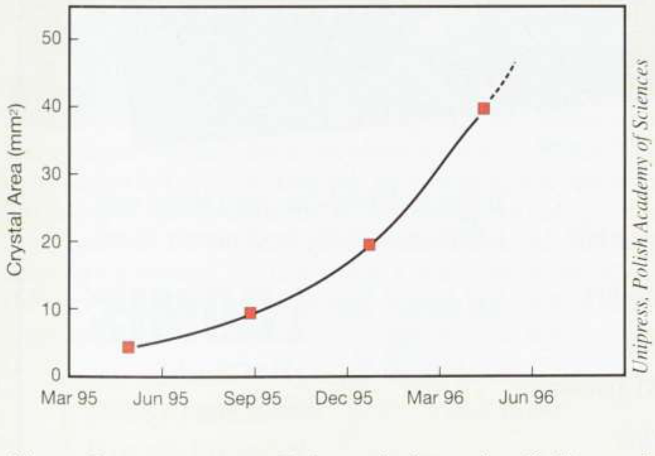


Figure One: Progress at Unipress in increasing GaN crystal size. Crystal area doubles every 3-4 months.

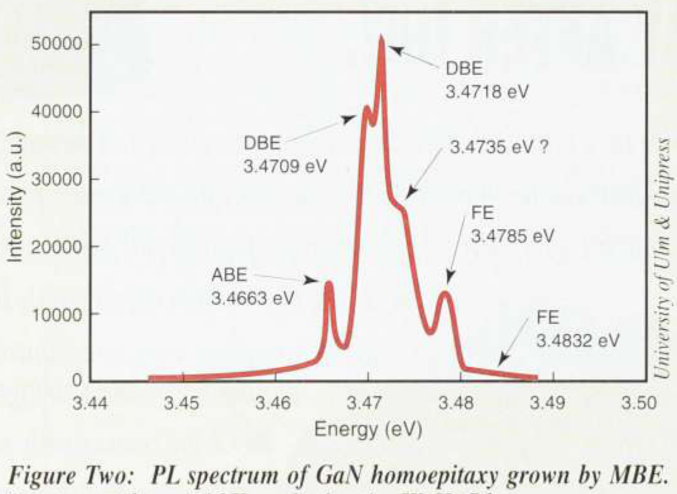


Figure Two: PL spectrum of GaN homoepitaxy grown by MBE. Spectrum taken at 4.2K, excitation 1 mW, HeCd.

Summary of Selected GaN-Related Papers from ICMOVPE VIII

ISHWARA BHAT
RENSEALER POLYTECHNIC INSTITUTE
ECSE DEPARTMENT
TROY, NY

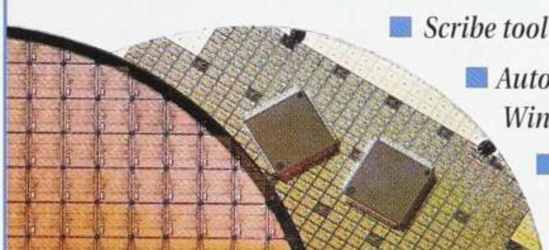
The 8th International Conference on Metal Organic Vapor Phase Epitaxy was held at the Cardiff International Arena, Cardiff, Wales from June 9 - 13, 1996. The conference attracted over 200 papers from around the world, out of which over 20 were on GaN and related materials. The following is a summary of some of the highlights.

As might be expected, Shuji Nakamura of Nichia Chemical Industries presented one of the plenary talks. He presented the recent results on blue and blue-green LEDs and violet/UV color lasers. The InGaN MQW laser diode had a threshold current of 610mA (density 8.7kA/cm^2). The differential quantum efficiency was 17% per facet and the pulsed output power was 57 mW per facet at a current of 700mA. The operating voltage was 21V. There were demonstrations of large panel color displays and violet/UV lasers during the talk.

During the regular sessions D. Kapolnek (UCSB, USA) presented results on selective area MOCVD growth of GaN on patterned GaN/Sapphire substrates. Circular patterns were delineated on GaN/sapphire substrates using SiO_2 masks. Under proper conditions, GaN growth was observed only on exposed regions. The selectively grown layers are of pyramid shaped, with sharp tips at the surface. These were tested for possible use in field emission displays. Preliminary results on an array of pyramids used as field emitters have been reported. This paper received the best student paper award.

S. Tanaka (The Institute of Physical and Chemical Research, Japan) reported that an ultra thin buffer layer (about 1nm) of AlN is needed to get high quality GaN on SiC substrates. Thin (less than 5 nm) AlN layer grows pseudomorphically and the surface of AlN is very smooth (as shown by AFM) and the subsequent GaN grown on this thin AlN/SiC had dislocation density in the range 1e7-1e8 cm^{-2}. The substrate should be atomically smooth without any steps, indicating that exact (0001) face is ideal. Thicker buffer layers of AlN result in rougher GaN caused by the three dimensional growth of AlN. Ambacher (Walter Schottky Institute, Germany) reported on the growth of high quality AlGaN and AlN using tritertiarybutylaluminum as the Al source instead of the more common source trimethylaluminum. K. Pakula (Institute of Experimental Physics, Warsaw) presented results of MOCVD growth of GaN and GaAlN on single crystal GaN. Homoepitaxial GaN had much narrower PL FWHM (about 1 meV) compared to GaN grown on sapphire. In addition, growths on N-terminated bulk GaN are much smoother compared to those grown on Ga-terminated surface. A research staff from Advanced Technology Materials, USA presented comparative results of AlGaN/GaN heterostructure growth on SiC and sapphire substrates. The electron mobilities and sheet carrier concentrations of several $Al_{0.15}Ga_{0.85}N$/GaN heterostructures grown on sapphire and SiC substrates were compared. The highest electron mobility of 7400cm^2/Vs was measured when the structure was grown on SiC substrate.

S. Denbaars (UCSB, USA) presented a talk on the growth of InGaN epitaxial layers. Lifetimes ofthe order of 300ps was measured in InGaN



films. For InGaN QW, quantization was observed only for QW thicknesses below 35Å. Very high V/III ratio (V/III ratio of over 10,000) was found to be necessary to get In-droplet-free films. V. Harle (University of Stuttgart) reported on the GaN-GaInN growth by low pressure MOVPE. One interesting result was that the In incorporation in InGaN increased as the reactor pressure was decreased. Two papers discussed the growth of GaPN and InAsN. H. Yaguchi (University of Tokyo) presented the PL and PLE spectra of GaPN layers grown by MOVPE. A systematic PL study of several $GaP_{(1-x)}N_{(x)}$ layers with x varying from 0.0 to 2% were presented, confirming the earlier observation that there is a large bandgap bowing in GaP-GaN systems. S. Sakai (University of Tokushima) presented the summary of their efforts to introduce N to InAs. Using conventional MOVPE, high percentage of nitrogen incorporation was found to be difficult. Results on plasma-cracked N_2 were also presented. All the layers were discontinuous when grown on GaAs substrates.

There were also several poster presentations on nitrides. B. Beaumont (CNRS, France) compared the results of GaN obtained using several nitrogen precursors, including triethylamine, terbutylamine, NH_3, plasma activated NH_3 and plasma activated N_2. The best results were obtained with NH_3. Triethylamine did not produce any GaN. A. Wickenden (NRL, USA) presented a systematic x-ray diffraction studies on GaN and sapphire and the effects of pre-growth thermal treatments on sapphire on the layer properties. T.F. Kuech (University of Wisconsin) provided experimental information on the high temperature gas phase reactions between TMG and NH3 using in-situ mass spectrometry. Using deuterium and deuterated ammonia, they studied the decomposition pathways for TMG in H_2 and ammonia. Y. Ohuchi and his group (Mitsubishi Cable Industries, Japan) provided the results on the use of tetraethylsilane as n type dopant and bis(ethylcyclopentadienylmagnesium) as p type dopant. They found that the results are similar to the results obtained using silane and CP_2Mg. The advantage of these precursors is that both are liquids at room temperature so that transport of these to the reactor is easier.

The papers from this conference will be published in a special issue of J. Crystal Growth.

U.S. Funding for Bulk Nitride Research

The United States Department of Defense, through the Office of Naval Research, is planning to supply around $1 million in funding for research into bulk nitride crystal growth. The funds, which are being made available through the Defense University Research Instrumentation Program, are earmarked for "instrumentation supporting research into single crystal bulk growth of GaN, AlN or InN, e.g. growth rate, impurities, defects, and, particularly, scalability issues as well as innovative techniques and equipment to reduce temperatures and/or pressures below those required by conventional synthesis from constituent elements." An announcement regarding the recipient(s) of the funding awards is expected this fall.

Samsung to Pursue Blue LEDs

It appears that Samsung's name should be added to the growing roster of companies that are pursuing, or planning to pursue, the blue LED market. The evidence for this proposition comes by way of MOCVD equipment manufacturer Emcore, which recently announced what it calls a "multi-million dollar multiple system order" from Samsung. According to Emcore, the order consisted of "a number' of new systems which "will be used to expand Samsung's production line in Kiehung, Korea to enable the manufacture of GaN blue LED's at present with an eye toward laser devices in the future". A possible schedule for introducing the devices to the market was not given.

More Nitride News in this Issue:

LED Update from Japan - page 16

Nitrogen/GaInP Compound for Laser Diodes - page 18

Recent Reports on Nichia's Nitride Laser

Two meetings held in Japan this summer provided an opportunity for updating the current status of Shuji Nakamura's nitride laser work at Nichia Chemical. At the Eighth International Conference on Solid Films and Surfaces (ICSFS-8), held in Osaka July 1-5, Nakamura reported a 24 hour lifetime for a low duty cycle, pulsed operation diodes at room temperature. The threshold current (I_{th}) was 150-350 mA, the threshold current density (J_{th}) was ~5kA/cm^2, and voltage threshold (V_{th}) was 20-30 V. These numbers, while generally consistent with previous results from Nichia, illustrate the large differences between the status of the nitride lasers compared to devices from the more fully developed III-V systems. For example, J_{th} ~300 A/cm^2 is routinely achieved in GaAs-based diodes. Also, V_{th} is almost invariably directly proportional to the bandgap of the material - e.g. for AlGaAs diodes, where the bandgap is ~2 eV, V_{th} is usually 2V. Obviously, in this case there is a large discrepancy between the bandgap of the material (~4 eV) and the V_{th}, which indicates that large voltage losses are occurring, most likely at the contacts.

Two weeks later at the First Optoelectronics and Communications Conference (OECC), held in Chiba July 16-19, Nakamura reported on a diode with a 50% duty cycle operation, and said that he expects to achieve CW operation "soon". No lifetime figures were given. I_{th} was 90 mA with J_{th} 3-10 kA/cm^2 and V_{th} was reduced all the way to 10V. The longitudinal mode spacing reported in this paper was 0.04 nm with length = 600 μm, and it is TE mode polarized when lasing.

Digital GaAs

The digital GaAs niche is full of surprises - not least of which is the fact that it still exists

MARIE MEYER

If you are familiar with the history of the compound semiconductor industry, you might have the impression that the topic of GaAs ICs for digital applications is a dead issue, now that interest in supercomputers has all but disappeared. And no one could be criticized for approaching the subject of digital GaAs with some degree of skepticism, given its history of unrealistic expectations and subsequent disappointments.

In the early 1980's there was a great deal of speculation that GaAs's superior speed meant that it would soon displace silicon as the technology of choice for microprocessors. By 1985, just in the United States, there were no fewer than *nine* companies offering merchant digital GaAs foundry services (Ford, Gain, Gazelle, Gigabit, Harris, MSC, Tachonics, TriQuint, and Vitesse). *Fortune* magazine proclaimed digital GaAs to be "sexier" than silicon, and forecasters were predicting that the market for digital GaAs ICs would reach $1 billion by the early 1990's - and at least one writer argued that GaAs could capture as much as *one-third of global semiconductor market* by the year 2000.

Today, of course, the picture looks very different. Analog applications rule the GaAs industry, and the majority of the digital GaAs companies fared poorly: the two biggest companies (Harris & Ford) left the field (the latter reportedly $100 million poorer for the experience); two disappeared into a merger (Gigabit & Gazelle, which merged into TriQuint), and the remainder went bankrupt or simply faded away. And a prominent captive manufacturing effort, Cray Computer, also came and went in that period. GaAs was no longer called "sexy". Instead, it was said that "GaAs is the material of the future...and it always will be". And as for the forecast: the actual worldwide market for digital GaAs ICs this year is less than $100 million.

Despite all this, the digital GaAs field remains a surprisingly interesting area. True, expectations may not be as high as they once were. But, nevertheless, the technology is currently enjoying something of a renaissance, thanks in part to the tremendous growth of the market for high data-rate telecommunications, as well as growing interest in technologies with very low power consumption requirements for battery-operated electronics. Of the nine companies listed above, only two - Vitesse and TriQuint - are still active in digital GaAs, but they are being rewarded for their patience by rapid growth and good profitability. Vitesse remains dedicated to digital GaAs; TriQuint, on the other hand, now allocates ~60% of its fab capacity to analog/RF GaAs. (See page 11). And perhaps the most telling indicator of the overall health of this niche is the fact that more companies - ones with very deep pockets - are getting ready to enter the market.

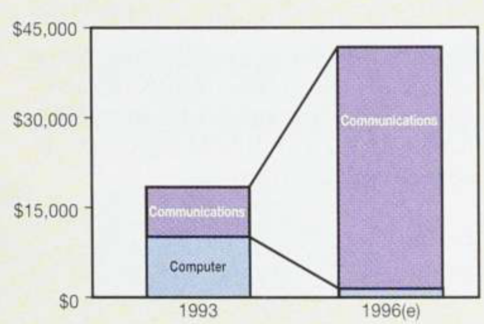


Figure 1: The changing nature of Vitesse's digital GaAs business.

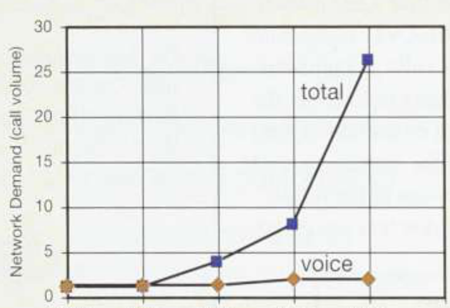


Figure 2: The forecast for network demand.

New Markets for Vitesse

Vitesse should have been rattled by the demise of the GaAs supercomputer business - but it wasn't. In 1993 the majority of their revenue came from the computer market. Now, three years later, that segment has all but disappeared, but company-wide revenues have more than doubled on the strength of the expansion of the company's communications business - see Figure 1. Everyone at Vitesse seems very happy with this flip-flop, especially given the forecast for continued explosive growth in the quantities of data that will be transmitted over phone lines. See Figure 2.

Data transmission is much more demanding than voice communications, creating problems for both the phone company and the local network administrator. So system designers everywhere are looking for new ways to move more data, as quickly as possible. Vitesse believes that their GaAs ICs can solve the problems by delivering 2 to 4 times the speed of silicon with half the power consumption, at a comparable price. Of course, at one point it looked like GaAs would be the solution to bottlenecks in the supercomputer field as well, because it could provide much faster clock speeds. In the long run, however, silicon parallel processing proved that the most cost-effective answer was to use multiple channels of lower-performing microprocessors. But Vitesse CEO Lou Tomasetta doesn't think history will repeat itself this time. The difference, as he sees it, is that in supercomputers the key to the cost of the system was not the number of channels used, but the cost of the circuits. But in telecommunications, the use of multiple channels is rarely, if ever, practical, because most of the cost of a communications link lies setting up the connection. Therefore the customer is highly motivated to move the maximum amount of data through each channel, and is, within reason, less sensitive to the cost of the circuits in it.

The majority of the internal investment at Vitesse is going into developing standard products for their communications business, which is currently growing at around 70% a year. Products are offered for all three of the major communications standards. SONET currently accounts for around 50% of revenues. Fiber Channel contributes around 10% of company revenues, but is expected to grow very rapidly. And production for the forth-coming ATM market is expected to be launched in 1998. In contrast to this "catalog" approach, it is interesting to note that the majority of Vitesse's business in computers and automated test equipment (ATE - their other major market segment) involves custom ASICs.

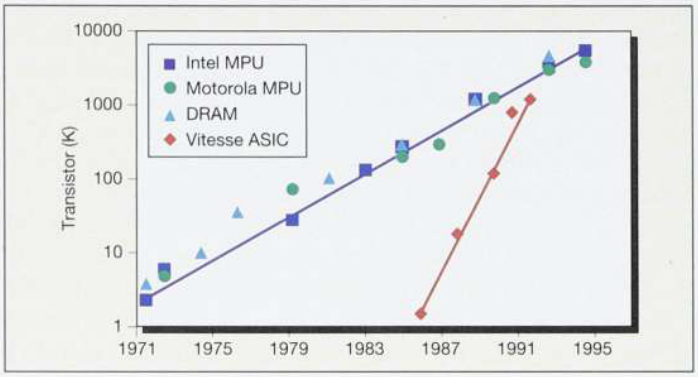
continued on page 28

VLSI GaAs & Moore's Law

Thirty years ago Gordon Moore, a founder of Intel, predicted that progress in the semiconductor industry would require that the number of transistors in silicon ICs double every twelve months. This prediction, which has become known as "Moore's Law", has proven very acurate, although the pace has recently slowed to every 18 months. To keep pace with Moore's Law, the industry has made a steady march from small scale integration (SSI, 2 - 10 gates) to medium scale integration (MSI, 10 - 100 gates) to large scale integration (LSI, >100 gates) to very large scale integration (VLSI, >1000 gates).

Vitesse executes VLSI GaAs using MESFET technology, and takes advantage of every opportunity to make it as similar as possible to VLSI CMOS. Therefore, when the occasion arises, the company is capable of demonstrating integration levels which approach the state-of-the-art in silicon - despite the fact that silicon has had a twenty year head start. Supercomputer manufacturers created the demand for the most highly integrated GaAs ICs. This niche reached its zenith in the early 1990's when Vitesse began producing a CPU (central processing unit) chip which included blocks of SRAM and multi-port register files, and which contained more than 1.2 million transistors - roughly equivalent to an Intel 486 microprocessor or a 1M DRAM chip.

Since then, the market for supercomputers has virtually disappeared, but Vitesse has found equal or better market niches in telecommunications, data communications, and automated test equipment (ATE). On the whole, the applications for super-fast GaAs circuits in these markets require only relatively modest levels of integration, which means that Vitesse is currently taking a break from the dictates of Moore's Law. However, the company's policy of taking advantage of CMOS tools means that state-of-the-art integration in MESFET GaAs will be accessible, when and if the need for it rises again.



Performance & Cost

Obviously, the key to Vitesse's marketing strategy is to take advantage of GaAs' superior properties to create chips offering higher levels of performance than their silicon counterparts. But performance is only half the battle - in the markets that Vitesse is pursuing, the company also needs to maintain cost parity with silicon. "We can easily beat silicon on speed alone, but the real issue in capturing new markets is lower cost", says Tomasetta. Fortunately, the high electron mobility in GaAs translates into lower power dissipation (see page 30). Therefore, Tomasetta reports, "in any frequency range we can come in with a part that consumes less power than Si bipolar or BiCMOS - a key cost consideration, due to the expense of packaging, which has far more impact on the cost of the product than the integrated circuit itself". The majority of Vitesse's products now use low cost plastic packages, and the company hopes to increase that figure to 80% in the near future.

And what about the cost of starting materials? Everyone knows that GaAs wafers cost more than silicon wafers. But Ira Deyhimy, Vice President of Product Development at Vitesse, says that doesn't matter. "This drawback is partially offset by the greater simplicity of the GaAs process." For example, the standard MESFET process at Vitesse, which yields f_t> 40 GHz, is currently done with 0.4 - 0.5 µm linewidths, and requires only 13 mask levels. See Figure 3. In contrast, 16-18 mask levels are required in CMOS, and >20 for BiCMOS. Deyhimy notes that "in the end, the cost of the blank wafer is only a small fraction of the cost of the completed wafer".

One factor that is very much in silicon's favor is wafer sizes. As Deyhimy says, "the larger wafers used in silicon processes mean that, for chips that are alike in size and yield, silicon CMOS offers you more for your money - although this is not true for other silicon processes, like BiCMOS and ECL". Thus Vitesse plans to implement 6" GaAs processing in its new fab which is currently under construction in Colorado Springs (see page 10). That facility, which is scheduled to be operational in 1998, will be capable of processing 600 6" wafers/week, and should give Vitesse cost parity with 6" CMOS.

Here Comes Honeywell

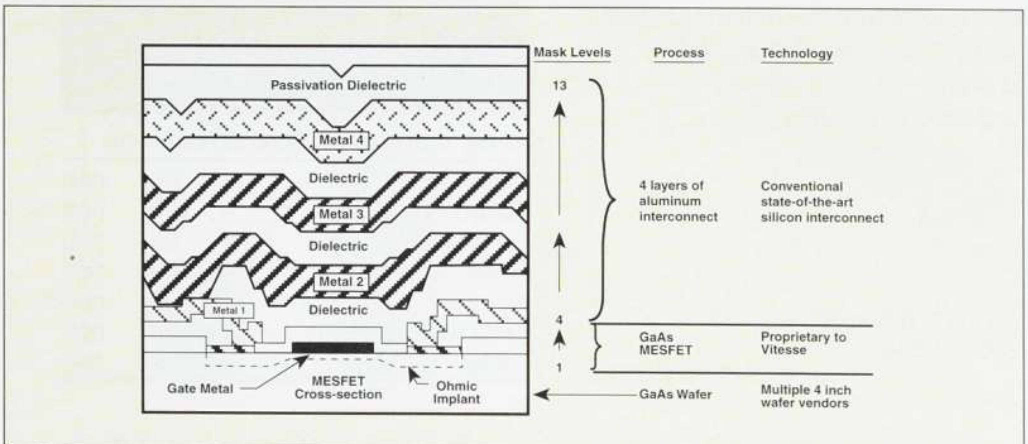
One of the most intriguing features of the digital GaAs scene is that a few new companies - and very large ones at that - are showing interest and investing resources. Attendees at last year's GaAs IC Symposium saw an invited paper which reviewed the capabilities of Motorola's Complementary GaAs process, which the company is exploring for low-power, high-speed digital and mixed-mode applications. It was reported that this technology, which is currently at LSI levels (10 - 30 K transistors), had yielded processors working at >1 GHz, with speed-power performance as low as 0.01 µW/MHz/gate. This year's meeting will include an invited talk from the University of Michigan reviewing microprocessor development for Motorola's process (see page 32.)

The historical roots of Motorola's technology lie at Honeywell, which developed what it calls Complementary Heterojunction FET (CHFET) technology and licensed it to Motorola. As the name suggests, this a very different technology from that used at Vitesse, in that it is complementary (using both n- and p-type channels), and it is based on a heterostructure (as opposed to MESFETs, which are implanted devices). See page 31 for a more detailed description. Since 1985, Honeywell has invested more than $60 million in this area. The company plans to build a GaAs processing line at its Solid State Electronics Center in Plymouth, MN, and plans to launch volume production of CHFET circuits in late 1998, using 4" MBE-grown wafers.

Honeywell's CHFET process will likely be used for a mixture of foundry or custom work and some standard products offering low power consumption and high speeds (100 MHz to 2 GHz) at LSI levels. The first target markets will be the aerospace/military/satellite applications, where Honeywell is already an established presence. Honeywell is most well-known for sensors and control electronics, and the company believes that this area will also be ripe with opportunities for low-power signal processing products as the use of wireless, battery-powered data transmission becomes more and more pervasive. However, this market probably cannot be exploited until high volume processing is in full swing, allowing lower costs.

Honeywell also has their eye on some other interesting areas. The company has worked with the U.S. Naval Research Laboratory to demonstrate that their technology can offer superior single event upset radiation hardness. The key is to add a low-temperature GaAs buffer layer onto the otherwise standard structure described on page 31.[1] Honeywell is the leading manufacturer of rad-hard CMOS, and they see digital GaAs as an excellent compliment to the existing capabilities that they can offer to the satellite market - an area which is very sensitive not only to radiation protection, but also performance and power consumption. They are also quick to point out that with a minor change in the ohmic contacts, their CHFET process can produce circuits which operate over a *huge* temperature range. Lows of 4 Kelvin and highs of 560°C have been demonstrated.

Honeywell's plans may seem a bit daring, mostly because the use of epi material raises several issues regarding materials cost and yield. But, as was noted earlier, the cost of the starting wafer is a small part of the cost of the finished product. And, like Vitesse, Honeywell will take advantage of a simplified process (13 mask levels) and routine linewidths (0.6 µm) to help keep their costs in line. And if it still seems hard to believe, consider this: five years ago the use of MESFETs, HEMTs and HBTs in consumer products like cell phones and DBS receivers also seemed unlikely. The digital GaAs market, far from dead, may have many more surprises ahead in the years to come.



Vitesse Semiconductor Corporation.

Figure 3: Schematic of Vitesse's HGaAs IV MESFET structure.

[1] See "GaAs Transistor with Improved Radiation Hardened Characteristics, CS 1(3), p. 10.

A Review of Digital GaAs Technology and Terminology

Current Status

Why is GaAs is of interest for digital applications? The standard answer to that question is that GaAs is fast: in terms of bulk material, its electron mobility is more than six times higher than silicon. However, it should be noted that, in practice, this distinction can become blurred due to velocity saturation in short channel devices. Table 1 provides a comparison of some basic properties of GaAs and silicon, showing three additional advantages of GaAs: a wider bandgap, which lends itself to higher temperature operation; better radiation hardness, which is advantageous in certain applications; and a high resistivity substrate, leading to higher frequencies of operation. But this table also shows two disadvantages. The first is thermal conductivity: silicon can dissipate three times the power per area compared to GaAs. And, of course, GaAs has no native oxide, which limits the types of transistor devices which can be fabricated.

Logic Families

There have been several logic families designed in GaAs over the past 20 years, but there are basically only two that have been successful in the commercial arena, at least as far as the U.S. manufacturers are concerned. They are DCFL (direct-coupled FET logic) and SCFL (source-coupled FET logic), and both are executed using MESFET technology. See Figure 1 for a schematic of a two-input NOR gate for each.

DCFL is the best choice for low power consumption and VLSI. This is the logic family Vitesse uses for its large gate arrays. It is similar in design to silicon n-channel MOS (NMOS), in that it uses an active load depletion mode FET (DFET) and an enhancement mode (normally off) FET (EFET) for the switch. DFCL has the important advantage of requiring only a single voltage power supply. The power consumption is low, due to the low power supply and logic swings.

SCFL is used by TriQuint and Vitesse for achieving the highest possible speed from a logic gate. It is a differential logic family similar to bipolar emitter-coupled logic (ECL). SCFL achieves its high speed by the gain increase afforded by a differential amplifier coupled with FETs which are maintained in their saturation state, thus reducing the FET capacitance to be charged. Its primary advantage is speed; its primary disadvantages are that it consumes the largest amount of power (because of its large power supply voltage - typically >5V) and it requires two power supplies. However, this complexity compares more favorably with DCFL when macros such as flip-flops, adders, or multiplexers are considered.

The most important point to remember regarding the comparison of DCFL and SCFL is that each has distinct trade-offs for a particular type of design, varying from low integration/high power/high speed for SCFL and high integration/low power but lower speed for DCFL.

Comparison with Silicon

No prizes for guessing the most important question in the digital GaAs field: how well does it compare with silicon? The key criteria are speed and power dissipation. GaAs can be compared to three silicon technologies: CMOS, BiCMOS, and ECL (bipolar emitter-coupled logic). For the following discussion, the comparisons applied to CMOS can be inferred to apply to BiCMOS as well. This is based on the premise that most bipolar usage in large BiCMOS digital designs are circuits used to drive the outputs and large capacitive loads, such as clock lines. Hence, the majority of the logic will consist of CMOS, not bipolar.

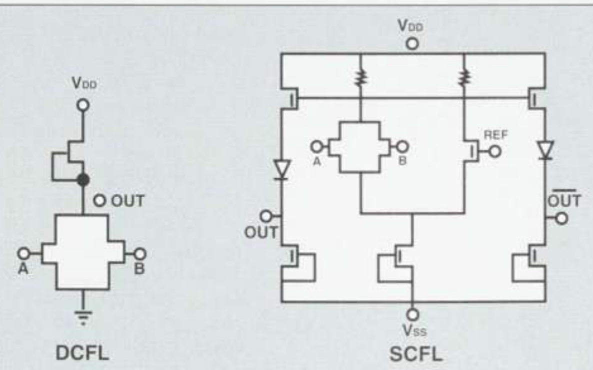
A good figure of merit for the high-speed performance of a transitor is the frequency at which the current gain reaches unity - the famous "F_t". CMOS has a much lower F_t than GaAs - typically 8 -10 GHz for 0.35 micron CMOS, compared to 30-40 GHz for 0.4 micron GaAs. This is due to its larger substrate capacitance and smaller transconductance (gm). (Transconductance is proportional to electron mobility, which, as discussed earlier, is much larger in GaAs - see Table 1.)

Property	*Silicon*	*GaAs*	*Advantage*
Bandgap (eV)	1.12	1.43	GaAs
Electron mobility (cm^2/Vs)	800	5000	GaAs
Hole mobility (cm^2/Vs)	300	250	None
Native oxide	SiO_2	None	Silicon
Radiation Hardness (rad)	1.0E + 6[a]	1.0E + 7[a]	GaAs
Thermal conductivity (W/CM^2-°C)	1.4	0.5	Silicon
Resistivity (ohm-cm)	4.0E + 5	4.0E +8	GaAs

[a]Total dose only; GaAs shows similar performance to silicon for transient upset.

TABLE 1. Comparison of semiconductor properties between GaAs and Silicon

GaAs IC Applications Handbook



Logic family	*No. FETS[a]*	*No. diodes resistors[a]*	*Typical power*	*Typical power*	*Typical power*
DCFL	3	None	Low	Low-med	VLSI
SCFL	8	2/2	High	High	MSI

[a]For a two-input NOR gate.

FIGURE 1. A two-input NOR gate and a summary of features of the two most popular digital GaAs logic families used today.

GaAs IC Applications Handbook

The situation with regard to the other performance factor, power dissipation, is a bit more complex, because of the large discrepancy between static and dynamic power in CMOS. In a CMOS circuit the gate is totally isolated from the power supply rail for a logic low state, and CMOS's static power dissipation is, therefore, in the range of a few microwatts. However, the dynamic power dissipation is determined when the gate switches, and it increases with increasing frequency, due to the logic gate having no precharge on the gate output. In contrast, GaAs and Si ECL have constant current sources in their logic design and hence the static and dynamic power dissipations are equivalent. Figure 2 shows the principal operating ranges and power dissipations for these three technologies, plus BiCMOS, all on a per gate basis. Note that "per-gate" is not the same as "per chip". In typical operation, all of the gates are not switching all of the time, and in a CMOS circuit, the static gates are not drawing power. Nevertheless, the commonly held belief that CMOS is the lowest power consumption technology must include a caveat for higher speed applications. Indeed, the commercial success that GaAs ICs are enjoying in the high speed telecommunications field are attributable, at least in part, to the fact that at high frequencies (80 MHz system clocks and higher), operating power for a GaAs chip can actually be lower than that of a complex CMOS chip, since for GaAs logic, power consumption is independent of frequency, whereas in CMOS the relationship is linear.

Sources: Gallium Arsenide IC Applications Handbook, D. Fisher, I. Bahl, ed., Academic Press (San Diego, CA) 1995, pp 59-63; Ira Deheny, Vitesse Semiconductor.

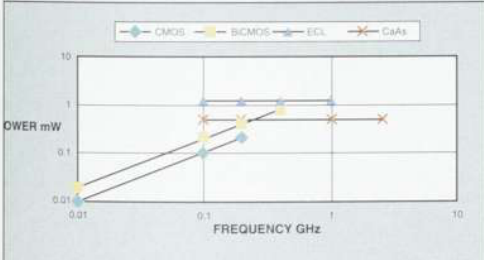


FIGURE 2. Frequency and power dissipation per gate for CMOS, ECL, and GaAs.

GaAs IC Applications Handbook

GaAs CMOS: The Next Generation?

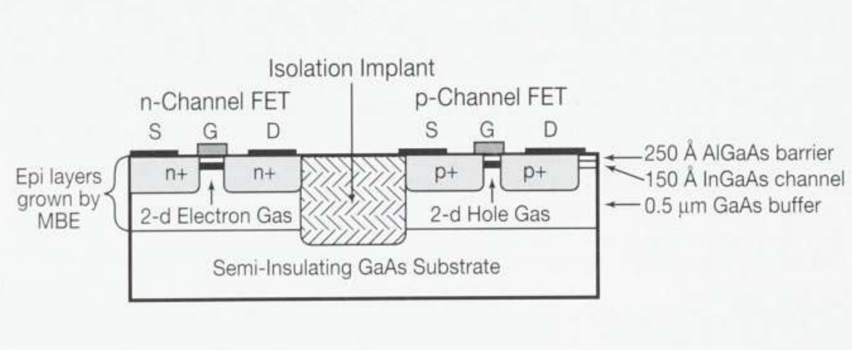
The digital GaAs picture could change dramatically with a new CMOS-like GaAs technology nearing production. Pioneered by Honeywell and called Complementary Heterostructure FET (CHFET), this new technology uses III-V bandgap engineering to create CMOS-like N and P channel FETs in GaAs. Essentially, CHFET offers the speed of GaAs at CMOS power levels. This has been the grail of GaAs electronics for over 20 years. Past efforts to build GaAs CMOS failed because the native oxide of GaAs is unstable[1]. Instead of a native oxide, CHFET uses a wider bandgap semiconductor ($Al_{0.75}Ga_{0.25}As$, Eg ~ 2 eV) grown by MBE as the gate insulator. To boost P-channel FET performance, the CHFET channel is a pseudomorphic $In_{0.2}Ga_{0.8}As$ layer which enhances hole mobility. A device cross-section is shown in Figure 3. With a 0.6 micron gate length, the N-channel CHFET has approximately 6X more current drive and the P-channel CHFET has ~2X more current drive than their silicon CMOS counterparts.

With high performance complementary FETs to work with, CHFET logic gates achieve very impressive speed/power results[2]. Propagation delays of 200-400 pS are typical for realistically loaded CHFET gates. They are much faster than CMOS and comparable in speed to GaAs MESFET logic gates. But unlike GaAs MESFET, CHFET gates draw minimal static power. And since its high switching speed is attained at a supply voltage of only 1.4 Volts, CHFET has approximately 6X lower power than 3.3V CMOS at the same speed - see Figure 4. (Power consumption varies as supply voltage squared for complementary logic). By lowering its supply voltage below 3.3V, CMOS can achieve the same power dissipation as CHFET but then CMOS is much slower. Even at 3.3V, the CMOS gate is more than 2X slower than CHFET. The bottom line is that, for digital circuits operating above ~200 MHz, CHFET is the lowest power IC technology available.

CHFET was invented by Honeywell, who is presently moving the technology into production at its Solid State Electronics Center in Plymouth, Minnesota. Honeywell has also licensed CHFET to Motorola (where it is called CGaAs™). Honeywell has developed several new logic families to extend the technology's speed and power performance. Buffered CHFET (BCHFET) is a true complementary logic family with minimal static power whereas the Feedback FET Logic (FFL) family uses push-pull N-channel transistors to increase speed at the expense of DC power. BCHFET and FFL cells are often mixed together in the same circuit, with FFL handling the high speed signal paths and BCHFET used everywhere else to minimize overall

[1] *Status of GaAs MOS Technology, T. Mimura and M. Fukuta, IEEE Trans. On Electron Devices, Vol. 27, No. 6, June 1980, pp. 1147-1155.*

[2] *CHFET Technology for Low Power, High Speed Digital Applications, D. Fulkerson, S. Baier, J. Nohava, and R. Hochhalter, Solid State Electronics, Vol. 39, No. 4, April 1996, pp. 461-469.*



Honeywell SSEC

Figure 3. Cross section of the Honeywell CHFET IC process. The CHFET approach uses heterostructure engineering to emulate CMOS with high performance III-V materials. The 2-level metal interconnect system is omitted for clarity.

power consumption. Both logic families are available in standard cell libraries with full CAD tools, auto-routing, logic synthesis, etc. and are being actively used by customers. The drawbacks of CHFET are higher wafer cost due to MBE growth and, at the moment, lower IC complexity. Honeywell has demonstrated digital CHFET circuits with up to 5,000 equivalent gates (40,000 transistors) but efforts are underway to scale up the process to yield 50K gate density designs.

Honeywell believes that CHFET will ultimately replace the existing N-channel GaAs technologies just as Silicon CMOS replaced NMOS. Also, with its substantial speed/power advantage over SOI-CMOS, CHFET could take market share from Silicon CMOS in the emerging low-power arena. Studies show that CHFET maintains its fundamental speed/power advantage over SOI-CMOS as gate lengths scale toward 0.1 microns. Stay tuned!

Steve Baier
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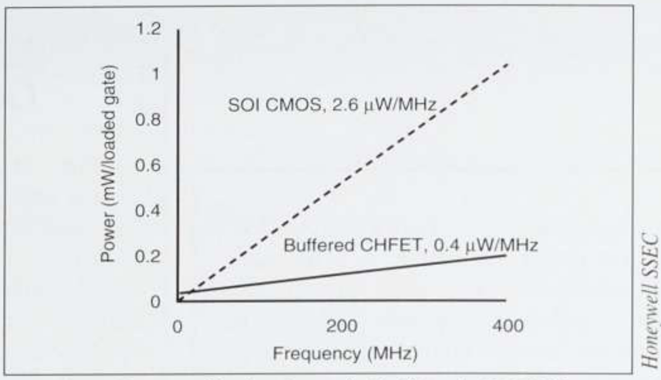

Figure 4. Power dissipation of Buffered CHFET compared to Honeywell's production SOI-CMOS process. Power is quoted at 100% duty cycle for a 2-input NAND gate realistically loaded (FO=2 plus 0.2 pF) at 85°C. Output transistors have same gate length, width, and capacitance. Note that CHFET has a small amount of DC leakage due to the lower bandgap of its oxide layer. The propagation delay of the CHFET gate is 350 pS compared with 800 pS for SOI-CMOS.

The PUMA Project: Digital GaAs at the University of Michigan

What are the future prospects for digital GaAs in high volume commercial markets? Research at the University of Michigan is motivated by two possible application areas. The first is high-end microprocessors. Over the past decade, the performance of CMOS microprocessors has improved at a compounded 59%/year, for an amazing increase of more than 100 fold in computing power. Much of this performance gain has come from pipelining, and from multiple instruction issue, both of which have been enabled by a 40%/year growth in integration level. Current microprocessors, however, already take pipelining and superscalar to their points of diminishing return, so staying on the performance curve will be increasingly more difficult in the future. Thus, technology improvements must provide more of the clock speed improvement which will contribute to the performance of future computers. This fact warrants evaluation of exotic processes such as complementary GaAs. The second motivation is the growing importance of power dissipation in circuits used in portable equipment such as notebook computers and cellular phones. These circuits typically need to have quite high performance, but must dissipate little power, since they operate from batteries. Complementary GaAs may be the answer because its low voltage operation reduces dynamic power dissipation, and static power consumption is limited by the complementary nature of the device structure.

Current research at Michigan focuses on evaluating Complementary GaAs HIGFET technology for VLSI digital applications in a DARPA-funded project called PUMA. The demonstration vehicle chosen for this evaluation is a microprocessor optimized for high clock speed - the target frequency being 1 GHz. The processor will execute a subset of the PowerPC™ instruction set. Subcontractors are Motorola, which is providing their CGaAs™ technology, and Cascade Design Automation, which is extending their EPOCH design tools to meet the CAD requirements of the project. The Michigan research group has previously designed prototype GaAs microprocessors [1, 2] in E/D MESFET direct-coupled FET logic (DCFL). While circuits in this technology are fast, they are restricted by source resistance and leakage currents to small fan-in NOR-only gates. The MESFET gate diode clamps input signals to about 0.7 V, reducing noise margins, increasing the drive requirements of logic gates, causing IR drops on signal lines, and making pass-gate logic difficult to implement. The most serious problem of E/D MESFET technology compared to CMOS for implementing microprocessors is that the lack of a complementary load device in static memories makes DCFL on-chip memories comparatively large and power-hungry.

A complementary heterostructure-insulated-gate FET process, on the other hand, has many of the characteristics of CMOS. While it, too, has a Schottky-diode gate, the forward voltage of the heterostructure diode is large enough to make gate current negligible under static operating conditions. Like CMOS, CGaAs transistors can be stacked into NAND structures. CGaAs has the flexibility to implement any of the P/N MOSFET logic families: unratioed complementary gates, pass-gates, and domino gates; ratioed unipolar logic (p-loaded DCFL);and source-coupled logic gates. These logic families can be mixed on an integrated circuit, offering the designer a wide range of speed and power. Speed and power can also be controlled by varying the power supply voltage from below 0.9 V to 1.5 V.

Memories implemented in CGaAs are similar to CMOS memories. The lay out density is limited by design rules, rather than by an area/power trade-off as in DCFL. The low power supply voltage however, does make the sense amplifier design challenging. Because the transconductance ratio of p- to n-devices is 1:4 in CGaAs, superbuffers are needed to drive large loads. CGaAs has several interesting advantages over CMOS: in CGaAs, there is no need to contact the well or substrate; latchup is not a possibility; and drains of p- and n-transistors can be abutted and can share an ohmic contact.

The major challenges in CGaAs seem to be developmental, rather than fundamental. The process is not yet mature. It lags CMOS by years in terms of device scaling and integration level. The difficulty of making ohmic contacts to III/V material will keep CGaAs layouts from being as dense as CMOS, even as the process is further scaled. To partially compensate for the limited integration level, the PUMA processor will be implemented on a fine-pitch, flip-chip, array-pad multichip module. The exact partitioning of the design will depend upon the status of CGaAs as the design nears completion.

Based on preliminary device models and architectural specifications, the University of Michigan group has been able to begin evaluation of both the technology and the proposed architecture by designing and simulating major microprocessor circuit blocks. Results of this evaluation are fed back to Motorola to help tune the CGaAs process to better suit digital VLSI applications. As work progresses it becomes more and more obvious that complementary GaAs has a number of very attractive characteristics for high-performance and for low-power circuits. Its success in high volume commercial applications will depend on how quickly it matures with better interconnect capability, reduced transistor thresholds, improved integration level, and scaled dimensions.

Prof. Richard B. Brown
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Editor's Note: A review of the most recent developments from the PUMA project will be presented in an invited talk at the Gallium Arsenide IC Symposium in Orlando, FL, November 3-6, 1996.

[1] *R. Brown, et al., "Gallium-Arsenide Process Evaluation Based on a RISC Microprocessor Example," IEEE Journal of Solid-State Circuits, vol. 28, no. 10, pp. 1030-1037, October 1993.*

[2] *M. Upton, et al., "A 160,000 transistor GaAs microprocessor," ISSCC Dig. Tech. Papers, vol. 36, Feb. 1993, pp. 92-93.*

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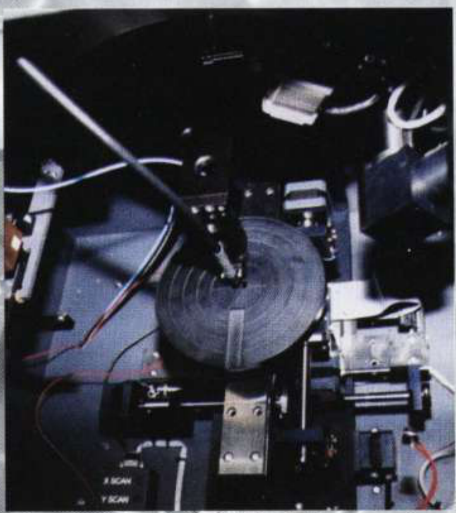

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Research Review

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

A DC-to-100 GHz InP HEMT 1:2 Distributor

Several 10 Gb/s ICs have been developed in recent years for very high speed optical fiber transmission systems, with some initial work beginning on the 40 Gb/s regime. In anticipation of future systems which will require operational capabilities beyond even the 40 Gb/s regime, a 1:2 Distributor utilizing 0.1 μm gate length InAlAs/InGaAs/InP HEMTs and a coplanar-waveguide technology is reported which exhibits a 3-dB bandwidth of 100 GHz with a low frequency gain of -2.5 dB. The transistors utilized in this circuit exhibit a f_t of 160 GHz, and a transconductance of 1.3 S/mm. This bandwidth performance is the widest ever reported for multi-RF-port wide-band IC. Work performed at NTT LSI Laboratories [Kanagawa, Japan]. See "A DC-to-100 GHz InP HEMT 1:2 Distributor IC Using Distributed Amplification," Y. Imai et al, IEEE Microwave and Guided Wave Letters, 6(7), 256, [July 1996

InAlAs/InGaAs MOSFET

The fabrication of metal-oxide-semiconductor FET structures implemented in III-V materials have been hampered due to the poor mechanical and electrical characteristics of the oxides used, whether they are the native oxides of GaAs and InP, or deposited insulators such as Al_2O_3 and SiO_2. In this work, InAlAs layers with thicknesses ranging from 500 to 1500 Å were oxidized at a temperature of 500°C, followed by a subsequent 600°C anneal for 30 s, which produced an oxide which exhibited a dielectric strength of $2x10^6$ V/cm. Utilizing this oxide in a 1000 Å n-type GaInAs channel MOSFET structure (channel Sn doped at $1x10^{17}$ cm^{-3}), a 8 μm gate-length device was fabricated which exhibited a maximum transconductance of 6 mS/mm, and required a -10 V gate bias in order to completely pinch off the channel. Work performed at the University of Texas at Austin [Austin, TX]. See "An InAlAs/InGaAs Metal-Oxide-Semiconductor Field Effect Transistor Using the Native Oxide of InAlAs as a Gate Insulation Layer," P.A. Grudowski et al, Appl. Phys. Lett., 69(3), 388, [15 July 1996].

p-Channel MISFET using Low Temperature GaAs

An alternate approach to the use of oxides as the insulating layer in metal-insulator-semiconductor structures is to use a high resistivity semiconductor layer as the insulator. GaAs grown by MBE at low temperatures (200-300°C) exhibits significantly higher resistivity than GaAs or AlGaAs grown at typical MBE growth temperatures (600 - 700°C), making it a good candidate as the insulator in a MISFET structure. Using a 3000 Å GaAs channel (p-type implanted with Be), and a 300 Å low temperature GaAs insulating layer, a p-channel MISFET was fabricated with a 1.5 μm gate length, which exhibited a transconductance of 22 mS/mm (competitive with the best p-channel devices of comparable gate-length), and a maximum drain current of 120 mA/mm at -8 V of gate bias, along with an f_t, of 2.0 GHz. Work performed at Lincoln Laboratory, Massachusetts Institute of Technology [Lexington, MA]. See "Self-Aligned p-Channel MISFET with a Low-Temperature-Grown GaAs Gate Insulator," C.L. Chen et al, IEEE Electron Device Letters, 17(8), 413, [August 1996].

Ka-Band Dry-Recess Etched GaAs PHEMT

The high energy species present during dry etching can result in degradation of device characteristics, particularly when the etching is taking place in the sensitive region of the device channel, as is the case during gate recess etching. As a consequence of this, gate recess etching is typically a wet etch process, which eliminates the potential for plasma-induced damage, but may result in nonuniform device characteristics across the device as a consequence of nonuniform wet etching. By using a low damage BCl_3/SF_6 plasma in the recess etching of AlGaAs/GaAs PHEMTs under a RF power of 20 W (total recess etch time of less than 1 min), the RF-induced dc bias was kept below -25 V, in order to insure low damage. The resulting 0.2 μm PHEMTs fabricated with this process were used in low noise amplifiers (LNAs) which exhibited an average noise figure of 2.2 dB from 31-36 GHz, with an associated gain of 22.5 dB. These are among the best values ever reported for Ka-band LNAs. Work performed at Rockwell Science Center [Thousand Oaks, CA]. See "High-Performance Ka-Band Monolithic Low-Noise Amplifiers Using 0.2 mm Dry-Recessed GaAs PHEMTs," Y. Kwon et al, IEEE Microwave and Guided Wave Letters, 6(7), 253 [July 1996].

High Transconductance AlGaN/GaN FETs

Wide bandgap III-N materials are ideally suited for high power electronic device applications, due to their large bandgaps (>3 eV). However, heterostructure FET devices fabricated from this material system typically exhibit low transconductances and current densities. Using a 1.0 μm gate-length $Al_{0.15}Ga_{0.85}N$/GaN structure, HFETs were fabricated which exhibited a transconductance of 120 mS/mm and a saturated current density of 0.35 A/cm^2, representing one of the best results for such a nitride-based device. It was determined that the transconductance was limited due to series resistance between the source and drain. Work performed at APA Optics [Blaine, MN], University of Virginia [Charlottesville, VA] and Dongguk University [Seoul, Korea]. See "High Transconductance Heterostructure Field-Effect Transistors Based on AlGaN/GaN," Q. Chen et al, Appl. Phys. Lett., 69(6), 794, [5 August 1996].

Narrow Base HBTs

In order to further improve the speed and power performance of HBTs, it is necessary to scale down device dimensions. A key scaling parameter is the reduction of the base width, which has a strong influence on f_t, bulk recombination, and surface recombination. If base thicknesses can be scaled into the sub-250 Å regime, minority carriers injected into the base may operate in the quasi-ballistic regime, rather than in the diffusive regime, and thereby reduce base transit time, which in turn will increase f_t. In addition, reduction in base widths should reduce both bulk and surface recombination processes, which will reduce noise figures.

Using carbon doped base regions in MOCVD-grown InP/InGaAs HBTs, researchers at the NTT LSI Laboratories [Kanagawa, Japan] have investigated the transport characteristics of HBTs with base widths which vary in thickness from 50 to 1300 Å and are carbon doped to a level of $2.5x10^{19}$ cm^{-3}. These HBTs utilizes a 700 Å InP emitter doped at $3x10^{17}$ cm^{-3}, and a composite collector which consists of 3000 Å of undoped GaInAs and 1000 Å of InP doped at $1x10^{17}$ cm^{-3}. It was determined that the base transit time, t_B, showed a quadratic dependence on base width, W_B, for base thicknesses greater than 150 Å, indicative of diffusive electron transport, while for narrower base thicknesses, a linear dependence was found, indicative of ballistic transport. This relatively small W_B value for the onset of ballistic transport implies that the influence of relaxed electrons on the base transit time behavior is large. It is estimated, that when operating in the ballistic regime, that the average electron velocity in the base is as high as 10^8 cm/s.

In similar work, researchers at the University of California [La Jolla, CA], grew AlGaAs/GaAs HBTs by MOCVD, with base thicknesses as narrow as 200 Å and carbon doping of $4x10^{19}$ cm^{-3}. It was observed in Gummel plots (collector current, I_C, vs. base-emitter voltage, V_{BE}), that I_C at a given V_{BE} was almost identical for devices with base thicknesses of 200 and 500 Å, which is to be expected if the minority carrier transport is ballistic rather than diffusive. Further evidence of ballistic transport is cited by the authors in the observation that the bulk current recombination, J_{Bulk}, shows a linear dependence on base thickness, W_B, in which the J_{Bulk} decreases from 120 A/cm^2 to 60 A/cm^2 for base thicknesses of 500 and 200 Å, respectively. They also observed that the surface recombination current varies as W_B^2. In this work, a current gain >50, for small 1x1 μm^2 HBTs, was obtained at current densities of 1x104 A/cm2 for devices with base widths as small as 210 Å.

See "Evaluation of Base Transit Time in Ultra-Thin Carbon-Doped Base InP/InGaAs Heterojunction Bipolar Transistors," H. Ito et al, Electronics Letters, 32(15), 1413 [18 July 1996] and "Experimental I-V Characteristics of AlGaAs/GaAs Heterojunction Bipolar Transistors with Very Narrow Bases," Y.M. Hsin et al, Electronics Letters, 32(14), 1323 [4 July 1996].

Compound Semiconductor Materials

Oxides for GaAs MOS Applications

One of the great advantages of silicon technology over III-V electronics is silicon's native oxide. Researchers from AT&T Bell Laboratories who are investigating gallium oxides recently reported the fabrication of Ga_2O_3-GaAs structures fabricated in-situ using a multiple-chamber MBE system. The oxide films were deposited on clean atomically ordered (100) GaAs surfaces, at a temperature of ~600°C by electron beam evaporation from a single-crystal $Gd_3Ga_5O_{12}$ source. Oxide deposition took place after substrates with As-stabilized (2 x 4) surfaces were UHV transferred from one MBE chamber to the other. Reflection high energy electron diffraction was used prior to oxide deposition in order to verify that the surface stoichiometry and atomic order are preserved during the UHV transfer process.

Metal-oxide-semiconductor (MOS) structures were fabricated on 1.5 µm thick n-type and p-type GaAs layers grown on Si or Zn doped (100) GaAs substrates. Capacitance-voltage (C-V) characteristics on n- and (p- type) wafers clearly display inversion layers of holes (electrons) for negative (positive) voltages, and the quasi-static capacitance is nearly equal to the insulator capacitance C_{ox} for Ga_2O_3 oxide thicknesses of 462 and 594 Å. A capacitance overshoot at the onset of inversion was consistently observed in both n- and p- type samples, and was tentatively assigned to the filling of traps in the oxide. The interface state density dependence on energy across the energy gap was determined by quasi-static/high-frequency measurements in the depletion mode. The extracted midgap interface state density is in the low 10^{10} cm^{-2} range, and rises toward the band edges. The interface state density D_{it} rise toward the band edges has been attributed to slow oxide traps located at more than 20 Å away from the interface. These oxide traps may be related to Gd incorporation in the Ga_2O_3 film during the e-beam evaporation from the $Gd_3Ga_5O_{12}$ source. Conductance-voltage (G-V) measurements indicate a wide-bottomed D_{it} versus E distribution between $E_V + 0.27$ eV and $E_C - 0.19$ eV.

The availability of in-situ fabricated Ga_2O_3-GaAs interfaces may significantly improve current GaAs-based technologies by providing low surface recombination velocities and thermodynamically stable interfaces. Further improvements in oxide properties will however be required before GaAs MOSFET applications can be realized.

Work done at AT&T Bell Laboratories, Murray Hill, NJ. See "C-V and G-V Characterization of In-Situ Fabricated Ga_2O_3-GaAs Interfaces for Inversion/Accumulation Device and Surface Passivation Applications," M. Passlack et al, Solid State Electronics, 39(8), 1133-1136 [1996].

Progress in the Growth of Nitride Semiconductors: A Review

In light of the rapid development and technological importance of column-III nitrides, readers of this magazine may be interested in a recent review published by Isamu Akasaki, one of the pioneers in the field. In the article, the importance of inserting a thin AlN (or GaN) buffer layer deposited at low-temperatures between the substrate and the GaN epitaxial material grown by MOCVD is illustrated. It is shown that a low-temperature AlN buffer layer drastically improves the material morphology and results in crack-free GaN surfaces and X-ray rocking curves as narrow as 110 arcsec. The use of an AlN buffer layer reduces the background electron concentration by nearly three orders of magnitudes, to ~10^{16} cm^{-3}, and results in room temperature electron mobilities of 600 cm^2/Vs. TEM and SEM measurements suggest that the AlN buffer supplies nucleation centers with the same orientation as the substrate and promotes the lateral growth of the overlying GaN by decreasing the interfacial energy between the film and the sapphire substrate. The article also reviews the growth of column-III nitride alloys such as AlGaN and GaInN, as well as the growth and properties of n- and p-type nitrides. See "Crystal growth of column-III nitride semiconductors and their electrical andoptical properties," I. Akasaki & H. Amano, J. of Crystal Growth 163, 86-92 [1996].

High-Density GaAs/AlAs Quantum Wires on (775)B GaAs Substrates by MBE

The implementation of high-density GaAs/AlAs quantum wires (QWRs) naturally formed in a AlAs/GaAs/AlAs quantum well grown on a (775)B-oriented GaAs substrate has recently been reported. The growth of a GaAs (5 nm) /AlAs (5 nm) superlattice on the (775)B surface results in a regular corrugation with extremely straight step edges along the [$1\bar{1}0$] direction. The corrugation lateral period is 12 nm and its vertical amplitude is equal to 1.2 nm. TEM measurements reveal that the AlAs layers are planar, while the corrugation develops during the GaAs layer growth. QWRs can therefore be formed by self-organization during the growth of AlAs/GaAs/AlAs quantum wells on (775)B substrates if the well width is sufficiently narrow.

GaAs/AlAs quantum wells with well widths of 10.5, 6.3, 4.3, and 3.3 nm were grown on (775)B-oriented substrates. The FWHM of the 4.2K PL peak for the 3.3 nm well was as narrow as 15 meV, indicating that the QWRs are very uniform. With decreasing well width, the 4.2K photoluminescence polarization anisotropy increased, indicating that the one-dimensional confinement of carriers becomes stronger as the well width is decreased. The degree of polarization reached 11% for the 3.3 nm quantum well. The fairly weak degree of polarization probably indicates that the well was still too thick for sufficient QWR confinement -however, in the GaAs/AlAs system, a lower bound of 3 nm exists in order to keep the confined carriers below the X band edge of the AlAs barrier. This rather low anisotropy could likely be improved by using thinner GaAs wells in conjunction with Ga incorporation in the barrier to eliminate the X-valley cross-over in the barrier.

Work done at Osaka and Kwansei-Gakuin Universities, Nissin Electric Co. Ltd., and Kubota Corporation. See "High-Density GaAs/AlAs Quantum Wires Grown on (775)B-Oriented GaAs Substrates by Molecular Beam Epitaxy," M. Higashiwaki et al., Jpn. J. of Appl. Phys, 35(2), L606-L608 [May, 1996].

Modification of the Kink in InP Based HEMTs by a Body Contact

The anomalous increase in output conductance (the so-called "kink" effect) at low drain biases is an especially noticeable problem in field-effect transistors with narrow energy gap channels such as InP-based InAlAs/InGaAs HEMTs. In general, the kink in III-V FETs appears to be correlated to epitaxial buffer layer quality; various reports have also assigned the appearance of the kink in HEMTs to impact ionization, deep level traps in the epitaxial structure, as well as to charge injection in the buffer layers.

A recent report analyzes the effect of a p+ body contact formed by Zn diffusion. With a zero body contact bias, a kink appears in the drain characteristics near V_{DS} ~ 0.7 V. It was found that the kink becomes stronger when a negative voltage is applied to the body contact (with respect to the grounded source electrode). With a positive body contact voltage, the kink is weakened because the low V_{DS} drain current is enhanced with respect to the unbiased current level. At high V_{DS}, the drain characteristics become insensitive to the body contact bias. By measuring devices with different threshold voltages V_{TH}, it was also found that devices with less negative threshold voltages benefit the most from the application of a positive body contact bias. Work done at the NTT LSI Laboratories, Japan. See "Kink Modification using body contact bias in InP Based InAlAs/InGaAs HEMTs," T. Suemitsu et al, Electronics Letters, 32(12), 1143-1144 [6 June 1996].

Low-Resistance Ni/Ti/Pt/Ti/Pt Ohmic Contacts to p-GaAs

The formation of low-resistance Ohmic contacts to p-GaAs is required in the fabrication of high-speed semiconductor devices. In particular, the realization of high-quality Ohmic contacts to the p-base of Npn GaAs heterojunction bipolar transistors (HBTs) is crucial in order to obtain low logic propagation delays and high maximum oscillation frequencies. To that end, Pt/Ti/Pt/Au Ohmics have recently been introduced but their optimal annealing temperature of 350°C is not compatible with the higher (370-450°C) temperatures used in the formation of AuGe/Ni contacts to n-GaAs.

Researchers from Matsushita Electronics Corporation have recently developed Ni/Ti/Pt/Ti/Pt Ohmic contacts to p-GaAs that result in a low contact resistivity of 2 x 10^{-7} Ωcm^{-2} for contacts formed to a beryllium-doped (2 x 10^{19} cm^{-3}) GaAs layer by means of a ten minute annealing cycle at 400°C in a flowing argon atmosphere. The contacts were defined by electron beam evaporation and lift-off process. The reliability of the Ni/Ti/Pt/Ti/Pt Ohmic contacts was assessed by storing samples in a furnace at a fixed temperature. The mean time to failure (MTTF) displayed an activation energies of that nearly coincide with the reported activation energy of 1.6 eV for the reaction of Pt on GaAs, hinting that the failure mode of the contacts occurs through the reaction of Pt with GaAs. The extrapolated MTTF at 150°C was determined to be equal to 4,000,000 hours. The availability of high-performance Ohmics to p-GaAs with and optimal annealing temperature of 400°C (the same as that for AuGe/Ni collector contacts) should simplify the fabrication of high-speed self-aligned GaAs HBTs.

Work done at the Matsushita Electronics Corp, Osaka, Japan. See "Ni/Ti/Pt Ohmic Contacts to p-GaAs for the Heterojunction Bipolar Process," M. Yanagihara et al, Electronics Letters, 32(13), 1238-1239 [20 June 1996].

Optoelectronic Devices

Quantum Dot Lasers

For over a decade there has been a modest activity in the MBE community in self-assembled growth of quantum dots. Very recently several laboratories have reported lasing in such structures. Self assembled quantum dots are constructed by growing strained, usually indium-rich material. Most common is GaInAs on GaAs, but InAs on GaAs and InP on GaInP have also been reported. If the appropriate growth temperature is selected, the strained material coalesces into islands, rather than growing in the usual layer-by-layer mode. These self assembled islands have dimensions on the order of a few tens of nanometers and are remarkably uniform in size. Layers of quantum dots can be substituted for the normally used quantum wells in conventional edge emitting laser structures. The interest in quantum dot lasers is based on several theoretically predicted advantages. Ideal quantum dot lasers are expected to exhibit lower thresholds, higher differential gains, higher modulation speeds and less temperature sensitivity (high T_0). Real quantum dots, however, may not achieve these advantages if size fluctuation is too large.

The first report of lasing in self assembled quantum dots used InAs dots grown on GaAs cladded by AlGaAs. The device exhibited a lasing wavelength of 1.25 μm at a temperature of 77K. When a single layer of quantum dots was used as the gain medium, gain saturation was observed at cavity lengths shorter than 750 microns. Lasers using six layers of quantum dots did not exhibit gain saturation down to the shortest cavity length tested, 260 microns. Lasing on the ground state transition was confirmed in the six layer structure. A second report used $Ga_{0.4}In_{0.6}As$ quantum dots on GaAs with AlGaAs clads. Room temperature lasing was reported at a wavelength of 1.028 μm with a threshold current density of 650 A/cm^2 in a 1 mm long cavity. The ground state transition was observed in photoluminescence and sub-threshold electroluminescence, but the lasing transition involved ground state electrons and heavy holes in the first excited state. The radiative decay times of the ground state and lasing transitions were measured at 2.5 ns and 200 ps, respectively. These results imply that the oscillator strength of the excited state lasing transition is comparable to, or greater than, that of the lasing transition. A third work used InP quantum dots grown on GaInP with AlInP clads. This device was optically pumped at room temperature. Lasing occurred at a wavelength of 704 nm in the TE polarization. See "Prevention of gain saturation by multi-layer quantum dot lasers", O. G. Schmidt et al, Electron. Lett. 32(14), 1302 [4 July 1996]; "Room temperature operation of inGaAs/GaAs self-organised quantum dot lasers", K. Kamath et al, Electron. Lett. 32(15), 1374 [18 July 1996]; and "Optical gain and lasing in self-assembled InP/GaInP quantum dots", A. Moritz, et al, Appl. Phys. Lett. 69(2), 212 [8 July 1996].

Long Wavelength Vertical Cavity Lasers

Vertical cavity surface emitting lasers (VCSEL's) have been very successful in the GaAs-based materials system, which produces lasers in the wavelength range of 0.7 - 1.1 μm. VCSEL's at 1.3 or 1.55 μm wavelengths would be desirable for optical fiber applications, but have run up against a materials limitation that affects the ability to construct high reflectivity laser mirrors. The GaAs-based materials system has two compatible materials, GaAs and AlAs, with a large refractive index difference, which enables a quarter wave stack to exhibit high reflectivity with only 20 or so periods. The traditional, InP-based materials for 1.3 and 1.55 μm lasers do not possess such a large refractive index contrast, which necessitates an exorbitant number of periods in the mirror stack to obtain high reflectivity. Two different solutions to this problem the mirrors of long wavelength VCSEL's were recently reported. In the first approach, an InP-based active layer was wafer fused between two mirror stacks constructed of GaAs-based materials. An AlAs layer near the bottom of the upper mirror was laterally oxidized for current confinement. Laser diameters down to 3 μm were investigated. Lasing wavelengths ranged between 1.545 and 1.570 μm. Room temperature lasing thresholds were as low as 1.3 mA for cw operation. Lasers operated up to 39°C in cw operation and 70°C under pulsed conditions.

The second approach was grown in a single run using all InP-based materials. The GaInAsP active layer was conventional. The mirrors consisted of stacks of InP layers (three quarters wavelength thick) and quarter wave thick air gaps. Because of the high refractive index contrast between air and InP, only three periods were needed in each mirror. The mirror was formed by growth of a GaInAs/InP stack, followed by selective etching of the GaInAs to create the air gaps. The device was optically pumped, producing a room temperature lasing wavelength of 1.26 μm.

Work performed at UCSB [Santa Barabara, CA USA] and Hewlett-Packard Labs [Palo Alto, CA USA]. See "Laterally oxidized long wavelength cw vertical-cavity lasers", N. M. Margalit, et al, Appl. Phys. Lett. 69(4), 471 [22 July 1996]; and "1.26 micron vertical cavity laser with two InP/air-gap reflectors", K. Streubei, et al, Electron. Lett. 32(15), 1369 [18 July 1996].

Use of GaInAs Substrate for the Growth of Lasers

In the III-V material system, the choice of substrates has traditionally been limited to the six non-aluminum-containing binary compounds, such as GaAs and InP. These six available substrate lattice constants limit the choices of epitaxial materials for device structures through the constraints of lattice-matching (for thick layers) and pseudomorphic critical thicknesses (for thinner layers). In a recent work, a new substrate lattice constraint was created through the use of a ternary substrate material, $Ga_{0.79}In_{0.21}As$. A double quantum well laser was grown on this novel substrate by MOCVD. The clads and core of the structure were lattice matched to the substrate, and consisted of GaInP and AlGaInAs, respectively. The quantum well material, $Ga_{0.62}In_{0.38}As$, was compressively strained. The device lased at a wavelength of 1.22 μm with a threshold current density of 355 A/cm2 at a cavity length of 900 microns. This approach may be able to be extended to include the important wavelength of 1.3 μm. Work performed at Fujitsu Laboratories [Atsugi, Japan]. See "InGaAs/InAlGaAs/InGaP Strain Double Quantum Well Lasers on InGaAs Ternary Substrate", H. Shoji, et al, Jpn. J. Appl. Phys. 35(6B), L778 [15 June 1996].

InSb and InAs Hall Elements from Asahi Chemical

The company that claims >70% of the world market for Hall sensors shows us their next generation of products

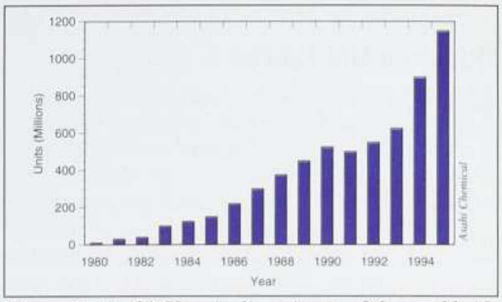


Figure 1: Asahi Chemical's estimate of the worldwide market for Hall elements as magnetic sensors.

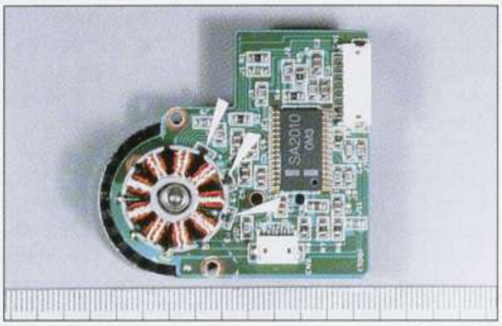


Figure 2: Photograph of a typical CD-ROM drive Hall motor showing three Hall elements (white arrows).

The current status of the market for Hall elements, as portrayed by Asahi Chemical Industry Co. [Fuji-city, Shizuoka, Japan] could be classified as a "good news - bad news - good news" story. The first piece of good news is that the market for Hall elements, in terms of units required, is huge, approaching 1200 million units in 1995 (see Figure One). Furthermore, demand is likely to continue to grow, due to ever-increasing sales of audio, video and computer electronics. These types of equipment need high performance, finely controlled DC motors to perform functions like driving and taking up the tape in a VCR, spinning a CD in an audio player, and accessing the drives in a personal computer. Figure Two shows the location of 3 such motors in a CD-ROM drive. It is now commonplace for these motors to be controlled by magnetic sensors instead of brushes, and the Hall element is the perfect sensor for the job.

The bad news, at least as far as most readers of this magazine are concerned, is that the very large majority of this market is served by a relatively "low tech" utilization of the classic Hall element material, InSb. Asahi Chemical, which entered the market in 1980, currently supplies around 70% of the world's requirements for Hall sensors by depositing a 0.8 μm thick layer of polycrystaline InSb on mica, then peeling off the InSb layer and transferring it to a ferrite substrate. See Figure Three. Electron mobilities in such a device are 20,000 - 30,000 cm^2 /Vsec, and the device produces output voltages of 150 - 270 mV. See Table 1. While the development of this these Hall elements is obviously a significant business achievement for Asahi - last year they sold 800 million such devices - persons with an interest in science and technology would likely prefer to see more reliance on state-of-the art compound semiconductor engineering.

The good news is that the next generations of Hall elements from Asahi are moving in exactly that direction, using different materials (InAs active layers, grown on GaAs substrates), different deposition methods (multiwafer MBE growth) and different device structures (quantum wells) to produce Hall elements which offer improved characteristics over current production models.

The Next Generation

Ichiro Shibasaki and his colleagues at the Asahi Chemical Corporate R&D Facility are responsible for finding ways to make the next generation of Hall elements. Like the very successful InSb models, the new products will need to offer small packages, low costs, and

Properties of InSb, InAs thin film, and InAs QW structures.

Material	Doping	Electron Mobility (cm^2/Vsec)	Electron Density (x 10^{16} cm^{-3})	Thickness (μm)
InSb	none	20,000 ~ 30,000	2	0.8
InAs	Si	11,000	8	0.5
InAs QW	none	20,000 ~ 28,000	50	0.015

Properties of InSb, InAs thin film, and InAs QW Hall elements

Material	Driving Voltage	Hall output voltage (mV) (B= 0.05T)	Offset Voltage (mV) (B=0T)	Resistance (Ω)
InSb	1	150 ~ 270	< + 7	240 ~ 550
InAs	6	100	< + 16	400
InAs QW	6	250 ~ 300	< + 16	700

Table 1. Selected properties of three different structures and Hall elements fabricated from them.

compatibility with high volume production. The primary improvements that are sought are in the area of operating temperature range, because the one significant weakness of the established InSb product line is the large temperature dependence of the input resistance (see Figure 4), caused by the narrow bandgap of InSb. This has the practical effect of restricting their use to near-room temperature conditions. A possible alternative is to use GaAs, which has a larger bandgap (1.43 eV, compared to 0.17 eV for InSb). However, the R&D team at Asahi concluded that the GaAs Hall elements did not offer sufficient sensitivity to magnetic fields, due to GaAs's lower electron mobility compared to InSb, and that they could not be used where high signal-to-noise ratios are required.

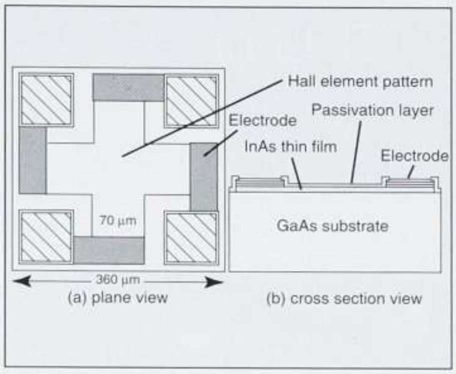
In the late 1980's, work began on another alternative: Si-doped InAs layers. The structures, with a typical thickness of 0.5 μm, are grown on 2" semi-insulating GaAs wafers, using one of the industry's first multiwafer (12 x 2") MBE systems. The variation in thickness uniformity among the wafers on the platen is + 3%, which is more than sufficient for this work. At 300 K and a doping level of 8 x 10^{16} cm^{-3}, electron mobilities of 11,000 cm^2/Vs are obtained. A device fabricated from these layers in described in Figure 5. The electrode structure allows highly reliable Au wire bonding using high volume equipment. Standard epoxy resin processes are used for packaging. Electron mobilities are ~11,000 cm^2 /Vsec, and typical output voltage is 100 mV. See Table 1. Although the sensitivity of these devices is reduced in comparison to the InSb models, they do offer much greater temperature independence - see Figure 6. This has helped them find a market niche, and, to date, Asahi has sold more than 5 million of these devices for use in brushless motors and as current sensors.

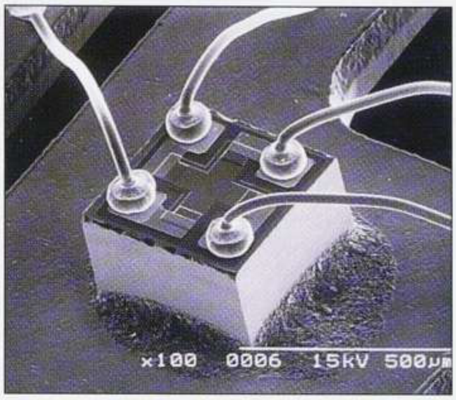
The State-of-the-Art

The challenge which is currently being addressed at Asahi is the development of low cost product that offers both the wide temperature range of the InAs Hall elements and the high output voltage of the InSb devices.

Higher sensitivity, and even lower temperature dependence, could be expected if it were possible to fabricate high quality ultra-thin films of InAs (<0.1 μm). However, it is virtually impossible to do this, because of the lattice mismatch (7.0%) between InAs and GaAs. As an alternative, researchers at Asahi have turned to quantum well (QW) structures, using InAs sandwiched between insulating barrier layers which are lattice-matched to InAs. The InAs/AlGaAsSb material system was chosen because of the large conduction band offset of ~1.3 eV - see Figure 7. The structure of a device using such a QW is shown in Figure 8. Experimental results show that the quality of the InAs layer is very high, yielding electron mobilties of ~20,000 cm^2/Vs. Higher mobilities have been reported for InAs QW structures which use AlSb barriers and buffer layers, but this approach was considered to unsuitable for high volume manufacturing due to the potential for oxidation of the Al-containing layers.

The typical characteristics of the InAs QW Hall elements have been found to be exceptional. As shown in Table 1, electron mobilities comparable to InSb have been obtained, but even higher Hall output voltages are achieved. According to Shibasaki, the Hall output voltage for constant drive voltage is as large as 600 mV @ V_{in} = 6 V and B=1kG, which is 2 to 2.5 times larger than that of the Si-doped InAs devices, and 4 or 5 times larger than that of conventional GaAs Hall elements. Under normalized conditions (the same Hall





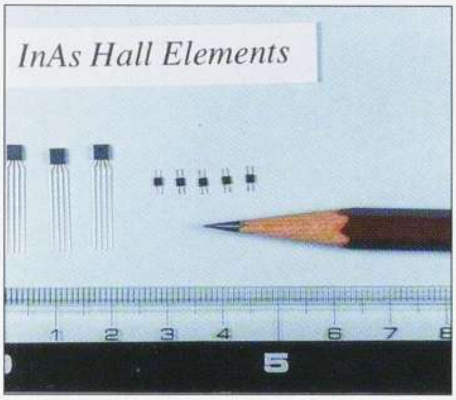


Figure 5: Top: structure of the InAs thin-film Hall element chip; Middle: photograph of an unpackaged chip (actual size = 0.36 x 0.36 mm²); Bottom: photograph of the finished product.

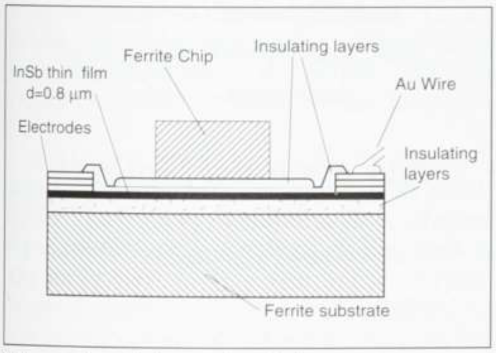


Figure 3: Schematic of the most common type of Hall element, formed by depositing polycrystaline InSb on mica, and then lifting off the InSb layer and transferring it to a ferrite substrate.

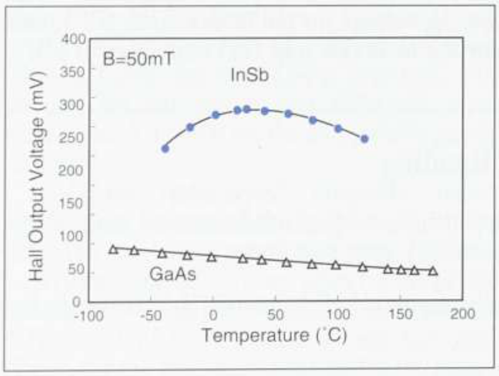


Figure 4: Temperature dependence of Hall output voltage for InSb and GaAs Hall elements. The driving voltage for the InSb models is 1 V, and for the GaAs models it is 6 V.

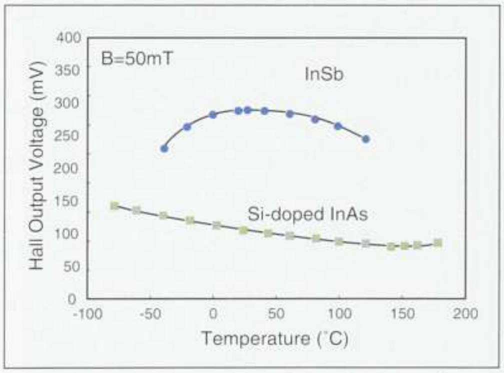


Figure 6: Temperature dependence of Hall output voltage for InSb and InAs thin-film Hall elements. The driving voltage for the InSb models is 1 V, and for the InAs models it is 6 V.

output voltage and the same magnetic field), the power dissipation of the InAs QW elements is 1/5 to 1/10 that of commercial GaAs Hall elements - an attractive feature for use in battery operated devices.

As shown in Figure 9, Hall output voltage at constant driving voltage decreases monotonically as temperature increases, corresponding to the monotonic decrease in electron mobility. The temperature coefficient of Hall output voltage for voltage driven InAs QW Hall elements is 0.1%/deg., which is the lowest figure for all reported Hall elements. Regarding sensitivity, the InSb devices characterized in Figure 9 may appear superior; however, Hall output voltage is proportional to the driving voltage and the maximum driving voltage for InSb Hall elements is limited up to 2 V due to burnout, and the breakdown voltage at room temperature is 4 or 5 V due to the negative temperature coefficient of resistance. On the other hand, a driving voltage of more than 12 V is possible for InAs QW Hall elements because of its positive temperature coefficient of input resistance. Therefore, InAs QW Hall elements are more than equivalent to InSb hall elements in their effective sensitivity.

The InAs QW structures are also suitable for mass production. They can be grown in the same MBE system which is used to produce the Si-doped InAs structures, and the growth time required is only one hour. Shibasaki and his colleagues believe that the InAs QW structures are the ultimate solution for industrial sensors, automotive sensors, and other new applications for the future. And, given the characteristics of the device, including its very high output voltage, low power dissipation, and small temperature dependence, the evidence suggest that they may be right.

***Editor's Note**: Ichiro Shibasaki was awarded the 1996 Commendation as "the person of scientific and technological merits" for the development of high sensitivity thin film Hall elements by the Japanese Ministry of State for Science and Technology.*

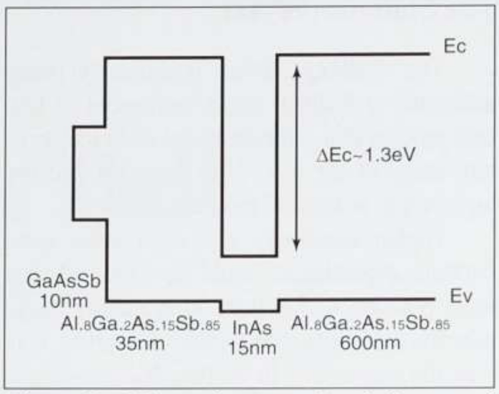


Figure 7: Schematic energy band diagram of an InAs quantum well with AlGaAsSb barriers.

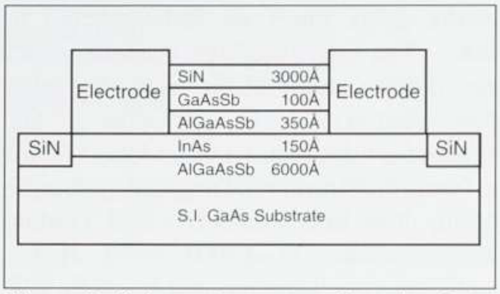


Figure 8: Schematic cross-section of an InAs QW Hall element.

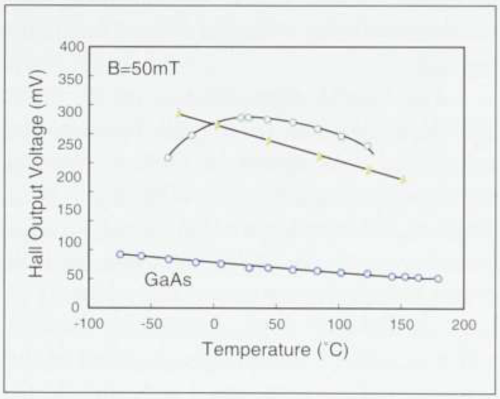


Figure 9: Temperature dependence of Hall output voltage for InSb and InAs QW Hall elements, with a commercially available GaAs Hall element shown for comparision. The driving voltage for the InSb models is 1 V, and for the InAs QW and GaAs models it is 6 V.

Additional Reading

"High sensitivity Hall elements made from Si-doped InAs on GaAs substrates by molecular beam epitaxy", T. Iwabuchi et al., J. Crystal Growth 150, 1302 [1995].

"InAs deep quantum well structures and their application to Hall elements", N. Kuze et al., J. Crystal Growth 150, 1307 [1995].

"AlGaAsSb buffer/barrier on GaAs substrate for InAs channel devices with high electron mobilitiy and practical reliability", S. Miya et al., J. Electron. Matls. 25(3), 415 [1996].

Invitation to Contribute

The mission statement for our magazine is "to provide a focal point for the global compound semiconductor industry". To help achieve that goal we encourage our readers to share their unique viewpoints or specialized knowledge about compound semiconductor science and technology by analyzing or explaining recent developments.

We are soliciting contributions from qualified individuals who wish to make a contribution to the general understanding of compound semiconductors and the industry which is based upon them. Almost any compound semiconductor-related topic is acceptable, provided that it is not too narrowly focused. Our primary selection criteria are the article's level of interest and/or usefulness to our readers.

If you are interested in contributing an article, please contact the editor for guidelines.

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In Our Next Issue

Solar Cells

What's behind the recent boom in demand for solar cells? And what is the current state of the technology? The cover story for our November/December issue examines this interesting niche of the compound semiconductor industry.

Also in our next issue:

A recap of a very interesting year in semiconductor laser technology

Bulk crystal growth in microgravity

Status report on ZnSe

Plus our usual features:

Nitride News

News from Japan

Portfolio

Research Review

Compound Semiconductor - your best source for news and information about the international compound semiconductor industry.

One Step Forward, Two Steps Back

Two companies are trading at historic highs - and a few others are moving in the opposite direction.

The biggest story over the past two months, as far as the Compound Semiconductor Portfolio is concerned, was semiconductor laser manufacturer **SDL**, which suffered a precipitous decline in share price due to **reports of manufacturing problems which are reducing production yields**. SDL led the loss-making stocks in the Portfolio, down more than 30% since our last report.

In mid-July SDL announced excellent revenue and income results for the 2nd quarter of 1996 (ended June 30). Revenues of $21.6 million and net income of $2.4 million were reported for the period, up over 70% from one year ago. But SDL was already trading at a very high multiple, and the news came at a time when the markets were in turmoil over other topics, and therefore there was no perceptible impact on share price.

In mid-August the company made an announcement that the market did notice. SDL CEO Donald Scifres warned that third quarter revenue would be flat or down due to manufacturing problems that were reducing yields and forcing the company to turn away some orders due to inability to guarantee delivery dates. The news sent SDL's share price tumbling by as much as 14 points - more than half its value. As this issue went to press the stock was still trading at less than 20, a substantial discount from its 52-week high of 32 3/8. While not down-playing the seriousness of their manufacturing woes, Scifres characterized the market's response as an "over-reaction".

The next largest loss-maker for the period was **Cree Research**, which was down nearly 35%. The company **continues to be plagued by manufacturing problems, dating back to the early part of this year**. The company reported record revenues of $5.1 million for the quarter ended June 30, but posted a net loss of $776,000 for the period. The explanation, as provided in the company's earnings announcement, is that the per unit cost for Cree's LEDs was higher than expected due to production problems in the epitaxial process resulting in a lower number of LED wafers being produced. Neal Hunter, Cree's President and CEO, commented that:

> *"1996 has been a critical transition year for Cree as we move from a research and development company to one that is increasingly driven by product revenue as we devote resources to refining our manufacturing process. We are allocating substantial resources to improve our epitaxial process and achieve a reliable and consistent production process for the super-bright blue LED. The Company's ability to ship slightly over 3 million LEDs in the [quarter ended June 30], which was an increase from the 1.5 million shipped in the [previous] quarter, is a step in the right direction."*

Cree has indicated that it may announce a stock buy-back program to boost share prices, which are currently down more than 60% from their 52-week high.

The Neutrals

Three stocks - Alpha, ATMI and TriQuint were down slightly or relatively neutral compared to our last report.

ATMI reported **significantly higher revenues** for the quarter ended June 30, up more than 70% to $12.3 million. Of that figure, $10.6 million were derived from product sales, almost double the results of a year ago. Net income for the quarter was $640,000, compared with $166,000 for the comparable period last year.

Alpha Industries' quarterly report showed the **impact of the company's earlier decision to leave some non-core business activities**. Specifically, net sales for the period totaled $20.1 million, compared with sales of $22.4 million for the same period last year. The company reported a net loss for the period of $3.4 million, compared with a net income of $1.1 million for the year ago period. Earnings were strongly impacted by Alpha's cancellation of "non-strategic technology contracts" worth $2.5 million, as well as the recognition of around $775,000 in severance costs for departing executives. Among those leaving the company was M.J. Reid, who had been the President and CEO since 1992. New orders were also down, totaling $15.3 million compared to $26.3 million for the same period last year. Commenting on the first quarter results, Thomas C. Leonard, Alpha's new President and CEO, said that the loss for the quarter was somewhat larger than expected, mostly due to the severance costs. He believes that Alpha's results reflect an "overall softness in the North American cellular market", and that they are also attributable to the delayed roll-out of the Personal Communications System (PCS). Leonard also added:

> *"Our costs remained high during the quarter, because we added and retained manufacturing capacity to meet the anticipated demand. We are paying particularly close attention to Trans-Tech, our Maryland ceramics subsidiary, which in addition to having excess capacity, needs improvement in all aspects of operations. We continue to project a break-even second quarter, and we expect continued performance improvements for the balance of the year, driven by the acceptance of our new product offerings and resumed growth in the wireless market."*

As grounds for optimism. Leonard points to recent volume production orders for power amplifiers for AMPS and DAMPS handsets, accessory and diversity switches in GSM handsets, control products in a Japanese Personal Digital Communication (PDC) handset, and control products for various new cellular programs worldwide. These orders are reportedly primarily from two of Alpha's largest customers, Motorola and Ericsson.

TriQuint reported **record revenues and profits and improved gross margins** for the quarter ended June 30. Revenue was $15.1 million, a 36% improvement over the comparable 1995 quarter and a 15% over the previous highest quarterly revenue figure. Gross margins improved to 45% from 40% for the last quarter, and net income was $1.9 million, compared to $1.0 million for the year-ago period.

TriQuint's President and CEO Steven J. Sharp reports that the quarter was also a record-setter for new contracts, as a new high of 32 major design wins were recorded - 28 in wireless, 4 in telecom, and 1 in computing. TriQuint defines a design win as "major" if it is expected to generate revenues of over $100,000 per year when it reaches productions.

In the face of all this good news, why didn't the price of TriQuint's stock move higher? For starters, there is the fact that evidence of rational behavior, always a bit scarce, has been in short supply in the markets this summer. Also, the company is already trading at a very high multiple, making it harder to budge it further up the scale. Analyst's expectations are also playing a role - at least one major financial house, Piper Jaffray, was expecting even better results than those that were announced, which may be contributing to the stock's relative softness. However, Piper is maintaining a "strong buy" rating.

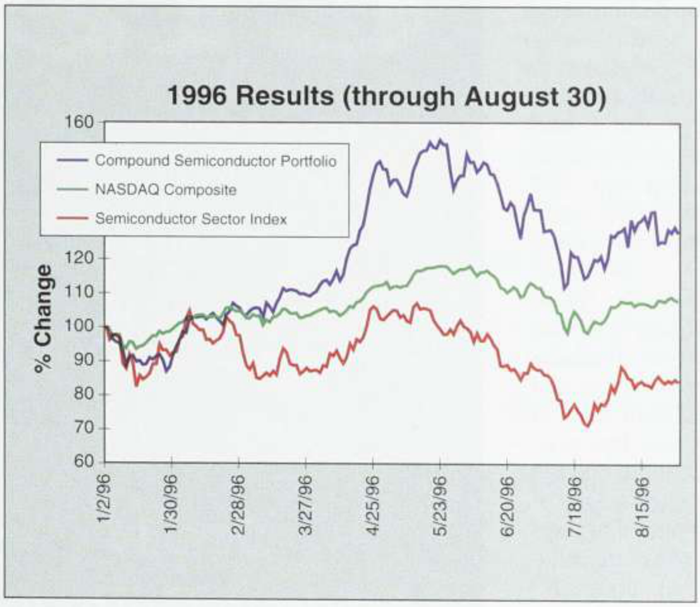
The Stars

The only bright spots in the Portfolio's performance over the past two months were Anadigics and Vitesse. **Anadigics** was **up 12% since our last report, and is currently trading at or near its historic high**. Share prices were bolstered by a report of record sales for the quarter ended June 30, totaling $15.9 million, compared to $12.5 million for the year-ago period. Net income rose 45% to $2.1 million, compared to $1.4 million for the comparable 1995 quarter. Ronald Rosenzweig, President and CEO of Anadigics, commented, "we are pleased with the revenue growth we achieved this quarter in comparison to both the year-ago quarter and the first quarter of 1996, with all four of our major market areas, CATV, DBS, Fiber Optics and Wireless Communications, contributing to the increase. We have said that 1996 would be a year of expansion of our presence in the cellular and PCS markets, with a major focus on the established and emerging digital standards. We made some significant advances in this regard in the second quarter, both through the addition of new customers and the introduction of new products for these standards."

Among the milestones recently passed was the achievement of a delivery rate of 100,000 GSM power amplifier ICs per month. The company also began production of its first 4.8 volt GSM power amp for a "major" cellular telephone manufacturer.

The only downside to Anadigics' report was a slight decrease in gross margin, which was 48% compared to 49.6% in the previous quarter. This result was attributed to the higher costs of new products, and "somewhat lower selling prices, offset by manufacturing efficiencies associated with higher volumes". The company is warning that gross margins will be further impacted in the next quarter, as production volumes increase for new products which are not yet up to desired yields. But Rosenzweig predicts that the margin will improve by the end of 1996, as the production yields bugs are worked out and the company completes the conversion of its current fab from 3" to 4" wafers.

The highest flier this summer has been **Vitesse**, which **reported record revenues and profits for the quarter**. Revenues were $17.3 million, a 57% increase over the $11.0 million reported in the year-ago period, and net income was $3.8 million, compared to $762,000 for the same quarter in 1995. These results helped to push up Vitesse share prices more than 25% since our last report. At the end of August the company was trading at 31 3/4, which is near Vitesse's historical high of 34 3/8.



The Compound Semiconductor Portfolio

Company	Symbol**	Closing Price 1/2/96	Closing Price 8/30/96	Change	52 Week Hi	52 Week Lo	P/E Ratio*
Alpha Industries	AHA	13 5/8	8	-41%	19 5/8	6 7/8	◆
Anadigics	ANAD	21 1/4	32	+51%	33 1/2	14 7/8	30
Advanced Technology Materials	ATMI	10 3/8	12 7/8	+24%	16	9 1/4	68
Cree Research	CREE	14 3/4	10 1/4	-31%	29 1/2	8 1/4	●
SDL***	SDLI	16 15/16	19 1/4	+14%	32 3/8	13 1/8	◆
TriQuint Semiconductor	TQNT	14 1/4	20 1/8	+41%	25 5/8	9	35
Vitesse Semiconductor	VTSS	13 1/8	31 3/4	+142%	34 1/8	9 3/4	65
*Portfolio Value****, 8/30/96*				*$14,387*			
Change since 1/2/96				*+28%*			

Notes:
* P/E Ratio is determined by dividing the closing price by the company's per-share earnings for the most recent four quarters.
** AHA traded on AMEX; all others on NASDAQ
***Split three-for-two on June 12. Historical prices adjusted retroactively.
****Portfolio valuation began on 1/2/96 with 100 shares of each company, but now includes 50 additional shares of SDL, following their split.

◆ - Loss in the most recent four quarters
● - P/E ratio exceeds 100

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These are exceptional opportunities for qualified professionals to make a difference on a grand scale at ANADIGICS. We are a global leader in the design and manufacture of high frequency GaAs ICs for consumer electronics, satellite systems, cellular telephones and local area networks. Located in scenic and suburban Warren, NJ, our school district is excellent, and we are close to the culture and excitement of New York City.

Applications Engineer

Must have thorough knowledge of RF test equipment/ measurements for device characterization. BSEE and at least 5 years of RF/Microwave design experience at component level required. *JOB #96-63/EET*

Sales Engineer

Develops forecasts and product requirements; defines winning designs for GaAs MMICs in terminal and base station applications for Cellular and PCS designs requiring RF/Microwave analog circuits. BSEE and at least 3 years of experience in sale of MW and RFIC products required. Must have knowledge of Cellular/PCS design requirements, strong technical background/design experience with RF Microwave MMICs. GaAs MMICs sales experience a plus. 40% travel required. *JOB #96-81/EET*

Senior Device Engineer

Responsible for GaAs MESFET device design and characterization with focus on circuit/device interaction and GaAs Hetero structure device. BS/MS/Ph.D. with experience in GaAs desirable. *JOB #96-99/EET*

Device Engineers

Responsible for GaAs MESFET device design and characterization with focus on circuit device interaction. BS/MS/Ph.D. with experience in GaAs desirable. *JOB #95-72/EET*

Design Manager/Fiber Optic Product Development

Leads a small team in the design, development and production of GaAs integrated circuits tailored closely to customer requirements. Must have 5-7 years of experience in the design of silicon or GaAs analog and digital ICs, 1-2 years leading a team of engineers and technicians and experience with: silicon or GaAs-based clock recovery ICs; transimpedance amplifiers; limiting amplifiers, comparators, multiplexers and demultiplexers. Should have familiarity with IC simulation, layout, processing and testing for manufacturability of volume products. *JOB # TL-74/EET*

Package Design Engineer

Handles design and development of plastic surface mount. IC packages. Must have background in thermal characterization, analytical skills and qualification of materials. Will need at least 2 years of industry experience in electronic packaging or equivalent. BS, MS in Mechanical Engineering or Materials Science preferred, or equivalent industry experience. *JOB #PG-67/EET*

CMOS Design Manager

To launch our development effort, you must have at least 10 years in designing analog/mixed signal CMOS ICs, including OP AMPS, A/D D/A converters and CODECS ISDN line interface circuits. 5 years of experience in leading a group of circuit designers is also required. MSEE or equivalent necessary. Strong interpersonal skills essential. *JOB #96-51/EET*

Senior Assembly Packaging Engineer

Responsible for new process development, continuing process improvement/cost reduction; troubleshooting; defining production control monitor systems; performing audit to process specification; writing process specifications; setting up new equipment and assisting in transfer of new products from Engineering to Production. Must have electronic packaging experience: die attach, wire bonding, encapsulation, plastic molding, cleaning, epoxy adhesive and assembly, marking systems and molding compounds. *JOB #96-17/EET*

ANADIGICS

Product Engineers

Monitors yield, analyses, summarizes and provides corrective action for electrical or visual failures. Design experiments, Fab through life test, to improve process for higher yield products; determines lot/wafer dispositioning; verifies quality of wafers: approves test software/fixture changes and approves final test and calibration. BSEE required. Must have at least 5 years of experience in semiconductor industry with product engineering experience or similar technical background. Will also need basic knowledge of semiconductor fabrication, testing and packaging. *JOB #95-195/EET*

Reliability Engineer

Develops life test strategies and performs life test studies; analyzes life test data and project reliability performance, interacts with designer and product engineers in developing and planning reliability programs, as well as with the FA laboratory in the analysis of test failures. Also conducts studies to determine thermal characteristics of various designs and packages. BSEE or Physics degree and at least 3 years of applicable experience required. Must have familiarity with microwave circuitry design and troubleshooting. Computer literacy essential. *JOB #96-65/EET*

IC FAB Equipment Engineer

Will need hands-on capability with all types of IC equipment for installation, process definition and sustaining production support. Must have background with ASM steppers, MRC sputter, Eaton Implanters, Matterson PECVD reactors, AG4100 RTA and generally used IC production equipment. BS/MS/Ph.D. and 5+ years of experience required. GaAs experience desirable. *JOB #WF 11/EET*

PROCESS ENGINEERS

• GaAs IC Process Engineer

Characterize GaAs wafer properties, IC device characteristics and processing for GaAs MMICs in expanding manufacturing facility. BS/MS Ph.D. in Physics or related engineering required, as is 5+ years of experience. GaAs background a plus. *JOB #WF 11/EET*

• IC Photo/Etch Engineer

Responsible for 0.5 CD steppers, dry etch and supporting process engineering. BS/MS and 5 years of experience required. GaAs experience a plus. *JOB #WF 11/EET*

• IC Metallization/Thin Film Engineer

Requires sustaining process engineer with IC metallization experience, as well as Sputter, E-beam, PECVD. BS/MS/Ph.D. in related discipline and 5 years experience required. GaAs and gold plating processes a plus. *JOB #WF 11/EET*

• Ion Implant/Materials and Parametrics Section Head

Provides hands-on technical leadership in ion implantation, substrate qualification and Idss control. MS or Ph.D. in Electrical Engineering or Physics and 5 years of experience required. Must have a thorough understanding of controlled process parameters influence on the final MESFET characteristics. GaAs experience a plus. *JOB #WF 11/EET*

• Ion Implant/Materials Engineer

Provides hands-on engineering in ion implantation, substrate qualification and activation. BS in Electrical Engineering or Physics and at least 2 years of exper-ience required. Must have a thorough understanding of the influence of these controlled process parameters on the final MESFET characteristics. GaAs experience is a plus. *JOB #WF 11/EET*

At ANADIGICS' attractive headquarters in Warren, NJ, you'll find a progressive management style and an ideal work environment. We also provide a very competitive package of salary and benefits. Send/fax your resume ***(indicating JOB #)*** with salary history and requirements to: ANADIGICS, INC., Human Resources, Attn: Job #, 35 Technology Drive, Warren, NJ 07059. FAX: (908)412-5933. **Principals Only Please!** INTERNET ADDRESS: hr@anadigics.com. ANADIGICS is an Equal Opportunity Employer.

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

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

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

Display Ads

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

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

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

Engineering Positions at Epitaxial Products International Ltd (UK).

Epitaxial Products International Ltd was founded in 1988 and has quickly established itself as a World Leader in the supply of custom III-V epitaxial material structures. In order to meet the anticipated growth in demand for III-V products, EPI aims to recruit professional engineers of the highest calibre from electronic engineering, materials science or physics disciplines. If your degree or post graduate experience has encompassed semiconductor theory and you have an understanding of III-V devices, epitaxial processes or material characterisation techniques such as x-ray diffraction, photoluminescence spectroscopy and other electrical/optical processes, then we want to hear from you. If you are interested in joining our team at EPI, please forward a copy of your current CV, quoting reference CS/96062 to Chris Meadows, HR/QA Manager, Epitaxial Products International Ltd., Cypress Drive, St.Mellons, Cardiff, CF3 0EG, UK. FAX: +44 1222 779929.

Research Opportunities in Wide Bandgap Semiconductors

The Semiconductor Research Group at the Materials Division of the Electrotechnical Laboratory (Tsukuba, Japan, 60 km from Tokyo) is looking for post-doctoral fellows or sabbatical researchers working in our group for 4 or 5 months. Called researchers will be expected to work on the characterization of III-V nitride epitaxial films or band calculation for III-V nitrides.

The requirements for candidates are as follows: Doctor's degree or equivalent; good communication skills in English or Japanese; experience in the research on semiconductor physics or semiconductor engineering (with experience of CVD or MBE preferable, but not mandatory), and interest in nitride semiconductors and their application. The fellowship award is a monthly living allowance of about ¥270,000; travel fee between the fellow's home country and Tsukuba, and a housing fee. The desirable beginning of the fellowship is between October, 1996 and February, 1997.

Interested applicants should send CV, name and contact information (address, telephone number, fax number, e-mail address etc.), and references. In the selection process, a publications list and a recommendation letter will be necessary.

Address information or inquires to: Dr. Sadafumi Yoshida, Chief, Quantum Materials Section, Materials Science Division, Electrotechnical Laboratory, 1-1-4, Umezono, Tsukuba, Ibaraki 305, Japan. TEL [81] 298 54 5222 FAX [81] 298 58 5434 E mail: e8101@etlrips.etl.go.jp

Postgraduate Research Opportunities at NEWI

Excellent opportunities currently exist for postgraduate research in the Advanced Materials Research Laboratory in Wrexham. This laboratory is a recognised Centre of Expertise in the growth of compound II-VI semiconductors by the MOCVD process. In addition to three dedicated MOCVD reactors, the laboratory possesses a comprehensive range of optical, electrical & structural material characterisation equipment. Current research activities include:

- MOCVD growth & characterisation of wide band gap II-VI optoelectronic semiconductors
- In situ studies of MOCVD growth mechanisms via novel optical (RAS) & structural (STM) techniques
- Novel thin film, flat panel display materials
- Fabrication of self-organising low-dimensional quantum dots by MOCVD.
- Computer modelling of MOCVD reaction chemistry

Generous postgraduate student funding is available for research in these increasingly commercially important areas. Two M.Phil studentships are now available starting this fall and would suit individuals with a background in chemistry and an interest in thin film growth mechanisms.

For further information, please contact: Dr Andy C. Wright, Advanced Materials Research Laboratory, North East Wales Institute for Higher Education, Mold Rd., Wrexham LL11 2AW UK. Tel: [44] 1978 293 001 Fax: [44] 1978 290 008 email: wrighta@newi.ac.uk

Research Positions in Optoelectronics

Three post-doctoral research positions, one graduate research position, and one UK EPSRC post-graduate studentship are available on the following UK EPSRC projects: 1) "Laser diode phase conjugate repeaters and amplifiers"; and 2) "Infrastructure for chaotic optical data encryption". These projects, which are due to commence by the end of 1996, relate to the exploitation of nonlinear properties of semiconductor laser devices. They form part of a collaboration between the University of Wales, Bangor - School of Electronic Engineering & Computer Systems and the University of Bath , School of Electronic and Electrical Engineering. Expressions of interest in these projects and requests for further information should be made to: Professor K Alan Shore, University of Wales - Bangor, School of Electronic Engineering & Computer Systems, BANGOR LL57 1UT, Wales, UK TEL [44] 1248 382618 FAX [44] 1248 361429 EMAIL: alan@sees.bangor.ac.uk

Engineering Positions at AIXTRON Inc.

AIXTRON is the World Leader in Compound Semiconductor CVD Technology and supplies the most capable epitaxial equipment to the major electronic and optoelectronic companies in the U.S. AIXTRON engineers continuously lead the R&D drive towards new applications in cooperation with major Government and R&D Centers. Due to consistently fast growth in the optoelectronics consumer business markets as well as new emerging markets based on AIXTRON's enabling technologies, our Field Engineering Team would be glad to welcome you at AIXTRON to add your experience to the strong technical and equipment base of a highly customer and service oriented world class company. You will take advantage of a unique level of independence in your work environment as well as an exciting travel schedule into all the renowned laboratories of North America. As a **Field Service Engineer** you will also take advantage of continuous updates on latest product developments as well as participating in Engineering Training in Germany. Your should have several years experience in Field Service, in CVD or related activities and the highest commitment to providing "Surprising Service". If you fit this profile join us, the CVD Leader, in a pleasant location close to the city of Chicago. Send/FAX resume or letter of interest to: AIXTRON Inc., Human Resources, 1569 Barclay Blvd., Buffalo Grove, IL 60088, FAX (847) 215-7341.

Growth/Characterization of GaN and Other III-V Materials

Epitronics, a wholly-owned subsidiary of Advanced Technology Materials, Inc., is a leading producer of novel semiconductor films and substrates. We seek to fill three new positions reporting to the Director - Mfg. & Tech. Viable candidates must have a Ph.D. in EE, ChE, Physics or Matls Sci coupled with proven expertise in the area of III-V materials.

Sr. Characterization Engr will be responsible for operations, protocol development and technician training/supervision. Also, will establish basic device fabrication and test procedures (e.g. HBT and HEMT) and conduct exploratory R&D studies on next-generation materials. Must be adept in XRD, PL, Hall and Polaron methods plus SPC techniques and have at least 3 yrs GaAs-related industrial experience. Location - Phoenix.

R&D Engrs (2) to develop growth and characterization processes for III-V Arsenides/Phosphides and GaN for electronic and optical devices. You must have hands-on familiarity with CVD systems, III-V characterization techniques and up to 5 yrs industrial experience. Locations - Phoenix and Danbury (GaN).

We offer competitive salaries plus a full benefits pkg which includes relocation assistance. ATMI has grown at 40-50% annually - visit our web site (http://www.atmi.com) to see why. Send resume and cover letter indicating job sought (please include salary history) to: ATMI, 7 Commerce Dr., Box 59, Danbury, CT 06810. FAX (203) 830-4116. We will respond to applicants only if mutual interest exists. EOE.


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.