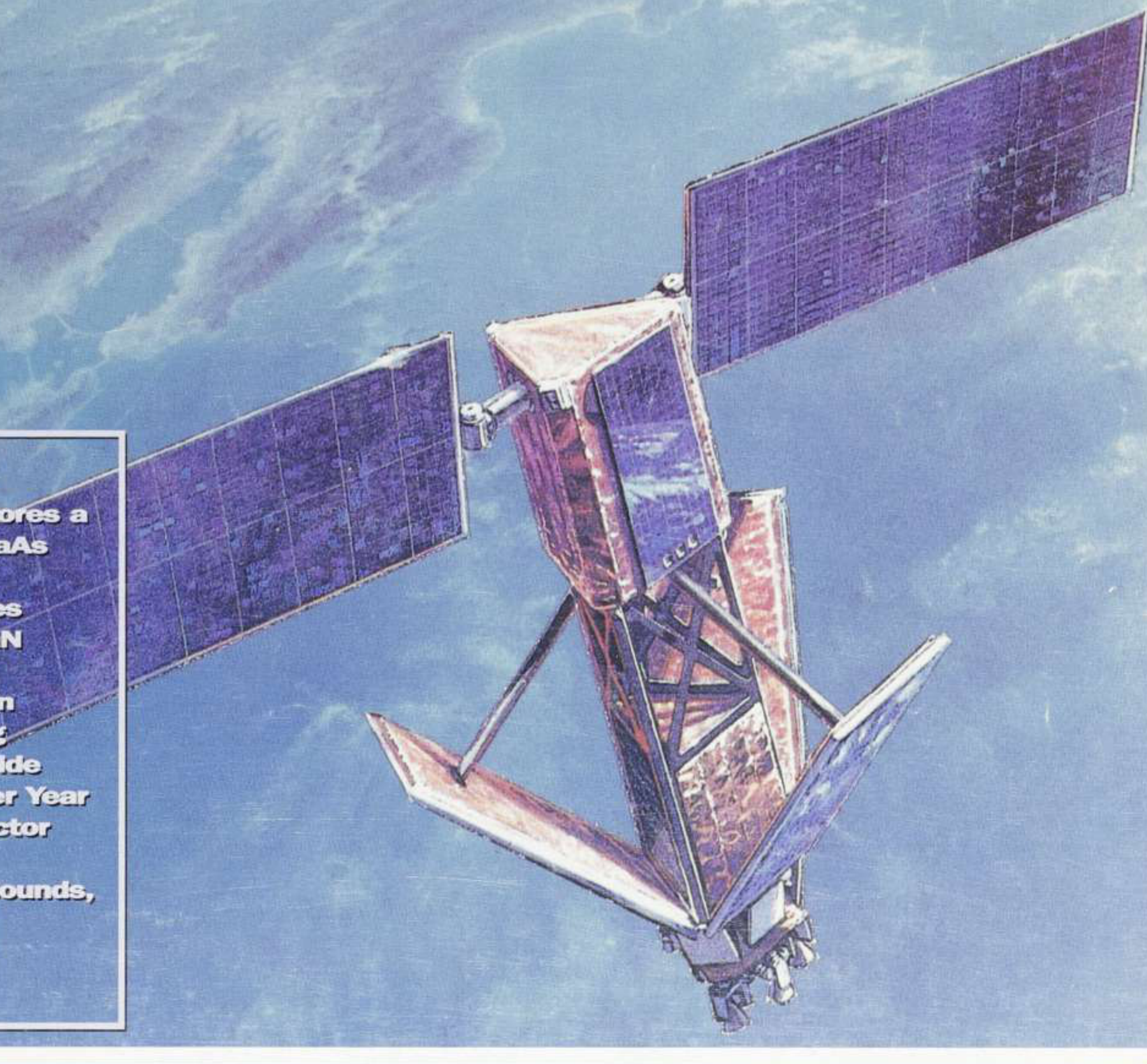
COMPOUND SEMICONDUCTOR

November/December 1996 Volume 2 Number 6

COMPOUND SEMICONDUCTOR SOLAR CELLS FOR SATELLITE APPLICATIONS



Also in this issue:

- Anadigics Explores a New Use for GaAs MESFETs
- Nichia Launches White Light GaN LEDs
- U.S. Initiative in Semi-Insulating Indium Phosphide
- 1996: A Banner Year for Semiconductor Laser R&D
- Thallium Compounds, Light Emitting Polymers, and much more!

NOVEMBER/DECEMBER 1996 VOLUME 2 NUMBER 6

COMPOUND SEMICONDUCTOR

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OTHER FEATURES

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On the cover: Artist's rendition of an Iridium satellite, built by Lockheed Martin. Motorola plans to launch 66 of these satellites - all powered by GaAs-on-Ge solar cells - to construct a new wireless communications network.

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UPCOMING EVENTS

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

Gallium Arsenide VLSI '96
November 26-29, 1996
at Maspalomas, Gran Canaria, Spain
TEL [34] 28 35 1232 FAX [34] 28 45 1243
NET gaas96@cma.ulpgc.es or
http://www.cma.ulpgc.es/GaAsVLSI96/

COMMAD '96
December 9-11, 1996 at Canberra, Australia
TEL [61] 6 249 0363 FAX [61] 6 249 0511
NET etj09@pys.anu.edu.au

1997 IEEE Int'l Solid-State Circuits Conf.
February 6-8, 1997 in San Francisco, CA USA.
TEL [1] 202 639 4255 FAX [1] 202 347 6109
Net or Web: isscc@mcimail.com

Photonics West 1997
February 8-14, 1997 in San Jose, CA USA.
TEL [1] 360 676 3290 FAX [1] 360 647 1445
Net or Web: PW97@spie.org

1997 Spring Meeting of the MRS
March 31- April 4, 1997 in San Francisco, CA.
TEL [1] 412 367 3004; FAX [1] 367 4373
Net or Web: http://www.mrs.org

OMVPE- VIII
April 13-17, 1997 in Dana Point, CA, USA
TEL [1] 412 776 9000 FAX [1] 412 776 3770
Net or Web: csc@tms.org

Advertiser Index

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

Contributions must be received by December 22 to appear in our next issue.

CALL FOR PAPERS

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: January 15, 1997
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

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

CLEO/QELS '97
The 1997 Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference will be held May 18-23, 1997 in Baltimore, MD USA. CLEO provides a central forum for an update of a wide range of laser and electro-optic disciplines; QELS is the largest North American conference concerning research in lasers, nonlinear optics, and the fundamental laser spectroscopy of atoms and condensed matter.
Abstract Submission Deadline: November 20, 1996
Contact: Optical Society of America
Conference Services
2010 Massachusetts Ave., NW
Washington, DC 20036 USA
TEL [1] 202 223 0920
FAX [1] 202 416 6100

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/

1997 Electronic Materials Conference
The 39th EMC will be held at Fort Collins, CO USA on June 25-27, 1997. This conference provides a forum for topics of current interest and significance in the areas of preparation and characterization of electronics materials. Individuals actively engaged or interested in electronic materials research and development are encouraged to attend this meeting, and papers in this general subject area are solicited.
Abstract Submission Deadline: February 17, 1997
Contact: TMS
Customer Service Department
420 Commonwealth Drive
Warrendale, PA 15086 USA
TEL [1] 412 776 9000 x241
FAX [1] 412 776 3770
NET csc@tms.org

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

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 measurement 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
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Ann Arbor, MI 48109 USA
TEL [1] 313 763 6678
FAX [1] 313 763 9324
Net or Web: pkb@eecs.umich.edu

Also in this Issue:

U.S. Getting Ready for a Semi-Insulating InP Program

If current funding projections hold out, in the spring of 1997 the U.S. Air Force, through Wright Laboratory at Wright-Patterson AFB, will award a contract or contract(s) aimed at improving the availability of high-quality, large surface area semi-insulating indium phosphide substrates. The details of program are currently being mapped out under the authority of Title III of the Defense Production Act, which allows the U.S. government to offer appropriate incentives to develop and expand the productive capacities of domestic sources for critical components and resources essential for the execution of the national security strategy.

Title III was used previously to improve the domestic supply of semi-insulating GaAs wafers, an effort which met with considerable success. Less money will be available this time - around $4 million is anticipated - and there is more work to be done, so comparable results are not likely. However, the program does have the potential to significantly impact the future development of InP microelectronics, given that the high price and inconsistent quality of the current supplies of InP substrates are a major complaint of virtually every researcher working in the field.

The stated objectives of the project are "to improve the quality, size, consistency and availability of (semi-insulating) InP substrates while concurrently reducing the cost". This translates into a primary focus on reproducible, consistent, and less expensive 3" wafers, but the program is also looking ahead to 4" wafers as well. The project will consist of one phase lasting approximately 30 months. At a recent conference for potential bidders on the project, the Title III contracting officers made it clear that the $4 million may be divided between two bidders. They also report that the criteria for the success of the program will be "the creation of a domestic, financially-viable provider of semi-insulating InP material, committed to continuous improvement".

An announcement soliciting proposals is expected to appear in Commerce Business Daily sometime in mid- to late-November, and proposals will likely be due in early January. A maximum of two awards is planned at this time.

New Business and Plenty of Activity at Cree

There has been no shortage of news regarding Cree Research lately. Coverage of a shareholder lawsuit filed against the company in late October appears on page 42.

Happier news came in September, when the company announced the receipt of an order from Siemens for more than $5 million worth of blue LED chips to be supplied through fiscal 1997. This is the largest order in Cree's history, and the contract will include joint development work between the two companies to achieve voltage improvements as well as a conductive buffer layer. Cree reports that filling orders under the contract will require the addition of space and the acquisition of another epi reactor that will be dedicated to the project. They also report that "Siemens will make available the full-time services of several of its scientists with epitaxial experience in an effort to advance Cree's and Siemens' knowledge of the epi process for both blue and green super-bright LEDs".

Cree has also recently signed a technology deal with their Japanese distributors, Shin-Etsu and Sumitomo. On October 8 the company announced a $2.7 million agreement with the two companies to license its LED epitaxial and fabrication processes and supply SiC wafers. Most of the funds will be delivered upfront, while the agreement runs for seven years. Under the terms of the agreement, Shin-Etsu will have the exclusive right to manufacture and market these LEDs in Japan, with payment of royalties to Cree.

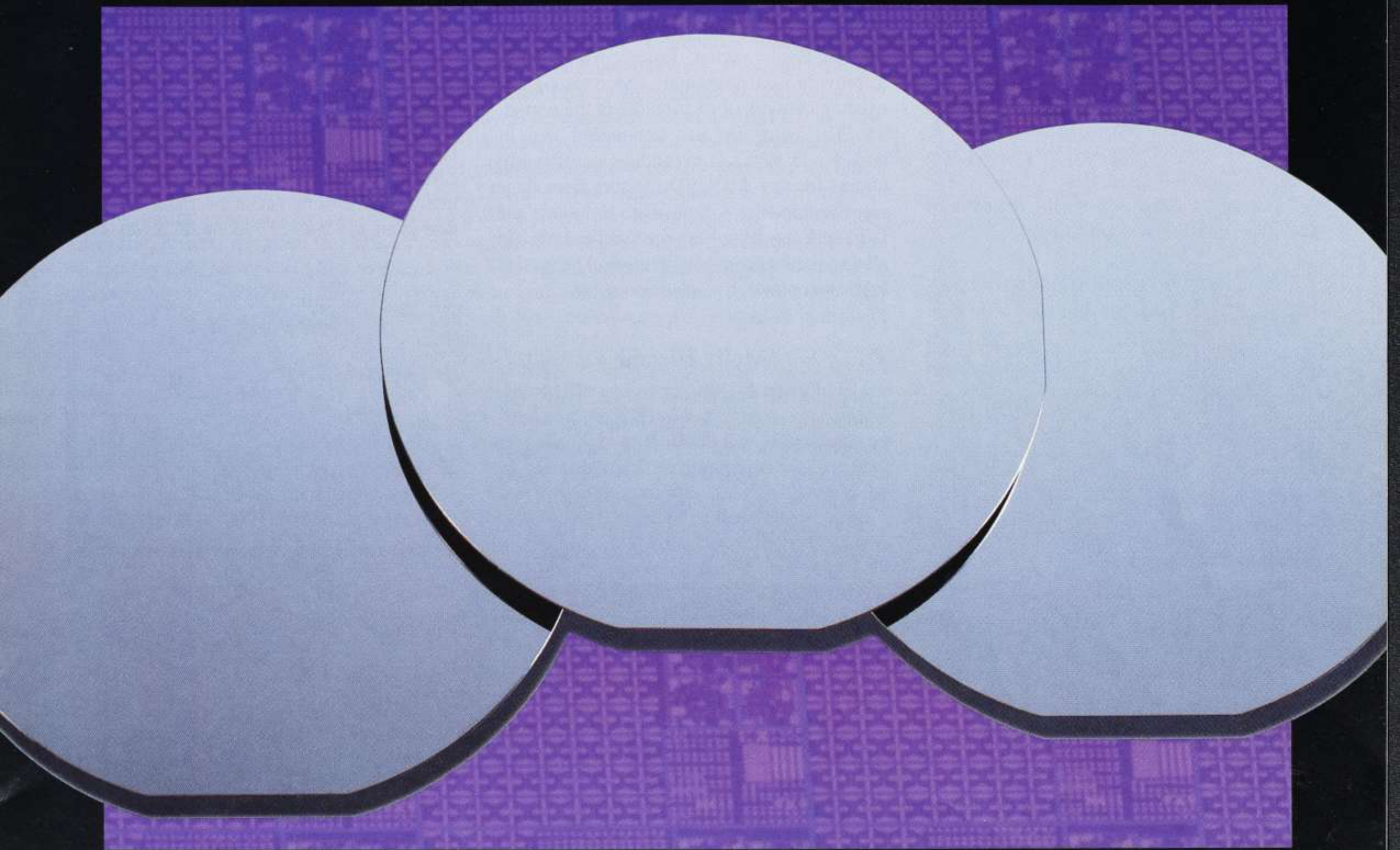
On October 2 Cree announced the receipt of three contracts from U.S. defense agencies that will provide $3.9 million for the development of sensors and high power, high frequency transistors. The first contract is being administered by the Air Force as part of the Defense Advanced Research Projects Agency's (DARPA) MAFET program. The goal is to deliver a 100 watt microwave amplifier based on SiC high-power transistors. Cree says that it will work with a major electronic systems manufacturer - believed to be either Westinghouse or Northrup Grumman - to develop the devices. The contract provides $2.4 million in funding over two-and-a-half years and requires the company to contribute an additional $400,000 to the effort.

The second contract is a $1 million, 16 month award funded by the Naval Research Laboratory for the development of high power transistors that could significantly improve phased array radar systems. The third contract focuses on the development of ultraviolet (UV) radiation detectors from GaN and related materials. It is being administered by the Air Force and includes funding of $500,000.

And finally, Cree also recently announced that it has closed its Eastern European Division in Russia, known as Cree EED, in order to consolidate research & development efforts at its North Carolina headquarters.

GaAs Diodes for High Voltage

International Semiconductor [Santa Monica, CA] recently announced that its subsidiary, GAD Semiconductors, has begun delivery of GaAs power diodes to Advanced Power Technology (APT). GAD's GaAs power diodes are based on a proprietary LPE technique, and are said to exhibit extremely high operating frequencies under very high operating temperatures. The recent shipments are part of five-year joint manufacturing/marketing agreement between the companies. GAD is an 11-employee spin-off from Ramot University of Tel Aviv, Israel which was formed in 1993 to develop GaAs p-i-n diodes as a commercial product. (See *CS* 2(4), p. 15.) APT is a $30 million company headquartered in Bend, OR, specializing in power semiconductors.



Vendor News

Aixtron Reports Sales

Aixtron [Aachen, Germany] reports the sale of an AIX 200/4 HT MOCVD reactor to Hewlett-Packard Laboratories [Palo Alto, CA] for the research of AlGaInN structures for lasers and LEDs. The company also recently delivered two reactors - an AIX 200/4 and a hydride VPE system - to th KTH-Electrum research institute [Kista, Sweden]. The MOCVD system will be used for research into long wavelength lasers and VCSELs. The VPE system will be used for the regrowth of InP-InGaAs for laser applications.

Epigress Appoints North American Agent

Epigress [Lund, Sweden] has appointed SVT Associates [SVTA - Eden Prairie, MN] as its agent in North America. Epigress, a specialist in equipment for epitaxy and sublimation of SiC, reports that SVTA was selected because of the presence it has established in the wide band-gap semiconductor community through its internal GaN and SiC development programs.

Emcore News

Emcore [Somerset, NJ] has opened a new office in Taipei, Taiwan which will be responsible for coordinating all sales and marketing of the company's MOCVD systems in the Asia/Pacific region. Emcore will continue to provide local sales and service through its existing network of distributors in the region

The company also announced that its business in Korea is expanding significantly. Orders for new MOCVD reactors from three major companies - Samsung, Hyundai, and LG Semicon - have been received in 1996. In all three cases the new systems will be used to fabricate optoelectronic components.

Molly Hits 50

EPI MBE Products [Saint Paul, MN] has announced that a recent installation at a European laboratory brings the total number of its Molly™ MBE Process Control Software Systems currently in use worldwide to 50. EPI offers the package as a retrofit for MBE systems from virtually any manufacturer.

MO Boosts Solkatronic

Solkatronic Chemicals [Fairfield, NJ], a subsidiary of Solvay specializing in electronic gases, is building a second plant at Catoosa, OK for the production of arsine, phosphine and other gases. Solkatronic's president Jean-Louis Anspach recently told *Chemical Week* that the company has seen a 30% increase in demand in recent years as demand for metal-organics, particularly those used in III-V processing, has bucked the otherwise downward trends in the semiconductor industry. The new plant will double Solkatronic's capacity.

New Web Sites

- **Epigress** - specializing in equipment for epitaxy and sublimation of SiC: http://www.epigress.se
- **PlasmaQuest** - ECR enhanced etch and CVD reactors: http://www.plasmaquest.com

Passings

Jim Turner

The GaAs industry lost one of its pioneers in late October with the death of Jim Turner. Although he had been dogged by ill-health for some time, it was his nature to conceal it from the outside world, and thus his short final illness and death from cancer on October 27 came as a shock. He was just 57 years old.

Turner began work on GaAs in the early 1960's at the Plessey Company's research laboratories in Caswell, Towcester, England, where remained throughout his career. His small team was one of the very first to demonstrate the potential of the FET as an amplifier at microwave frequencies. Plessey later become the first company to release a commercial MESFET in 1970. Turner was convinced that the potential of the GaAs FET could be enhanced by embodiment in an integrated circuit, and after spending some years raising the necessary development funds, Jim's team was the first to incorporate the GaAs FET into what became known as the Monolithic Microwave Integrated Circuit, or MMIC, in 1974. Never one to be satisfied by laboratory curiosities, he next turned to the difficult tasks of bringing these devices to production. In 1989 the Plessey Laboratory was taken over by GEC. The GEC-Marconi GaAs Foundry in operation at Caswell today- the only commercial operation making MMICs in Britain - owes a deep debt to his work. He took early retirement from GEC in 1994, but remained a very active consultant right up to his death.

Jim Turner's contributions to science and technology were formally recognized by several awards, including a "Member of the British Empire" (MBE) award in 1981, the GEC Nelson Gold Medal in 1992, and the Heinrich Welker Gold Medal in 1993. The later is the premier award in the GaAs field. He was a Visiting Professor at the University of Wales in Cardiff, and served on research council committees to promote the study of GaAs at British universities. He also served on the Advisory Committee for the GaAs IC Symposium., and was much involved in the international development of GaAs, both within the European Union and in the United States.

He was born on March 4, 1939, and lived his entire life in the village of Milton, a remarkable achievement for someone of his talents. He studied physics at Sheffield University. He leaves a wife, Nina, who he met while still at school, and a son and two daughters. His many friends and colleagues will miss him greatly and will fondly remember his cheerfulness, tact and sense of humor.

Seymour Cray

Seymour Cray, a legendary figure in the supercomputer industry, died on October 5 as a result of injuries suffered in a car accident two weeks earlier. Readers of this magazine will most likely remember Cray as the founder of Cray Computer [Colorado Springs, CO], which attempted to produce the world's most sophisticated supercomputers using GaAs circuits. But before that venture, which ultimately failed, Cray had established his reputation as a pioneering genius with a passion for building ever-faster and more powerful computers.

Cray graduated from the University of Minnesota in 1951 with a B.S. in electrical engineering and a M.S. in applied mathematics. From 1950 to 1957 he worked as a computer scientist at Engineering Research Associates [Saint Paul, MN - later known as Sperry Rand, Univac Division]. In 1957 he co-founded Control Data Corporation [Minneapolis, MN]. In 1972 he left Control Data to found Cray Research [Eagan, MN], which became the leading company in the supercomputer field. By 1987 Cray Research's revenues had reach \$785 million, and the company commanded two-thirds of the world's supercomputer market. But Seymour Cray no longer controlled the company, and that same year company management killed Seymour's plans for the development of a GaAs-based computer to be known as the Cray-3, citing lack of funds.

In November, 1989, Cray Research spun off around \$150 million in cash and assets to found Cray Computer [Colorado Springs, CO] to pursue the Cray-3 project. The new company, which was headed by Seymour Cray, included a captive GaAs fab based on a 4" MESFET process - a necessary asset, as all of the logic in the Cray-3 was executed in GaAs, and more than 500 different ICs were required. But both manufacturing difficulties and the changing nature of the computer business worked against Cray Computer, and in March, 1995 the company was forced to declared bankruptcy. The GaAs fab was purchased by M/A-COM and re-tooled for analog devices, and the remaining assets were liquidated in October, 1995. Undaunted, and still driven by the desire to advance computer technology, Seymour Cray launched a new company in July, 1996, and at the time of his death he was actively planning to build a new generation of silicon-based supercomputers.

Industry News

Much of the compound semiconductor news from Japan in recent months has involved lasers, due in large part to the introduction of DVD technology, This trend continues in this issue, with the news that Sharp, one of the world's largest opto component manufacturers, is doubling its semiconductor laser production. More optoelectronics news appears on page 10.

Sharp Doubling Semiconductor Laser Production to 120 Million Units

Sharp has announced that it will double semiconductor laser production from the current 5 to 10 million units per month by the end of fiscal 1997. The company says that the focus of its efforts will be on the production of semiconductor lasers for DVD, CD and MD (Mini-Disk) players. Sharp plans to invest about ¥10 billion ($91.7 mil) in its optical device division and expand the investment to ¥20 billion ($183.5 mil) in fiscal 1997. The company also reports a growing demand for its hologram laser, which integrates a signal detection photo diode and a laser.

As we reported in our last issue, several companies are announcing plans to ramp up semiconductor laser production in anticipation of the successful launch of the new DVD optical disk technology. (*CS* 2(5), p. 15). Sharp's announcement mirrors similar production forecasts released by Sony and Sanyo, among others. The DVD standard will require 635 - 650 nm AlGaInP diodes as compared to the 780 nm AlGaAs diodes which are used in the current generation of CD players.

NEC and OKI to Boost Their Analog GaAs Capacity

Optoelectronics news may be dominating the Japanese compound semiconductor industry this year, but there are also some signs that analog device activity is picking up as well. **OKI Electric** has announced that it will **boost microwave device production by 50%** to 3 million units per month by next summer. The decision to bolster the compound semiconductor business is a response to strong demand in the mobile communications systems area. The company will start sampling new products to coincide with the planned launch in 1997 of the IRIDIUM project and other satellite-based mobile communications services. The satellite-ready devices are scheduled to be mass-produced from late 1997. OKI intends by 1998 to increase output on the 3-inch line at its Hachioji plant to the full capacity of 15,000 units per month, from the current 700-800.

NEC is also reporting that it **will raise its compound semiconductor production capacity by 80% by March 1998**. The company says that the additional capacity will be used, in part, for DVD lasers, but it also plans to increase its output of microwave devices. As part of this effort the company will convert its GaAs processing line at NEC Kansai from 3" to 4", maintaining the current capacity level of 2400 wafers/month. A new post-processing plant in Taiwan, which was scheduled to become operational in October, plans to produce 1 million hetero-junction FETs and 14 million photo couplers per month.

NEC also announced that its Cable Media division will introduce broadband CATV relay amplifiers incorporating GaAs FETs. The company claims that the new amplifiers provide 4-5dB better distortion characteristics compared to conventional amplifiers incorporating silicon chips yet consume 5-10% lower power. Shipment begins on December 1.

Showa Denko Expanding LED Material Production

Showa Denko reports that it is expanding its compound semiconductor business. The company will spend a total of ¥1.5 billion ($13.8 mil) on its Chichibu plant by the end of 1997 to allow a five-fold increase in production capacity for super-high-brightness quaternary LED and optical communications photo detector materials. Showa Denko will raise its monthly LED material production capacity to the equivalent of 15 million chips. Epitaxial wafer capacity will also be increased. The company reports that this move is part of its effort to expand its compound semiconductor business to ¥5 billion ($45.9 mil) by 2000.

Gallium Prices Rising

Japanese producers report that gallium prices are set to rise as supplies remain tight. Prices were raised by 20% last year and the market attempted to rein in prices by making use of recycled scrap. However, difficulties with insuring adequate scrap supplies have led again to a focus on virgin gallium. Price rises have not yet been implemented because of the retrenchment in the semiconductor industry, but higher prices are likely from late fall or winter.

Fujitsu, NEC Tops in GaAs ICs

Recent market research from Dataquest, Inc. shows that Fujitsu and NEC are the world's top suppliers of GaAs ICs, with market shares of 32% and 12% respectively. Four U.S. companies occupy the next spots: Anadigics (6.3%), Vitesse (5.8%), TriQuint (5.6%) and M-A/COM (4.8%). Dataquest forecasts that sales of GaAs ICs should top $1 billion in 1996.

R&D Reports

High Temp InGaAs Photo Diode

Kyoto Semiconductor has developed an InGaAs photo diode that can operate at temperatures of up to 125°C. The company has worked with Professor Takahashi of Hokkaido University to develop the photo diode that uses a new device structure. The company plans to commercialize the development as an optical communications photo diode with a detection wavelength range of 0.9-1.65 microns and a near- infrared sensor with a detection range of 1.2-2.6 microns. It will soon launch production at its subsidiary in Hokkaido, but sample prices and production volumes are yet to be determined.

Matsushita in the Trenches

Matsushita Electric has successfully created a 20nm-wide, 600nm-deep quantum fine line. Six times deeper than conventional quantum fine lines, the line is deep enough to accommodate 20 layers of quantum wells. The line has been cut on a GaAs substrate with a ZnSe active layer by a helium cadmium laser. Previously, the company succeeded in producing lines of the same width, but only 100 nm deep. The deeper line brings the technology a step closer to development of a practical optical switch. The company plans to create a quantum box using the line in order to develop a device which will operate optically.

Quantum Device Results

Several research groups in Japan are reporting progress in fabricating and understanding quantum devices. The **Institute of Physical and Chemical Research** reports that it has **developed a technique to create SiC/GaN quantum boxes**. The technique laminates a one- atom-thick layer of SiC on the surface of a substrate upon which quantum boxes are to be formed. The technique is characterized by its capability of flexibly controlling the size and the density of quantum boxes. In an experiment, the research group used MOCVD to successfully create 40nm-wide GaN hexagonal quantum boxes, a candidate for blue light emitting devices, and manage to keep the number of quantum boxes to 10-10,000 million/sq. centimeter.

Fujitsu claims that it has become the first company that has **observed a resonance tunnel effect between quantum boxes**, paving the way for 1Tbit memory development. Collaborating research for a resonance tunnel effect with the Electrotechnical Laboratory, the New Energy Development Organization, the Institute for Solid State Physics of the Tokyo University, and Hokkaido University, Fujitsu has formed a double quantum well structure made of InGaAs having three barriers through molecular beam epitaxy, created a quantum box which has zero-dimensional electron activities within a quantum well by applying a magnetic field of 39 teslas, and observed a resonance tunnel effect between quantum boxes.

Sony reports that has **designed a unique logic device employing a quantum effect** in a project being sponsored by MITI to develop quantum function devices. The new device can carry out by itself logic operations which typically requires multiple devices. It has two 10nm-diameter quantum boxes, each of which can contain one electron. However, one is slightly larger than the other, so that the device can create four conditions: electrons are in both boxes; an electron is in a smaller box; an electron is in a larger box; and neither box contains an electron. Since the device can function as a logic operation circuit by itself, it is expected to help lower the power consumption of logic circuits and reduce the area they require.

Matsushita II-VI Solar Cell

Matsushita Battery has developed a II-VI thin-film solar cell with a photo-electric conversion efficiency of 15.1% and will aim to commercialize it by 2000. The company has worked on solar cells which use CdS (cadmium sulfide) for the negative electrode and CdTe (cadmium telluride) for the positive electrode for ten years and now supplies products with a 11.3% conversion efficiency. Matsushita claims that it has developed a low-cost process for forming CdS and CdTe thin films under normal pressure and lower sintering temperatures.

For more on solar cells, including news about increased production of silicon solar cells in Japan, see this issue's cover story, beginning on page 22.

Optoelectronic Devices

For more opto news from Japan, see our "Nitride News" section on pages 13 & 14.

Also in this issue: A review of the highlights of semiconductor laser research in 1996 - see page 16.

1.25 Gbps Data Link Using 0.78 Micron Laser and Plastic Optical Fiber

Fujitsu Laboratories has succeeded in 1.25Gbps data transmission over a distance of 100m in an experiment with a plastic optical fiber (POF) link. The optical link's transmitter incorporates a technique for directly connecting a high-speed logic device and a 0.78-micron semiconductor laser to a signal circuit, and together with its receiver the POF link requires no dedicated modulation circuit. Measuring 17x17x8.5mm, the optical link is about 1/3-1/2 the size of conventional devices.

Cheaper Opto Module from Toshiba

Toshiba has developed what it describes as a significantly cheaper optical module, which houses a semiconductor laser, a light-receiving device and lenses. This has been achieved mainly by eliminating the need for highly precise alignment in the assembly process. The new optical module can be produced for about 1/10 the cost for a conventional product, whose price typically runs in the ¥20,000-60,000 ($182-545) range. It features a structure which allows an optical fiber with a connector to be inserted directly into it. Toshiba hopes to develop a practical model in two years.

NEC Optical Amp/Switch

NEC has developed a switch capable of amplifying optical signals. Using MOCVD, the company has formed a waveguide and an amplifier, both made of InGaAsP on an InP) substrate. In an experiment, the 1x4mm prototype which switched signals coming in from an optical fiber to four output optical fibers successfully functioned as a switch when 60mA of current ran, achieving a switching speed of 0.8ns, the speed required to enable 10Gbps optical communications.

2.5 Gbps Laser from Mitsubishi

Mitsubishi Electric has developed a 2.5Gbps semiconductor laser with an integrated external modulator for next-generation trunk optical fiber networks. The ML9XL15 Series integrates a semiconductor laser and an optical modulator on chip and provides a transmission range of 300km without repeaters, a 200% increase over conventional direct modulation systems that use stand-alone semiconductor lasers. Samples will become available from this fall at ¥250,000 ($2,294) apiece. Plans call for producing 300 units monthly in fiscal 1996 and 1,000 units monthly in fiscal 1997.

NEC 4 Mbps IR Modules

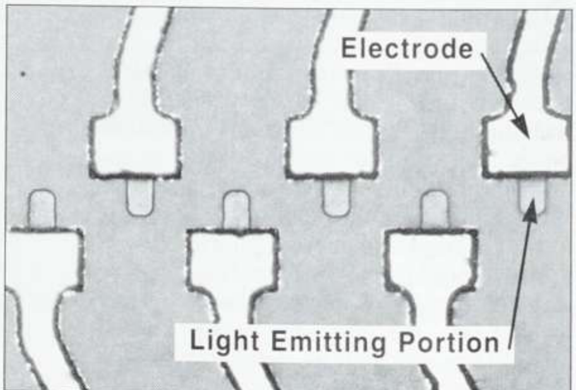
NEC has developed an optical communications module featuring a data transfer speed of 4Mbps, about 40 times the speed of conventional products. The infrared module integrates LED, signal reception and LED driver chips on a substrate and conforms to the IrDA (Infrared Data Association) 1.1 (FIR) standard. It operates from a 5V supply and is sample-priced at ¥1,000 ($9.01). NEC will produce over 500,000 units per month from January 1997. Plans call for unveiling a smaller, 3.3V version next summer

Hewlett-Packard LEDs for Japanese Automotive Market

Hewlett-Packard Japan will release an automotive LED in the fiscal year to October 1997. Developed by HP for use in cars' tail lamps and turn signal indicators, the new LED achieves nearly four times the brightness of a conventional product, or a luminous flux of 2,500 millilumen. It features a proprietary four-lead structure and a maximum rated current of 70mA. In an attempt to cultivate a potential market estimated at tens of billions of yen, HP Japan intends to actively market the new LED to Japanese automakers for installation in their fiscal 1998 models.

High Resolution LEDs for Printing Applications from OKI

Oki Electric has developed an ultra-high-density LED array for print heads. The company has developed a new solid-phase diffusion technique for forming a shallow, high-density diffused zinc region in the GaAsP layer to create fine patterns and increase the resolution of the LED array, paving the way for the implementation of high-definition, high-quality printers that use LEDs. The new array features a recording density of 1,200dps, twice that of today's LED heads.



Photograph of a portion of the new high-density LED array developed by Oki, capable of providing a resolution of 1,200 dots per inch. The interval between electrodes is 42.2 micron.

NEW DEVICES

Toshiba Enters the Surface Mount LED Market & Introduces Quaternary LEDs

Toshiba America Electronic Components has announced the availability of a new line-up of Surface Mount Device (SMD) LEDs. The new products consist of 18 SMD diodes available in both flat lens and dome lens types. Toshiba claims that that these new products are "the brightest SMD LEDs offered in the industry today", with up to 450 mcd typical. The colors offered range from greens in the 555 to 570 nm region, yellow at 590 nm, orange at 612 nm, and a variety of reds in the 635 to 700 nm range. The target markets for the new devices include backlighting applications such as cellular and cordless telephones, industrial equipment, portable instrumentation, car instrumentation, and signboards. Aisle lighting such as that in airplanes and movie theaters is also of interest. Pricing ranges from \$0.15 to \$0.50 in 3,000 piece lots.

Toshiba has also recently announced that it has begun selling AlInGaP-based LEDs in "soft red" (636 nm), orange (612 nm) and yellow (590 nm). The company is marketing the new devices, which it calls the U-series, on the basis of their ability to reduce power consumption for lighting and display applications. According to a Toshiba press release, "by achieving 10 times the brightness of standard LEDs, the new U-series attains the same level of luminance at 1/10 power consumption". The specifications for brightness range from 1800 mcd for red to 2600 mcd for orange and yellow. Pricing ranges from \$0.20 to \$0.30 in 5,000 piece lots.

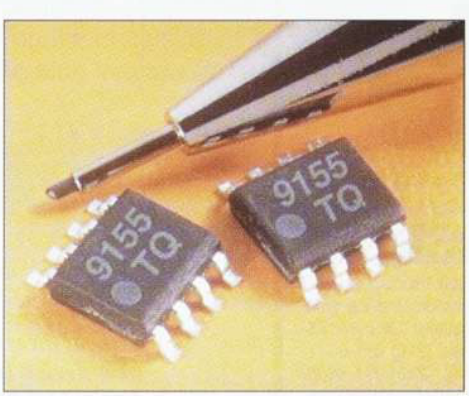
New surface mount device (SMD) LEDs from Toshiba include the Flat Lens 1002 Series (shown above), which offers a brightness of up to 60 mcd and a peak wavelength ranging from 555 to 700 nm; and the Domed Lens 1005 Series (not shown), with a brightness of up to 450 mcd and a peak wavelength ranging from 555 to 660 nm.

TriQuint SPDT Switch up to 2.5 GHz

TriQuint Semiconductor has introduced the TQ9155, a single-pole, double-throw (SPDT) reflective radio frequency RF switch IC for the wireless communications market. Potential uses include a wide range of RF switching applications, including systems that require routing of an RF signal to one of two locations, such as transmit/receive (T/R) switching, antenna diversity switching, and switch matrices. Systems include cable TV, test instrumentation, medical instrumentation, cellular and PCS handsets and base stations, cordless phones, fiber optic modules, and wireless local loops, among others

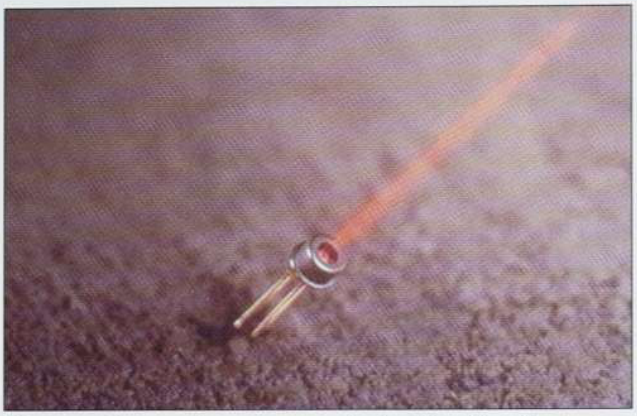
Operating in the DC to 2.5 GHz frequency range, the RF switch is intended to offer portable and stationary RF system manufacturers "a low cost, integrated alternative to discrete solutions". Delivered in a small SOIC-8 package, the device consists of four depletion-mode transistors configured in a classic series/shunt arrangement. Dual negative control voltages, whose values are already available in many systems, determine switching/selection by creating either a low impedance or high impedance path to the RF signal. An external circuit is needed to drive the two control voltages pins. If a negative voltage supply is not readily available, the TQ9155 can operate from a single positive supply with the addition of a few external components.

Key performance specifications include insertion loss of 1.0 dB maximum, isolation at 22 dB minimum, and return loss at 14 dB maximum. Performance is guaranteed at 2.0 GHz, and parts are 100% RF tested. The TQ9155 is available from stock at a unit price of \$1.25 in order quantities of 100,000.



The TQ9155, and industry-standard SPDT RF switch for the DC - 2.5 GHz range, now available from stock from TriQuint.

Honeywell Micro Switch Offers VCSELs as Catalog Items



Honeywell recently announced what it calls "the industry's first high-volume, commercially available VCSEL". The 850 nm device is available from stock from the company's Micro Switch Division.

Honeywell's Micro Switch Division [Freeport, IL] has begun offering 850 nm VCSELs in TO-46 packages. This is believed to be the first instance of VCSELs being offered as discrete components. The devices are being fabricated at Micro Switch's Dallas, TX facility. Honeywell is widely recognized as a leader in switching and sensing technology, and the Micro Switch Division is one of the two largest manufacturers of LANs for datacom, and is already engaged in the manufacture of LEDs for fiber optic communications. This new product announcement marks their first foray into the laser diodes area.

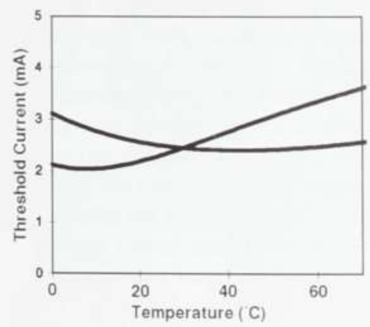
Honeywell's marketing message for VCSELs is simple and direct: "All the desirable features of an LED with the benefits of a laser diode." Characteristics include:

- Low drive current requirements (5 to 15 mA);
- Low EMI/RFI
- High coupled power (> 1 mW typical);
- High reliability (MTTF > 10^7 hours); and
- Wide bandwidth (f_t > 10 GHz).

Other selling features of the new device will be familiar to anyone who has been tracking VCSEL development: a symmetrical beam, low coherence, and a narrow beam angle. Another feature is stability of operating characteristics with temperature (see figure), which Honeywell says "potentially allows operation without continuous photodiode feedback control", which would simplify drive circuit design.

The new device, which is called the HFE 4080-321, is intended for high-speed data communications. Data rates can vary from DC to above 2 GB/s depending upon the application. Honeywell says that it is specifically designed to interface with 50 micron and 62.5 micron multi-mode fiber, and that while larger fiber sizes are possible, "essentially of the VCSEL power can be coupled into even the 50 micron fiber if necessary".

Technically speaking, this is not the first instance of VCSELs being commercialized. Hewlett-Packard recently began offering a VCSEL-based transceiver for gigabit+ data links handling multimedia information. (CS 2(3), p. 40). Similarly, Motorola offers a series of optical interconnects which they call the "Optobus family" that are based on 850 nm VCSELs combined with high performance ICs on a multi-chip module. However, it does appear that Honeywell is the first company to make VCSELs available as standard catalog items available from stock. List price in the U.S. is $24 per piece.



Typical threshold current vs. temperature characteristics for the new device (two available characteristics shown). Honeywell says that the stability of operating characteristics with temperature potentially allows operation without continuous photodiode feedback control.

NITRIDE NEWS

Nichia Closing in on CW GaN Laser Operation

Nichia Chemical appears to be close to achieving CW room temperature operation of a GaN-based blue laser diode. In a paper that will be appearing soon in *Applied Physics Letters*, Shuji Nakamura and co-workers report CW operation of InGaN MQW laser diodes at 233K (-40°C). Moreover, Nakamura should soon be announcing CW operation exceeding one hour, perhaps as early as December.

The *APL* paper represents yet another milestone in the short history of GaN lasers, as it is the first report of CW operation at any temperature. The device structure used was similar to previous papers, but Nichia reports that they were able to reduce the operating voltage at the threshold current to 11 V (compared to a previous best of around 30 V) by "adjusting the growth, Ohmic contact and doping profile conditions". The threshold current density was 8.7 kA/cm^2, and a differential quantum efficiency of 8% per facet and an output power of 9.5 mW per facet were obtained at a current of 250 mA. The diode lasted under CW conditions for more than 30 minutes at 233K. No attempts were made to measure the lifetime beyond 30 minutes. Approximately 1 second of room temperature CW operation was also achieved, but that lifetime was too short to obtain any useful measurements.

Since this paper was submitted Nakamura has publicly presented marginally better room temperature results, and he reports that he hopes to present more significant improvements - one hour or more - very soon, perhaps at the LEOS and MRS meetings in December.

Toshiba Reports Successful GaN Laser

Researchers from Toshiba have become the third group to announce the successful operation of a GaN-based laser diode, following Nichia Chemical and Meijo University. On September 12 Toshiba reported that it had demonstrated a room temperature pulsed-mode 417nm laser diode. The company used what it describes as "a proprietary MOCVD technique" to grow a multiple quantum well structure (25 periods of 20Å-thick GaN and 40Å-thick GaAlN layers) on a sapphire substrate. Threshold current was 5A and operating voltage was 20V.

In a press release announcing their breakthrough, Toshiba cited two factors which were important for achieving this milestone. First was Toshiba's MOCVD capability, which allowed the fabrication of very thin and precisely controlled GaN and InGaN layers. The second was what the company describes as "a new technology for cleaving the GaN crystal grown on the C-face sapphire substrate and assuring a smooth surface". Most, but not all, of Nichia's work to-date has involved dry etching of the facets, and conventional wisdom says that sapphire is not amenable to cleaving. However, Toshiba believes that the ability to cleave the facets will result in a more manufacturing-friendly processes, which will give them an advantage in the future as the technology moves toward production.

Toshiba reports that it hopes to commercialize a blue laser within two years, and plans to use the device for a 15 G-byte DVD optical pick-up.

White Light Burning Bright at Familiar Site

Nichia Chemical establishes another "first" with the release of a white light LED

Nichia Chemical has announced that it is ready to begin volume production of a highly efficient white LED lamp. The new device combines a blue GaN LED with a yttrium aluminum garnet (YAG) fluorescent layer to emit white light. One lamp has the brightness of 5 lumen per 1W; two units of the lamp will be brighter than a typical "dome light" inside a car. Samples of the new lamps are shown in Figure 1. The actual color of the emission is indicated on the CIE Chromaticity Diagram in Figure 2. Nichia's standard LED products (blue, green and bluish green) are shown for comparison, as are the "traditional" III-V light emitters, GaP, AlInGaP, and AlGaAs.

Nichia has become famous in the compound semiconductor industry because of the pioneering work in shortwavelength optoelectronics conducted by its head of R&D, Shuji Nakamura. But before Nakamura unleashed his GaN juggernaut in 1993, the company was well-known in other circles as the world's largest independent supplier of phosphors for color television picture tubes. Thus there is a neat symmetry to this new development, as it brings together Nichia's traditional area of expertise with its newest capabilities.

We asked Nakamura about the role that the blue LED plays in this new product. After all, shouldn't it be at least theoretically possible to produce white light by combining an orange or red LED with a different phosphor? He was quick to acknowledge that "the idea of making a different color by combining LEDs and phosphors is not new". However, he states that the Nichia blue LEDs are the key to the commercial practicality of the device. As he puts it, "To excite a phosphor, the blue LEDs must be required because the short wavelength LEDs have a higher energy, and the phosphors require a high energy to be excited in order to emit the different color." As an example, he points to fluorescent lamps, in which the phosphors are excited by UV light. Nichia's blue LEDs are capable of producing a luminous intensity of up to 2 cd at a forward current of 20 mA, with a dominant wavelength of 470 nm and a half width of just 30 nm.

There is an alternative way to generate white light using LEDs: combine the output of three different red, green and blue LEDs. This method is already used to produce white (and 16 million other colors) in LED-based full color displays. We asked Nakamura how Nichia's new product compares with this approach. He cited one possible disadvantage - the efficiency of the Nichia white LED will be inferior because the conversion efficiency of the phosphor is below 100%. But he points out that the new lamp is much better suited to applications where only white light is needed. It uses only one LED, and therefore requires only simple circuitry; in contrast, to produce white light using LEDs of different colors requires three chips and a special circuit to adjust the current to each chip to balance their output. Therefore, the 3 color approach will likely always be more expensive than the phosphor-based white lamp.

Nichia is currently offering the new technology in two packages. The first is a standard domed LED package as shown in Figure 1. They are sample-priced at ¥ 300 a piece in lots of 100. The other option is a flat panel, either 40mm x 136mm or 102mm x 126mm in area. These products are shown in Figure 3, and a schematic of their operation is shown in Figure 4. Nichia reports that their first target markets are car-mount panels, LED back lights and many other applications.

Other Nichia LED News

Nichia has also recently begun shipping blue and green LEDs in surface mount (SMT) packages, samples of which are shown in Figure 5. This new option is expected to be popular with manufacturers of color scanners, sensors and indicators, who can take advantage of the small footprint and easy assembly offered by SMT technology. The characteristics of the new devices are output power of 2.0 mW and luminous intensity of 45 mcd for blue, and 1.2 mW and 150 mcd for green, which is between 50-66% of the performance of the top-of-line domed models. As we reported in our last issue, SMT LEDs are expected to constitute the majority of the LED market within the next two years.

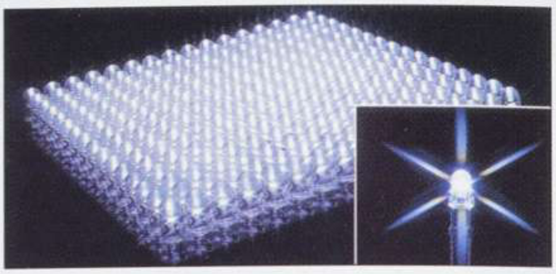


Figure 1

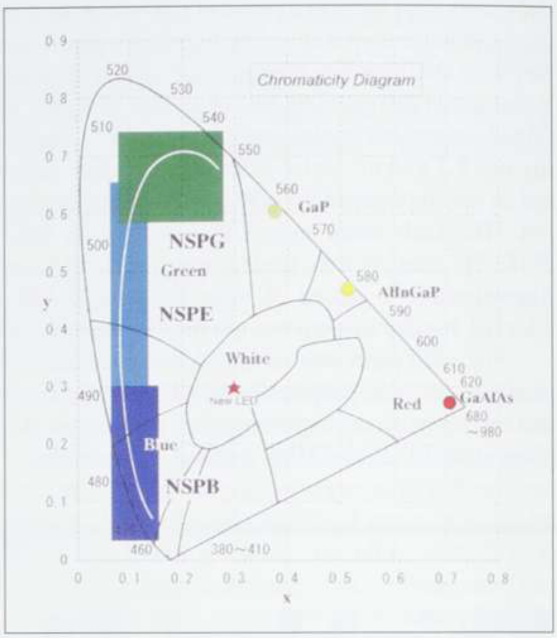


Figure 2

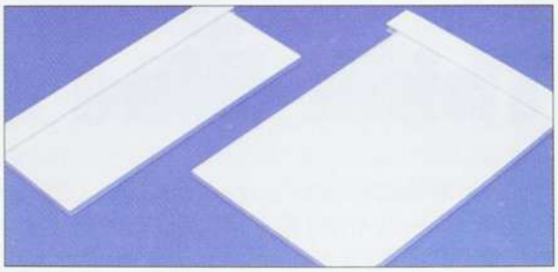


Figure 3

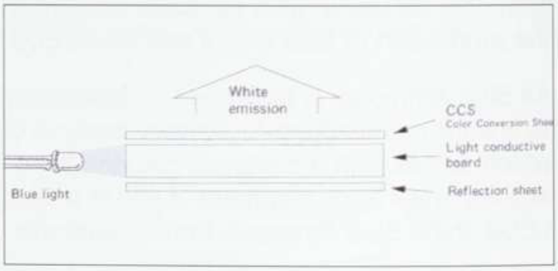


Figure 4

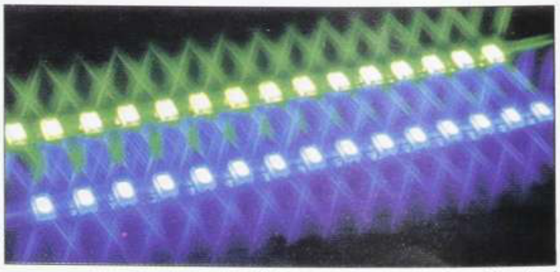


Figure 5

All figures courtesy Nichia Chemical

III-V Highlights at the IEDM

This year's International Electron Device Meeting (IEDM) will be held December 8 -13 in San Fransisco. As in years past, this meeting will serve as the premiere venue for the presentation of state of the art device results. III-V based devices continue to find greater penetration into commercial markets, and this growth is reflected in the papers presented at the IEDM, in which many III-V emerging technologies will be highlighted. Some of these include:

* **III-V Nitrides.** Even though this materials system is most recognized in terms of optical applications, it is also being utilized for electronic applications. Asif Khan and coworkers from APA Optics [Blaine, MN], University of Virginia [Charlottesville, VA] and Cornell University [Ithica, NY] will report on improved III-V Nitride based HFET's. HFETs which exhibit transconductances of 120 mS/mm, along with f_t and f_{max} values of 49 and 105 GHz, respectively, were used in the fabrication of 0.75 µm x 0.25 µm devices which are capable of delivering cw output powers of 0.3 W/mm at 10-15 GHz - the first power measurements for these type devices at X-band.

* **SiGeC Alloys.** Advances in the implementation of SiGeC alloys for device applications will be reported on by S.K. Ray and coworkers from the University of Texas [Austin, TX], with the fabrication of a SiGeC channel Heterojunction PMOSFET, in which the C is used to partially compensate for the strain present in the SiGe. A hole channel mobility of 209 cm^2/Vs is achieved in the SiGeC-based PMOSFET, as compared to 160 cm^2/Vs in a comparable all Si-based PMOSFET.

* **SiC Transistors.** Due to a critical breakdown field that is 7.5 times greater than that of GaAs, a saturated drift velocity at high fields that is 2 times greater, and a thermal conductivity that is 10 times larger, 4H-SiC is an ideal candidate for high power device electronic applications. A.K. Agarwal and coworkers from Northrop Grumman Science and Technology Center [Pittsburgh, PA], will review a wide range of SiC-based electronic devices, including: static induction transistors with 300 V breakdowns and capable of producing 450 W of output power at 600 MHz; MESFETs with drain currents exceeding 500 mA/mm at gate-drain breakdown voltages of 100 V; fast turn-off Schottky diodes with breakdowns in excess of 1000V; and SiC-based PIN diodes with breakdown voltages of up to 4.5 kV.

* **III-V Lasers on Silicon.** Utilizing self-formed nanometer-scale GaAs island active regions generated by droplet epitaxy during the growth of GaAs on Si substrates, Takashi Egawa and coworkers from the Nagoya Institute of Technology [Nagoya, Japan], have used this growth technique in the fabrication of AlGaAs/GaAs laser diodes on silicon substrates. These lasers operate at 791 nm, with a J_{th} of 5.4 kA/cm^2, and exhibit lifetimes of up to 14 hours - significantly in excess of the few minute lifetimes generally observed when conventional quantum-well GaAs-based laser structures are grown on Si.

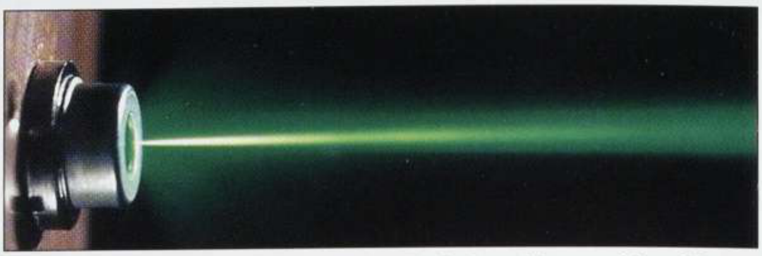
* **GaAs-on-Insulator.** Using a GaAs on Insulator (GOI) technology, in which a 500 Å $Al_{0.98}Ga_{0.02}As$ layer beneath a device active layer is converted to Al_2O_3 through oxidation at 450°C, P. Parikh and coworkers at the University of California [Santa Barbara, CA] will report on the first demonstration of a PHEMT fabricated in GOI technology, in which the insulating layer is used to reduce substrate leakage current and improve device output conductance. The 1.2 µm gate length device exhibits a peak transconductance of 140 mS/mm, a maximum drain current of 140 mA/mm and a negligible output conductance.

* **InP Microelectronics.** InP-based HBTs, with f_t and f_{max} values of 70 and 170 GHz, respectively, were used in the fabrication of a 94 GHz VCO as will be described by John Cowles and coworkers from TRW [Redondo Beach, CA]. This is the first report of a W-band bipolar fundamental oscillator.

* **New MESFET Record.** Using 0.06 µm gate length MESFETs, which exhibit a record breaking f_t of 168 GHz, Masami Tokumitsu and researchers from NTT LSI Laboratories will report on the fabrication of a 32 Gbit/s super-dynamic decision circuit.

***Tunable VCSEL.** By incorporating a surface micromachined movable reflector as the top mirror in a vertical cavity surface-emitting laser (VCSEL), M.C. Larson and coworkers from Stanford University [Stanford, CA], will report on a broadly tunable AlGaAs/InGaAs-based VCSEL which exhibits a continuous tuning range of 18 nm around a center frequency of 970 nm, without experiencing mode hopping. This is the largest continuous wavelength range reported for any monolithically-fabricated laser diode.

1996: A Banner Year for Semiconductor Lasers



One of 1996's highlights: a 515 nm ZnSe-based laser with a lifetime exceeding 100 hours from Sony Corporation.

GARY W. WICKS

It has been quite a year in the field of semiconductor laser research and development. New records were set for both long and short wavelength performance, and low thresholds and high efficiencies. In addition, new and potentially significant lasing materials have been established, and there were even reports on new types of lasing transitions. In short, there has been an unusually high level of significant achievement over the past twelve months. To commemorate these events, here is an overview of some of the highlights of laser diode research in 1996.

Short Wavelengths

Undoubtedly the biggest story of the year has been the emergence of GaN-based lasers. Shuji Nakamura and co-workers of Nichia Chemical Industries [Tokushima, Japan] started the year off with a bang with their January 15 paper[1] demonstrating the first nitride-based laser diode. This first device used an InGaN strained multi-quantum well active region in a GaN core with AlGaN clads grown on (0001) sapphire by MOCVD. Since this orientation of sapphire does not cleave along planes perpendicular to the surface, laser facets were etched by reactive ion beam etching. With high reflectivity coatings on the facets, the device lased at a violet wavelength of 417 nm under pulsed conditions at room temperature with a threshold current density, J_{th}, of 4 kA/cm^2 and a threshold voltage, V_{th}, of 34 V. Both J_{th} and V_{th} were fairly high by diode laser standards, but understandable for a first result. Not only was this the first report of a nitride-based diode laser but, at the time, it also represented the shortest wavelength ever by a semiconductor laser. Since then, however, Akasaki and co-workers of Meijo University [Nagoya, Japan] have achieved UV lasing in these GaN-based materials[2]. Nitride lasers continued prominently in the news all year as incremental improvements were made. The most recent report showed that V_{th} had dropped to 11 V, through improved ohmic contacts, and pulsed lasing up to a temperature of 70°C and continuous (cw) lasing up to T=-40°C had been achieved. It appears that room temperature operation under cw conditions will likely be achieved very soon.

The II-VI material system was the first to provide a shortwave length, bluish-green laser diode. Now, however, it seems almost forgotten due to the enormous level of interest in nitride compounds. Nevertheless, a remarkable leap forward was recorded in this area researchers from Sony Corporation announced in February that they had produced a green ZnSe-based diode laser that operated cw at room temperature with a lifetime of 100 hours[3]. The previous best mark for a II-VI laser had been just 4.5 hours. The Sony laser had a ZnCdSe quantum well active layer and lased in the green at a wavelength of 515 nm. Sony's data over the last few years shows that lifetime is increasing each year by an order of magnitude, which suggests that their target for commercialization, 10,000 hours, is not far away.

Long Wavelengths

Short wavelength lasers attracted the most attention in 1996, but there was also some considerable activity at longer wavelengths. Researchers developing laser diodes for infra-red wavelengths longer than 3 μm reported a variety of new record performance levels, new lasing materials, and, most interestingly, new lasing transitions.

The traditional approaches, which use lead salt or antimonide materials, are still going strong, and new benchmarks for operating temperature and power were established this past year. The new state-of-the-art in IV-VI lead salt lasers was established in a report from Laser Photonics [Andover, MA] of a cw 4.4 μm PbTe laser operating at temperatures up to 223K[4]. This work represented the highest cw operating temperature of any type of mid-IR diode laser. In the III-V antimonide area, researchers at MIT Lincoln Labs reported quantum well InAsSb/InAlAsSb diodes that lase at 3.5 μm. These devices now operate cw up to T = 175K and pulsed up to 250K. At 80 K these devices emit 215 mW/facet[5], which is a new power record for cw power beyond 2.2 μm wavelengths.

But 1996 also provided clear evidence that the lead salts and antimonides are going to face stiff competition from a relatively new direction. Until recently, all semiconductor lasers, regardless of their operating wavelength, relied upon direct band-to-band transitions in bulk material or analogous transitions in type I quantum wells. But rapid progress has been reported this year in mid-IR lasers based on new types of transitions. The most notable examples of these new types of lasers are the quantum cascade laser and the type II quantum well laser. Quantum cascade lasers operate on transitions within the conduction subbands of multiple quantum wells and have been pioneered by Bell Laboratories. Operation above room temperature was recently reported[6] for the first time for a quantum cascade laser emitting at 5 μm in the pulsed mode, and up to T=140 K cw operation. The other new development, the type II quantum wells, involve spatially indirect transitions between neighboring quantum wells. Reports were made in 1996 of type II quantum well lasers in GaInSb/InAs which operate pulsed at 250 K at 3.2 μm[7]. While these new types of lasers are still in the experimental stage, they appear to offer the prospect of more robust construction and higher temperature operation than is possible with the materials which have been used up to this point.

Con't on page 18

Dr. Wicks is a Professor at The Institute of Optics at the University of Rochester, and is the Optoelectronics Editor for Compound Semiconductor

Circle 10 on Reader Service Card

Materials for Red and Near-IR

In the red and near IR, the lasing materials are already mature and highly efficient. Nonetheless, materials improvements continued in 1996 with the further development of aluminum-free lasers. In these structures, the conventional material for the cladding and core, AlGaAs, is replaced with phosphorus-containing alloys such as GaInP and GaInAsP. Lifetime, reliability and high power benefits involve reduced reactivity to oxygen. University of Wisconsin [Madison] researchers have recently reported an aluminum-free laser operating at 980 nm that has a record cw wallplug efficiency of 66%[8].

Additional research in near-IR lasing materials involved quantum dots constructed of strained InAs islands grown on GaAs. The islands grow naturally by MBE if the appropriate growth temperature is selected - no high resolution processing is required. Several groups have reported lasers constructed of one or more layers of quantum dots inserted into the core of an otherwise conventional AlGaAs-based laser[9]. 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). It's too early to tell with these preliminary devices whether such advantages will actually be realized. Size fluctuation in the quantum dots may be one factor that limits their usefulness.

VCSELs

The most popular topic in the area of device design is definitely vertical cavity surface emitting lasers (VCSELs), which are being enthusiastically pursued for optical communication and optical interconnects. They have circular beams and low thresholds, are amenable to 2-D integration and on-wafer testing. 1996 saw the first aggressive commercialization of VCSELs. For example, Hewlett-Packard is offering a transceiver for multi-mode fiber optic data links that uses a 850 nm VCSEL as the light source, and Honeywell Microswitch has begun selling VCSELs as standard catalog items.

Most of the R&D news regarding VCSELs has involved the pursuit of low threshold devices, wavelength tunable devices and efforts to develop VCSELs that operate at longer wavelengths. The latter goal is both particularly challenging and important. Most of the VCSEL work done to date has been on GaAs, and has therefore involved the 0.7 to 1.1 µm region - but most telecommunications applications will require operation at 1.3 / 1.55 µm. Traditionally this has meant that the device must be fabricated from the InP materials system. Unfortunately, the InP-based materials do not provide the large refractive index difference needed to produce the high quality mirrors that VCSELs require. However, recent work has shown that the use of air gaps alternating with InP may improve performance[10]. Another promising approach, demonstrated by the University of California at Santa Barbara and Hewlett-Packard, involves fusing an InP-based active layer between mirror stacks constructed from GaAs-based materials which have the requisite index of refraction[11]. Lasing wavelengths around 1.55 µm have been achieved using this technique.

1996 Semiconductor Laser Highlights

- **1st GaN Laser** - Nichia Chemical
- **Shortest Wavelength Laser** - Meijo University
- **100+ Hour CW Room Temperature Operation of a 515 nm Laser** - Sony
- **Highest Temperature CW Operation (223K) of a Mid-IR Laser (4.4 µm)** - Laser Photonics
- **Highest CW Power (215 mW/facet) for a Mid-IR Laser (2.2 µm)** - MIT Lincoln Labs
- **1st Room Temperature or Higher Operation of a Quantum Cascade Laser**- Bell Labs
- **Pulsed Operation of a Type II Quantum Well Laser** - Multiple
- **Al-free Laser with Record CW Wallplug Efficiency (66%)** - University of Wisconsin
- **Quantum Dot Lasers** - Multiple
- **Long Wavelength VCSELs (>1.3 µm)** - Multiple

Looking Ahead

It has been 35 years since the concept of stimulated emission of photons due to recombination across a p-n junction was first proposed, and next year will mark the 35th anniversary of the first working semiconductor laser diode. Looking back across that period, one sees a steady accumulation of new capabilities. Many of those breakthroughs were enabled by the harnessing of a new materials system, beginning with GaAs/AlGaAs, then the InP-based materials, on up to the more recent demonstrations of mastery over the GaN system. Is it too much to expect that there are still more materials systems waiting to be exploited? Elsewhere in this issue there are reports of two new possibilities. On page 39 there is mention of mixed nitride/arsenide structures, which have the potential to extend the range of wavelengths than can be accessed by diodes grown on GaAs. And on page 34 there is an argument that the addition of thallium to the traditional III-V materials might have a similar effect on InP-based lasers. The practical value of these proposals remains to be proven, but their potential is intriguing.

R&D of semiconductor lasers flourished in 1996. The excitement surrounding the blue nitride lasers seems to have spread to the entire field. And as there are no signs yet of a slow down, look for the rapid progress to continue in 1997.

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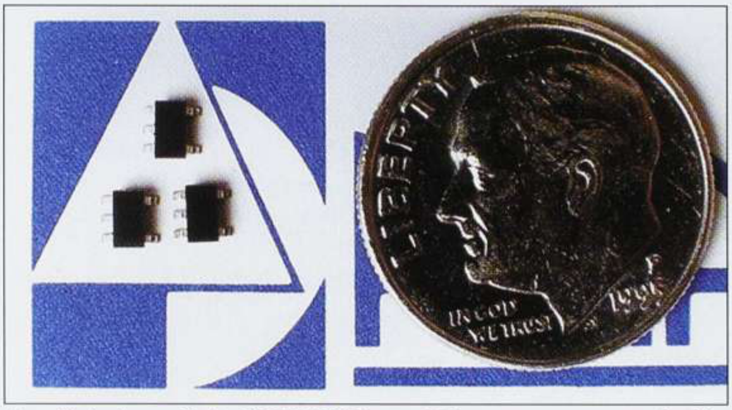
A GaAs Switched Capacitor DC-DC Converter

Anadigics tests a new market with GaAs MESFETs for voltage conversion



Anadigics' new GaAs MESFET Dc-to-DC converters are packed in the small footprint SOT-25 package.

Anadigics is well known as a supplier of analog GaAs components for wireless applications, especially the RF front ends of portable phones. But now the company is trying to use its MESFET technology to gain entry into another niche of the handset market - voltage conversion products. This summer Anadigics introduced a switched capacitor GaAs DC-DC converter, the AVC 7660, which the company says is "the first such product to leverage the advantages of GaAs technology in voltage conversion." The new device offers improved low voltage operation over its silicon competition, and it comes in the world's smallest package. The key to the tiny dimensions is the low ON resistance of GaAs MESFETs, which result in a smaller transistor periphery and reduced die size. According to a company spokesperson, unlike similar silicon converters, which have a clock frequency of 10 kHZ and require 10 μF external capacitors, the Anadigics device runs at 250 kHz, resulting in smaller capacitors, typically on the order of 0.1 to 2 μF. This permits the use of ceramic capacitors, saving cost and space. The high clock rate results in turn-on times of 150 μsec. Anadigics also points out that another advantage of using GaAs over Si is that the low output resistance is maintained at low supply voltages.

The target markets for the new device are said to be any products which operate with a self-contained power supply and where size and/or weight are critical design factors. In practice, Anadigics' strong ties to the wireless equipment manufacturers make it clear that the initial emphasis will be on wireless communications devices such as cordless and cellular phones, and pagers.

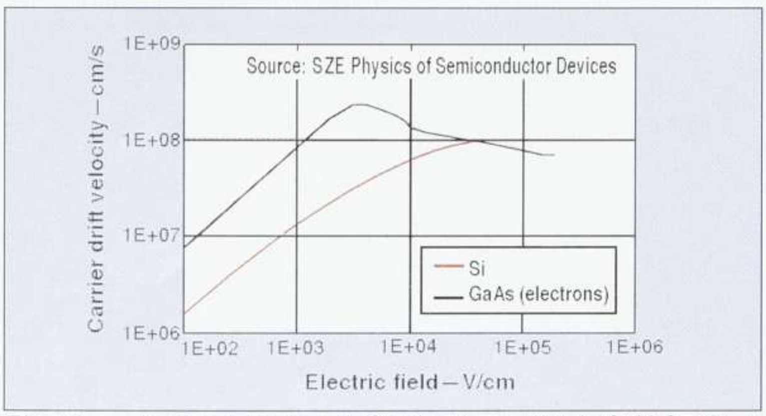


Figure 1. Measured electron drift velocity vs. electric field for GaAs and Si. The higher electron velocity for GaAs leads to low ON resistance for MESFETs, which results in a smaller transistor periphery and reduced die size for switches.

In order to make inroads into the voltage conversion market, Anadigics will need to displace the existing, well-established silicon technology. We asked Robert J. Bayruns, Vice President of Research and Technology at Anadigics, about the prognosis for GaAs's success in this area. Bayruns admits that this new product line is somewhat of an experiment for the company - while Anadigics believes that it has a superior product, there is no clear evidence at this time that the market is actually ready for something new. But the company believed that it would be worthwhile to sample the product and test response - "run it up the flag pole and see who salutes", so to speak. Why take such a chance? Bayruns identified for us several general advantages of GaAs switches and described the products that they hope will have an edge in voltage conversion.

General Advantages of GaAs

The first reason why GaAs MESFETs are a potential candidate for switches is that they are majority carrier devices, which means that they can switch quickly without the minority carrier storage seen in bipolar devices. Of course the same is also true of Si MOSFETs, but GaAs has several advantages over Si for this application.

Figure 1 shows the familiar chart of electron drift velocity (V_{drift}) versus electric field for GaAs and Si. The faster the electrons move, the lower the ON resistance. For high electric fields (>10^4 V/cm) the electrons in both silicon and GaAs saturate, and the advantage of GaAs over silicon is minimized. But when used in a switch with V_{ds} approaching 0 V, GaAs technology is far superior. For the customer, this means a much smaller die than he corresponding silicon chip, enabling packaging in the tiny SOT-25 outline shown above.

GaAs MESFETs can also provide a higher current at a lower voltage than silicon. Anadigics specs the voltage conversion efficiency of the AVC 7660 at 99%. And in terms of switching speeds, a typical 0.5 μm GaAs MESFET has F_t on the order of 25 GHz, which is "essentially infinite compared to switching frequencies of typical applications", according to Bayruns.

The semi-insulating nature of the GaAs substrate, with high resistivity of 10^8 to 10^9 Ω-cm, is also an advantage in this arena, because it results in very small parasitic capacitance. In addition, DC isolation between devices is good, and unlike CMOS, there are no "latch up" conditions. The substrate is grounded and both positive and negative supplies can be routed on chip with no special concerns.

Nichrome resistors with p = 50 Ω/square + 2 percent are used in biasing. GaAs N resistors with 1000 Ω/square are also available. Metal-insulator-metal (MIM) capacitors use silicon nitride and have a capacitance per unit area of 360 pF/mm². The capacitance between plates compared to the capacitance to ground is about 10:1. The ratio for silicon is close to 3:1. Thus in GaAs technology, DC blocking capacitors are very useful even down to several kilohertz operation.

And one last general advantage of GaAs switches: GaAs MESFETs have a Schottky-diode gate which can also be used as a switching diode. Breakdown voltage for the MESFETs and diodes can be as high as 25 V.

DC-to-DC Conversion

Anadigics expects that its GaAs MESFETs will be used as charge-pump DC-to-DC converters and pulse-width-modulated (PWM) DC-to-DC step upconverters and step downconverters. Schematics of these two devices are shown in Figures Two and Three.

Operation of the charge pump is as follows: When signal ϕ_1 is "high", transistors M1 and M2 are switched on, charging the capacitor C_{pump} to $+V_{gen}$. ϕ_1 goes low and ϕ_2 then turns "on" transistors M3 and M4. Transistor M3 grounds the positive plate of C_{pump}, which produces a negative voltage at V_{out}. A stable mulitvibrator oscillator drives an output stage with drives the switching transistors.

A PWM step-up DC-to-DC converter is now under development at Anadigics. Transistor M1 in Figure 3 can be designed to handle up to 5 A and fit into an SO-8 type package. Diode D1 could also be integrated, but will provide an approximate 0.7-V drop, which is a disadvantage compared to Si. Therefore, D1 may remain a discrete device.

Operational amplifiers (opamps) can be made in GaAs which are capable of regulating the 12-V supply to within a +5 percent tolerance. The oscillation frequency will be targeted to be from several to tens of megahertz. Actually, operation at 100 MHz to several gigahertz is possible, but the external components LEXT, CEXT, and D1 will limit the frequency.

While this particular application is new to Anadigics, much of the technology is not. The output transistor (M1), inductor and capacitor used in these converters are the basis for most GaAs power amplifiers that are used in cellular phones. In that arena, GaAs has proven that it provides higher efficiencies than Si at 900 MHz and beyond; similarly, GaAs will have an efficiency advantage over Si DC-to-DC converters at high switching speeds.

A simple model for DC-to-DC converters is a battery of Vdd volts in series with a resistor. As the load current is increased, the negative voltage becomes more positive as voltage is dropped across this output resistor. The low threshold voltage of GaAs MESFETs (typically -0.5 V) allows the Anadigics converter to maintain its output impedance even at low supply voltages. This is important for portable applications that may run off of only one battery cell, such as pagers. Figure 4 shows how the output voltage of the Anadigics converter changes with the load current. A typical Si part is shown for comparison.

Conclusion

Anadigics believes that GaAs technology will be a strong competitor to Si in some voltages conversion applications, because of the advantages it offers: higher switching speeds; smaller and less costly associated circuitry; better performance at low voltages; and smaller packages. With this new product launch they have begun the process of "testing the waters". With a sound technology and manufacturing base, and excellent ties to the manufacturers of wireless equipment, their chances of proving their theory seem very good.

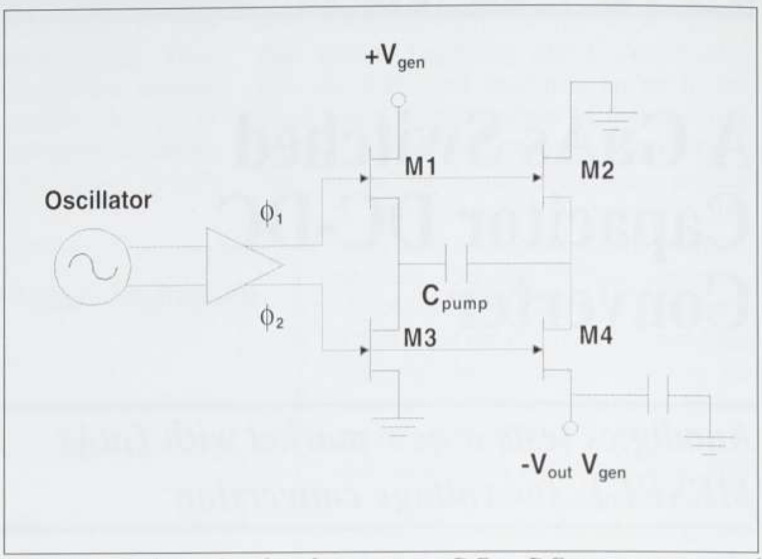


Figure 2. Schematic of a charge-pump DC-to-DC converter, one of the target applications for the new Anadigics device.

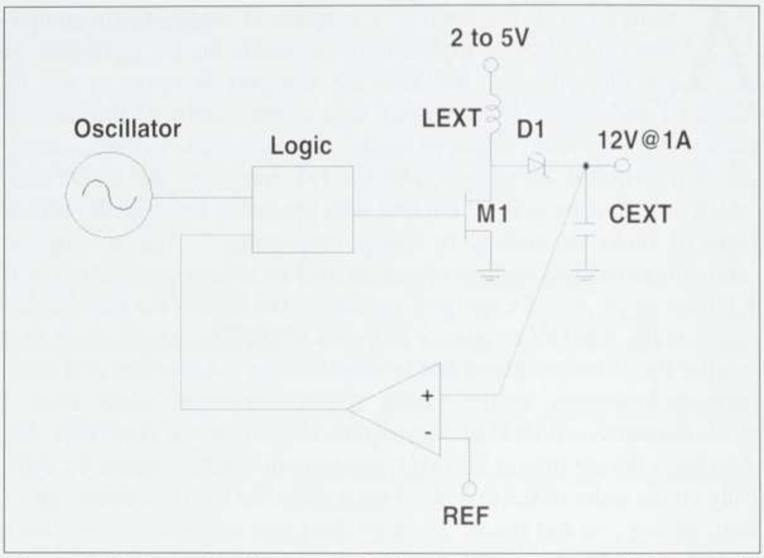


Figure 3. Schematic of a step-up DC-to-DC converter, which is another target application for the AVC 7660.

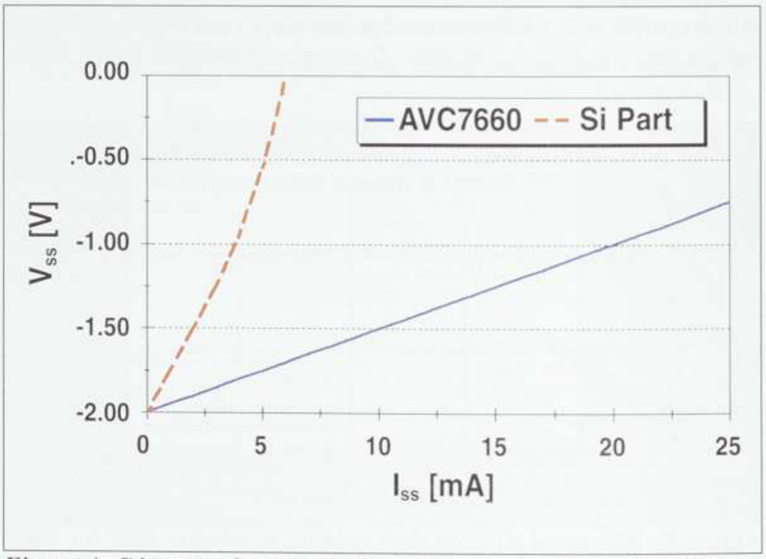
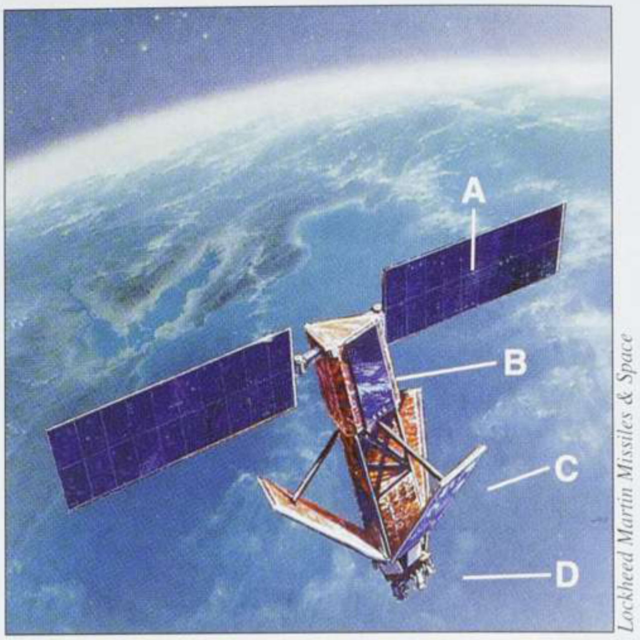


Figure 4. Diagram showing the how the output voltage with 2-V supply changes with the load current for the Anadigics converter in comparison with a similar Si converter.

EMERGENCY
POWER ON
POWER OFF
RESET
SURFSCAN 6220

Flying High: The Commercial Satellite Industry Converts to Compound Semiconductor Solar Cells

They are still more expensive than silicon, but benefits gained at the system level make III-V devices competitive



Artist's rendition of an Iridium satellite. Components include: A = solar panels; B = command module; C = main mission antenna; and D = crosslink antenna (for satellite-to-satellite communications).

MARIE MEYER and ROBERT A. METZGER

This winter, if all goes according to plan, Motorola will make the first space launch for its massive Iridium project, which is a 66-satellite network that is scheduled to begin providing worldwide mobile communications services in 1998. On board each of those satellites there will be 24 square *meters* of III-V material, in the form of GaAs-on-Ge solar cells. And Iridium is not the only GaAs-powered project in the works: experts estimate that between 50 - 70% of all of the commercial satellites now under construction will be equipped with III-V solar cells.

The switch to compound semiconductor solar cells is something of a revolution in the satellite industry. The traditional material of choice has been silicon, because it is lightweight, reasonably efficient, and inexpensive. But improvements in III-V solar cell design, coupled with demand for satellites with more on-board power, have changed the market dynamics in favor of compound semiconductor materials. The transition happened so fast that it may have caught the suppliers by surprise, because by all accounts the demand for GaAs solar cells is currently outstripping supply.

Benefits at the System Level

GaAs solar cells first became a viable option around five years ago. As the technology moved into volume production the price of GaAs solar cells dropped from around ten times the price of Si cells to closer to five times. However, the current shortages, exacerbated by insufficient supplies of Ge substrates (see page 25), are pushing the price ratio back up to around seven or eight to one. See Figure 1. This may be the upper limit for GaAs: according to Klaus Bogus, Head of the Solar Generators Section of the European Space Agency, once the ratio exceeds 8:1, GaAs ceases to be price competitive with Si. However, Bogus believes that GaAs has a promising future because corrections in the Ge substrate supply and increased epi capacity at the manufacturing facilities should improve price competitiveness.

III-V solar cells will never be as cheap as Si on a per/meter sq. basis. However, price parity in terms of surface area is not the goal. Satellite manufacturers are willing to pay a premium for GaAs because of its higher effi-

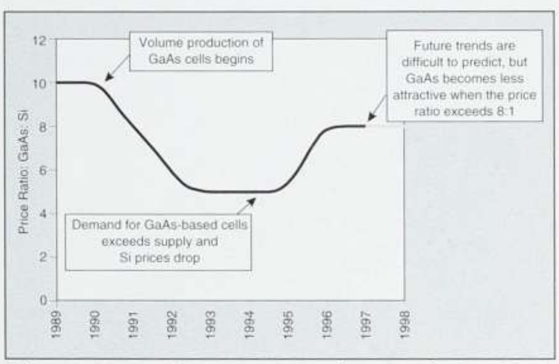


Figure One: Summary of price trends for GaAs and Si solar cells in this decade.

Power (Watts) Per One Square Meter of Solar Panel

Material	Efficiency[2] (%)	BOL Power (W) Un-Irradiated		EOL Power (W)[1] 1 MeV Electron Fluence 3x10^{14} e/cm³		1 10^{15} e/cm²	
		28°C	50°C	28°C	50°C	28°C	50°C
Silicon	14.8[3]	170.9	149.5	129.0	112.2	113.0	98.8
GaAs/Ge	18.5	218.1	208.2	188.1	179.6	166.8	159.3
GaInP/GaAs/Ge	21.5	253.5	242.8	223.0	211.9	192.7	183.0

[1] Mev Electron Fluence [2] Minimum Average Cell Efficiency at 28°C.
[3] Values given for silicon are for the best available commercial product. Less efficient models are also available.

Table One: Comparison of specifications for three types of solar cells offered by Tecstar [City of Industry, CA USA]. The power specifications are for output in Watts (W) for a one square meter solar panel.

ciency. On a laboratory test bench one would likely measure a typical efficiency of ~19% for a GaAs cell and ~15% for a Si cell. Thus the "beginning of life" (BOL) difference between the two is ~25%. But satellite companies base their designs on "end of life" (EOL) specifications, because they need a system that functions properly right through to end of its mission - anywhere from 5 to 15 years for a communications satellite. Because of its wider bandgap, GaAs has superior radiation hardness characteristics and suffers reduced degradation in high temperature operation (in orbit, the typical ambient temperature for a solar panel is ~50°C). Thus its EOL output is 40-60% higher than silicon. And new III-V solar cells based on GaInP/GaAs compounds grown on Ge substrates are now commercially available, providing even better BOL and EOL performance. See Table 1 and Figure 2.

Most commercial satellites share a relatively similar structural framework which allows two wings, each holding up to four solar panels with a maximum dimension of ~2.5 x 3.5 meters for each panel. A satellite designer can take advantage of GaAs's greater efficiency in two ways. One is to make use of the full panel area allowed (~ 70 sq. meters) to provide the maximum amount of power to the system. Current technology can deliver up to 15 kW (EOL value) to the satellite using GaAs, compared to ~6 kW for a Si-powered unit. Among others, Hughes is using this approach to win commercial satellite contracts by offering superior payload power. The other option is to simply use fewer solar panels, which reduces the materials and assembly costs for the satellite, and also reduces its overall weight. Commercial launches currently cost around $20,000 *per kilogram*, so the later factor is clearly important.

Practical considerations, not least of which is the need to mesh with existing commercial launch capabilities, mean that satellite developers will continue to adhere to this framework for the foreseeable future. But there is still need for additional development of solar cell technology. For example: the industry would welcome a high efficiency III-V solar cell that could be grown on substrate which is more readily available than Ge. Silicon would be the obvious candidate, but its use requires that techniques be developed to overcome the lattice mismatch. Also, there may be future requirements for satellites that can exceed the current maximum power supply. Since adding more solar panels is not an attractive option, the best way to achieve this goal is to further increase the efficiency of the cells. Technology which is not currently price competitive, such as InP-based cells, might be able to find a niche here. And, thirdly, the availability of a very rugged solar cell technology would facilitate the use of orbits that intersect the Van Allen belts. These orbits are attractive for commercial reasons, but are extremely challenging for the satellite designers because of particle radiation. Whereas the main body of the satellite can be shielded, the solar cells must, by definition, be exposed, so superior rad-hard characteristics will be needed to exploit this niche. (See page 26 for a more complete discussion.)

Constellations of Satellites

The traditional telecommunications satellite is intended for a geosynchronous orbit (GEO), where from one spot it can "see" around 1/3 of the earth's surface. Iridium, however, is part of a new class of commercial venture, the so-called "satellite network", wherein a chain of interlinked satellites are put into low earth orbits (LEOs)[1]. The surface coverage of each satellite is much reduced, but the time required to transmit data is also reduced, making LEOs well suited for broadband communications. Because of the reduced coverage of the LEOs satellite, more spacecraft are needed - which means that LEO projects could be a huge boost for the entire commercial space industry. Two of the highest profile "big LEO" projects are listed in the table below. The Iridium projects is the furthest along, but there is an even bigger one in the developmental stage: Teledesic, a project which is being developed by Craig McCaw and Bill Gates, requiring a staggering 840 satellites. But even if Teledesic fails to get off the ground, the forecast for the satellite business looks rather good, with plans for several dozen units a year for the next several years. Whether III-V solar cells can hold the majority of the market remains to be seen. The typical power requirements for a LEO satellite are much lower than for a GEO satellite (1-2 kW, as opposed to ~6-8 kW), which may make it easier for silicon to recover lost market share. For now, though, the III-V solar cell business is flying high.

[1] *There is also an intermediate range of orbits call MEOs. See page 26 for a discussion of their use.*

System	Proponents	# Satellites	Orbit Altitude (km)
Spaceway	Hughes	8	35,000 (GEO)
Odyssey	TRW	12	10,350 (MEO)
Immarsat P	Immarsat	10	10,350 (MEO)
Globalstar	Loral/Qualcomm	48	1,390 (LEO)
Iridium	Motorola	66	740 (LEO)
Teledesic	McCaw Cellular	840	700 (LEO)

Table 2. Summary of some of the major satellite communications systems which are under construction or have been proposed.

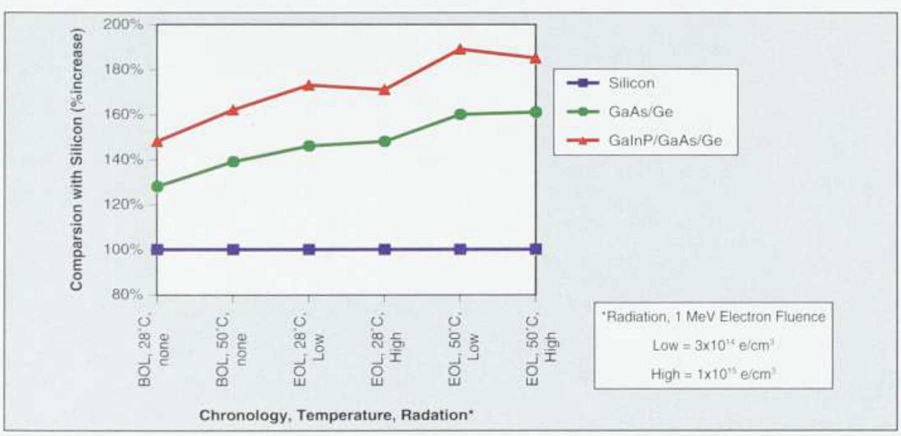
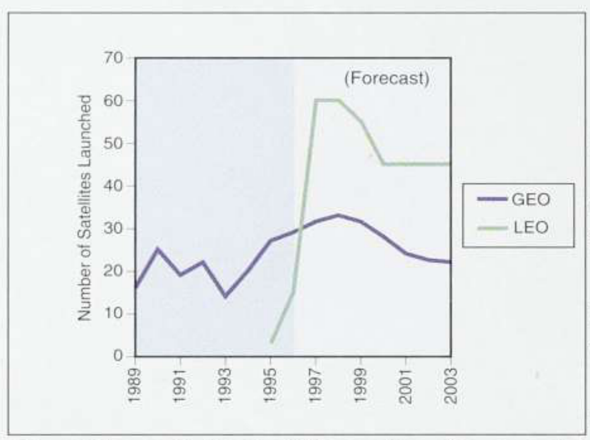


Figure Two: Comparison of the output power of three types of solar cells offered by Tecstar at different times (BOL or EOL), temperatures (28°C or 50°C) and for EOL measurements, radiation levels (low or high).



Sources: Teal Group, The Economist

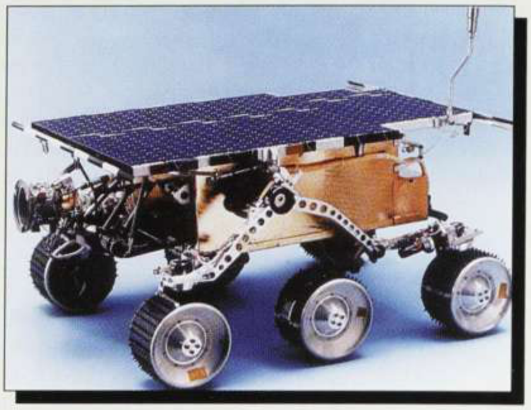
Figure Three: Estimate of the number of commercial telecommunications satellites launched/to be launched for GEO and LEO orbits. The proposed Teledesic project, which would require more than 800 LEO satellites, is not included in the forecast.

Silicon Solar Cell News from Japan

Until recently, Japanese electronics manufacturers have not played a significant role in the U.S. satellite components market. But two recent announcements suggest that some Japanese firms are making in-roads with silicon solar cell technology. **Mitsubishi Electric** has signed a three-year agreement with Space Systems Loral under which it will become the sole supplier of solar panels and heat pipe-embedded panels for the U.S. satellite giant. Mitsubishi reports that as of this fall it will begin shipping to Loral enough silicon-based components to equip a large satellite every month. This is believed to be the first instance of a Japanese manufacturer has supplying a Western satellite leader with key components for commercial satellites on a regular basis. The deal is worth ¥ 2-3 billion ($18.3-27.5 million) for Mitsubishi.

Another leading Japanese company, **Sharp Corporation**, has announced plans to double its production of silicon space-use solar cells from the current levels of 10,000-20,000 units of 4x6cm cells to 20,000-40,000 units. The company claims that its silicon-based solar cells are 1/5 to 1/3 cheaper in price than GaAs-based units and offer a conversion efficiency of about 17%. Sharp estimates that is holds 10-12% of the world's space-use solar cell market, and the company reports that it has signed a long-term supply contract with an unidentified leading U.S. satellite maker and is confident that it will be able to receive orders for solar cells for use in 10 or more satellites annually.

GaAs on Mars?

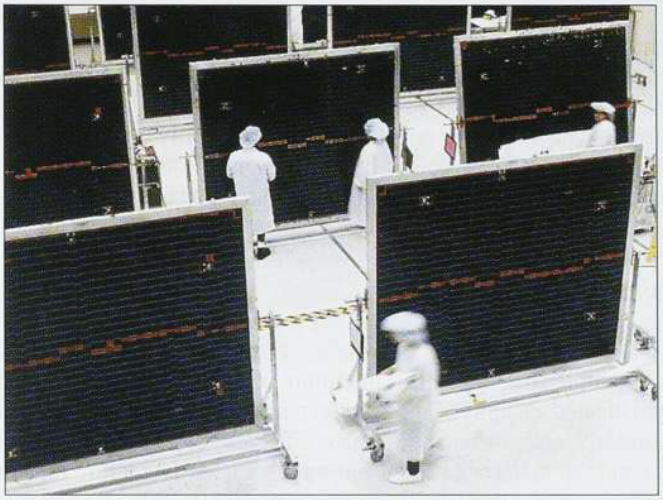


"Life on Mars" has been a popular topic of conversation lately. But how about "GaAs on Mars"? The photo above shows Sojourner, a rover vehicle which will begin exploring the Martian surface during a NASA's mission next summer. This "Mars buggy", which is the size of a large toy truck, is powered by GaAs/Ge single junction solar cells manufactured by Tecstar. The panel employs 234 GaAs/Ge solar cells, delivering 45.2 watts, BOL. The NASA mission, which will be known as "Pathfinder", and the Sojourner project were in the works long before this summer's revelations, but they are now sure to attract a wide following. And for those of you who have a taste for puns: yes, as far as we know, this is the first GaAs-powered vehicle.

Technology Update:

Manufacturing III-V Solar Cells for Space Applications

ROBERT A. METZGER

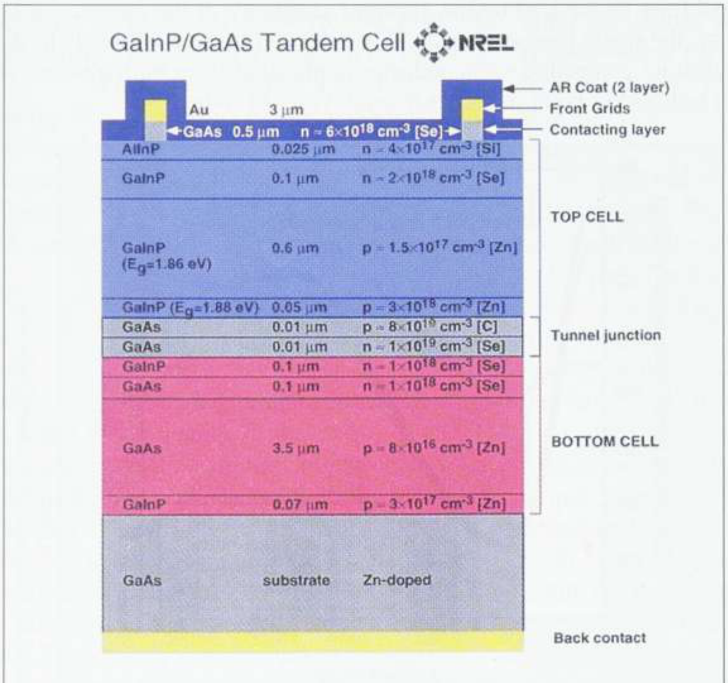


Spectrolab

The final assembly area at Spectrolab, a Hughes subsidiary which is a leading manufacturer of solar panels for satelites.

The basic GaAs solar cell consists of a simple GaAs p-n junction. A unique feature of this application is that the GaAs growth is done almost exclusively on Ge substrates. There are several reasons for using this approach. Ge is structurally more rugged than GaAs, an important issue in manufacturing large area devices (up to 4 inch in diameter), and a valuable contribution to increasing reliability. The latter factor is extremely important, because in the space industry equipment failures can be catastrophic. In addition, the cost of a Ge substrate is typically half that of GaAs - $10/in² as compared to $20/in² for GaAs.

Another unique aspect of solar cells is that unlike the rest of the semiconductor industry, where thousands of devices can be obtained from a single substrate, for solar cell manufacturers a single substrate represents a single device. Grown by MOCVD, these single p-n junction GaAs solar cells typically have an efficiency of 19%, and can deliver 20 mW/cm² of power. At this power density, a 2-10 kW power requirement for a typical satellite translates into a requirement of 10-50 m² of solar cells. Ge substrate sizes used in solar cell manufacturing typically range from 1.5 to 4 inches diameter, with a large number of rectangular substrates also used. If using 3 inch Ge substrates, a satellite which requires 2-10 kW of power would require between 2,000 - 10,000 GaAs/Ge solar cells.



Daniel Friedman, NREL [Golden, CO]

Figure 1. Cross-section of a cascade cell developed at NREL which has demonstrated 25.7% efficiency.

Ge Supplies

The two principal suppliers of Ge substrates are Eagle-Picher [Quapaw, OK] and Union Mineire [Olen Belgium]. Ignace DeRuijter, marketing manager for Union Mineire, says "the Ge substrate market is growing at a dramatic rate, driven by satellite systems, and represents a market of many hundreds of thousands of substrates." Fueled both by increasing Ge demands, as well as decreased Ge stockpiles, the cost of high purity poly-Ge used in the manufacturing of Ge substrates has risen by a factor of 7 in the last 18 months. But DeRuijter says, "because the Ge substrate is a high value added product, the cost of materials only represents 20% of the substrate cost, so these rises in Ge costs have impacted the cost of Ge substrates, but not dramatically".

The explosion of interest in solar cells has been a boon for the manufacturers of MOCVD reactors. The two most prominent U.S. merchant manufacturers of solar cells are Spectrolab [Sylmar, CA], a subsidiary of Hughes, and Tecstar Inc. [City of Industry, CA].[1] Production at these two companies is dominated by the AIX 3000 reactor produced by Aixtron [Aachen, Germany] and the Enterprise 400 reactor produced by Emcore [Somerset, NJ]. According to Egbert Woelk of Aixtron, the AIX 3000s currently being used in solar cell production have a capacity of 270,000 4 inch wafers per year. Tecstar operates three AIX 3000 reactors, and has a fourth on order. Spectrolab currently operates four Enterprise 400 reactors, giving it capacity for 200,000 4 inch wafers per year. However, even that is apparently not enough to meet present demand: the company recently placed an order for three more reactors, which Emcore says will boost capacity to more than 500,000 4 inch wafers per year.

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[1] Other merchant manufacturers include Spire Corporation [Bedford, MA]. In addition, many satellite manufacturers and aerospace companies also have internal, captive solar cell manufacturing capability.

Suzanne McGrath of Tecstar reports that the company will produce the equivalent of 140 kW of solar cells in 1996, most to be delivered as system-level projects, rather than discete devices. That equates to 200,000 3 inch wafers. Taking all these factors into account, it appears that the Ge substrate consumption is currently around 300,000 to 500,000 substrates a year, with sizes ranging from 1.5 to 4 inch. Thus this application represents a substrate market of some $30-50 million/year - similar in size to the entire market for GaAs substrates.

Cascaded Designs

As noted earlier, the III-V solar cells which are currently in use are fairly simple structures. But the future of the market may lie with more sophisticated designs. The next generation of products will likely be "cascaded" cells, where up to three different p-n junctions, using different bandgap materials in order to more efficiently capture the sunlight, are used to make the cell. Tecstar reports that in 1996, 10% of their production will be in cascaded cells, and this figure should grow to as much as 30% in 1997. Figure 1 shows a typical cascade cell design. This device, produced by researchers at the National Renewable Energy Laboratory (NREL) [Golden, CO], has produced a record efficiency of 25.7%, at 1 sun concentration and air mass AM0. It consists of a top GaInP p-n junction which has a bandgap of 1.85 eV, and a bottom GaAs p-n junction with a bandgap of 1.42 eV. The two junctions are connected in series through a low resistance GaAs tunnel junction which is formed by heavily doped p and n-type regions. This cell represents an increase in efficiency of 6% over production single junction cells, and could be used to build a panel with only 77% of the area of a panel using a standard single junction cell, while delivering the same power. This would result in significant weight reduction of the satellite, which in turn would reduce launch costs. Even more sophisticated cells are being investigated. Triple junction cells, in which a Ge p-n junction is placed beneath the GaInP and GaAs p-n junctions, and once again connected in series through a GaAs tunnel junction, have been fabricated at Spectrolab. This device is projected to have an efficiency of 26.5%, which represents an increase in efficiency of 2.3% over Spectrolab's production double junction cell.

The next generation of products will likely be "cascaded" cells, where up to three different p-n junctions, using different bandgap materials in order to more efficiently capture the sunlight, are used to make the cell. Tecstar reports that in 1996, 10% of their production will be in cascaded cells, and this figure should grow to as much as 30% in 1997.

Future Materials

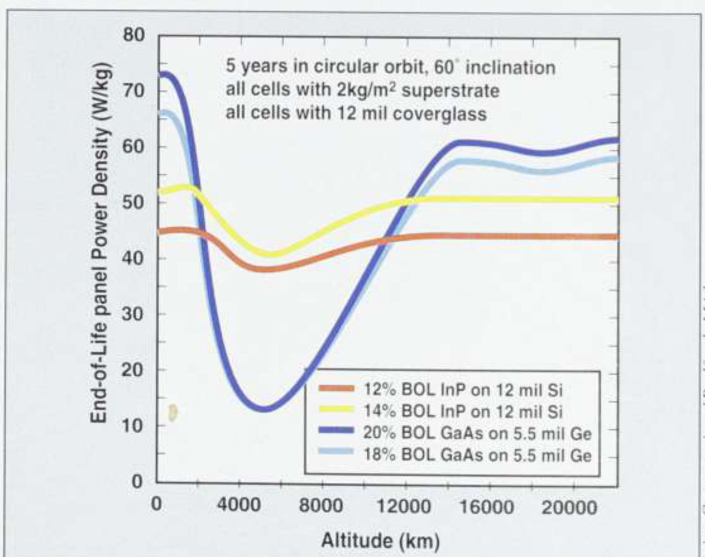
The previous article made the distinction between the traditional geosynchronous orbits (GEOs) and the newly popular low earth orbits (LEOs). See page 23. But for satellite communication systems, when taking into account such things as satellite coverages, launch costs as a function of orbit altitude, and transmission delays, it is quite possible that the optimum orbits are those in the 2000 to 10000 km range, known as medium earth orbits or MEOs. The problem with MEOs is that they are in the midst of the Van Allen radiation belts. Despite their superior radiation tolerance, even GaAs cells quickly degrade in this region of space.

A possible solution for high radiation environments is InP/Si solar cells. InP exhibits even higher radiation tolerance than GaAs, and the use of Si as a substrate offers major cost and weight savings compared to Ge, GaAs or InP. In addition, Si offers superior mechanical toughness. The obvious difficulty with this approach is the 8% lattice mismatch between Si and InP, which results in large levels of dislocations generated in the InP p-n junction.

Researchers from Spire [New Bedford, MA], working in a program sponsored by the U.S. Naval Research Laboratory, recently reported[2] an InP/Si cell which shows BOL efficiency of 12%. This performance is 6-7% less than InP p-n junctions grown on InP. However, the InP/Si cells still shows promise, because they are extremely radiation tolerant. Radiation induces damage which increases the recombination time of the electron-hole pairs in the cells, thereby effectively reducing the diffusion length of the carriers and degrading efficiency. The dislocations and defects in the InP/Si cells have the same effect on carrier diffusion lengths as does the damage induced by radiation. Therefore, it could be said that the InP/Si cells are "predamaged", so that radiation can do little to further degrade performance. Figure 2 shows the calculated EOL power density for 12-14% BOL InP cells grown on 12 mil Si wafers vs. 18-20% BOL GaAs cells on 5.5 mil Ge wafers.[3] Despite the higher BOL figures for GaAs cells, after 5 years in orbit the EOL power density, calculated as output power/kg, is significantly higher for the InP/Si cells in the high radiation MEO orbit.

Lattice mismatch is not the only problem facing the InP/Si approach. Another concern is that cracking may result in these cells during thermal cycling. Researchers at Tecstar, under another NRL program, are investigating the growth of InP/GaInAs/Ge solar cells. In these structures the In content in the InGaAs region is graded from very small levels at the Ge substrate (to improve lattice matching to the substrate) to larger levels prior to InP growth ($Ga_{1-x}In_xAs$ is lattice matched to InP at x=0.53). In this way, the strain and resultant dislocations are distributed over a wider volume of material, and cracking may be avoided.

Further enhancements, based on even more sophisticated epi layers, seem likely. For example, Dieter Zemmrich, President of Spectrolab, reports that his company is developing a quaternary-based solar cell that may provide >33% efficiency. Thus it appears that one should not be mislead by the apparent simplicity of the current workhorse, the single junction device. The solar cell market will likely be an interesting compound semiconductor application from both a business and technology point of view for many years to come.



Spire Corporation [Bedford, MA], 25th IEEE Photovoltaic Specialists Conference.

Figure 2. End-of-life (EOL) power density for InP/Si cells in comparison to GaAs/Ge cells as a function of altitude.

[2] *25th IEEE Photovoltaic Specialists Conference [Washington, DC, May 13-17, 1996].*

[3] *Because Ge is almost twice as dense as Si, the cells weigh approximately the same.*

High Efficiency III-V Solar Cells

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The conversion of sunlight to electricity provides a clean, inexhaustible energy resource. There are several markets, most notably the space-satellite market, in which photovoltaics are the preeminent power source. Solar cell research and development is making major strides in lowering the cost and increasing the efficiency of these devices, expanding the economic viability of photovoltaic power. This article will describe the workings of a solar cell, with an emphasis on leading-edge III-V-based cell technologies.

Solar Cell Principles

A solar cell is a large-area pn junction which when exposed to light will efficiently separate photoexcited hole-electron pairs. A simplified schematic of a solar cell is shown in Fig. 1. When connected to a load the light energy is converted to electrical energy. The current-voltage relationship for an ideal single-junction solar cell is given by the familiar diode equation with addition of a light-generated current term J_L:

$$J = J_{0n} (\exp(qV/nkT) - 1) - J_L \quad (1)$$

where J_{0n} is the dark saturation current density, n is the diode quality factor, and q, k and T have their usual meanings. Figure 2 shows a plot of the solar cell current-voltage (J-V) relation, eq. 1, for an idealized GaAs solar cell. The plot shows the quadrant in which power is sourced rather than sinked. The point on the J-V curve at which this power (per unit cell area) is maximized, (J_{mp},V_{mp}), is noted on the figure. It is also useful to summarize the J-V curve in terms of the open-circuit voltage V_{oc}, the short-circuit current J_{sc}, and the fill factor FF. The FF term, which is defined as $FF=J_{mp}V_{mp}/(J_{sc}V_{oc})$, is a measure of the squareness of the J-V curve, and generally ranges from 0.25 for low efficiency cells to 0.9 for ideal cells. The power output is then $P_{mp} = J_{mp}V_{mp} = J_{sc}V_{oc}FF$ and the efficiency of the device $\eta = P_{mp}/P_{in}$ where P_{in} is the incident energy flux.

The light-generated current, $J_L = J_{sc}$, is proportional to the number of photons converted to hole-electron pairs. Figure 3 shows an "air mass 1.5 global" solar spectrum representative of what a solar cell might see under typical atmospheric conditions on the surface of the earth. The total incident energy flux P_{in} in this spectrum is about 1 kilowatt/m^2. (The "real" solar spectrum depends on atmospheric conditions, time of day, and geographic location.) The shaded area in Fig. 3 represents the photons whose energy is greater than the GaAs bandgap of 1.42 eV, and thus would be available for conversion into current by a GaAs solar cell. Photons with energy in excess of E_g are absorbed but the excess energy, $h\nu - E_g$, is lost to heat. Photons below bandgap are not absorbed, and therefore do not contribute to J_L or the power output of the solar cell. The photovoltaic conversion efficiency for this spectrum as a function of solar cell band gap is broadly peaked at about 1.4 eV, quite close to the band gap of GaAs. A solar cell with a smaller band gap will absorb a larger portion of the solar spectrum, giving a high output current. However, this high current comes at the expense of inefficient conversion of the above-bandgap light energy, and, as a result, the voltage of the device is low. In contrast, a higher-bandgap solar cell will have a higher V_{oc} but lower J_{sc}. This tradeoff between output current and output voltage represents a fundamental efficiency limitation for a single-junction device.

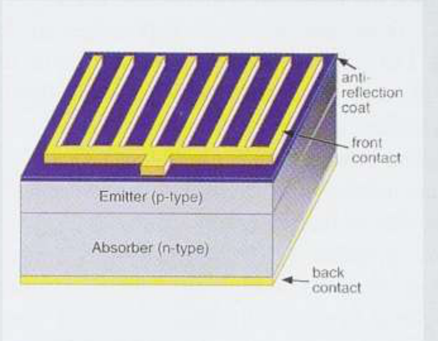

Figure 1. Schematic of a typical single junction solar cell.

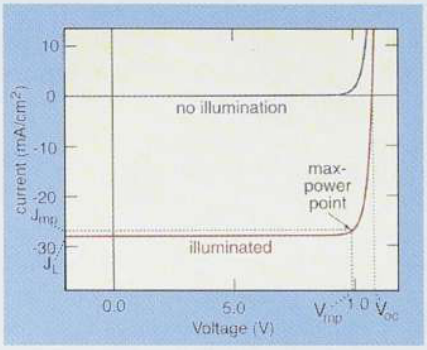

Figure 2. Ideal J-V characteristics of a GaAs solar cell.

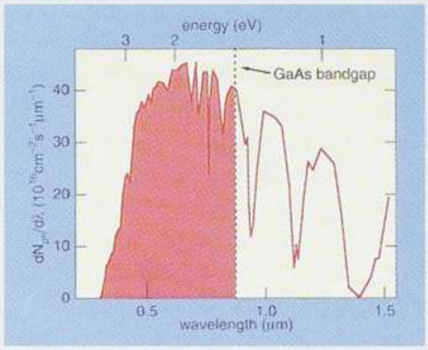

Figure 3. Standard air mass 1.5 global solar spectrum. Shaded area shows th photons absorbed by a GaAs solar cell. The yields more than 28 mA/cm² for a state-of-the-art GaAs solar cell.

Solar Cell Design

Most single junction solar cells are one sided step junctions in which the bottom "absorber" component of the junction is lightly doped to maximize the minority carrier diffusion length, while the "emitter" or window component is more heavily doped to minimize series resistance losses. The back or "dark side" of the device is usually coated with a continuous metal contact and the "sunny side" contact is usually a metal grid. The metal grid (width and spacing) and emitter doping are designed to yield the optimum J_{sc} and low series resistance. The top surface of the cell is generally covered with an antireflective coating to reduce the reflectance and boost the J_{sc} by 30% or more.

There are two basic approaches to the fabrication of solar cells: (1) The cell is deposited as a thin film on an inexpensive substrate such as glass or sheet metal which usually results in an amorphous or polycrystalline structure. Although thin film cells based on II-VI semiconductors have recently exceeded 17% (AM1.5 global) in the lab, large area modules are currently only about 8-11% efficient. (2) The solar cell junction is fabricated on or in a high quality, single crystal substrate. This approach is dominated by silicon- and GaAs-based solar cells and the emphasis is on high efficiency. GaAs cells are 5 times more expensive than Si solar cells (mainly because of substrate costs); both are considered too expensive for large-scale, flat-plate applications and are more appropriate for space satellite power and concentrator systems (*vide infra*).

The highest single junction efficiencies achieved to date for the most common semiconductor materials are summarized in Table 1. Efficiencies as high as 25.7% for a single junction GaAs cell have been demonstrated.

Multijunction Solar Cells

Over the last 15 years, multijunction or tandem solar cells have attracted increasing attention. They are designed to reduce the two major loss mechanisms in a single junction solar cell: the loss of photons for $h\nu < E_g$ and the thermalization loss of hot photocarriers for $h\nu > E_g$. Several solar cells with different band gaps are configured in an optical stack so that the incident light interacts sequentially with cells of decreasing Eg. The top-most cell absorbs and converts the high energy portion of the spectrum and transmits lower energy photons to the underlying cell(s) with lower E_g. Optically buried cells absorb and convert increasingly longer wavelength, lower-energy photons. The thermalization losses are minimized by converting photons in cells where $h\nu \approx E_g$. The optical stacking can be done in several ways as shown in Fig. 4. Two (or more) separate cells can be stacked mechanically; e.g., a GaAs cell (with transparent back contact) is stacked on GaSb cell and separate electrical connections are made to each of the terminals. Mechanical stacks can be very efficient but are also more expensive due to the extra cost of the additional crystalline substrate materials; the mechanical and electrical complexity also adds to the cost of integration into a module. A less costly but more challenging configuration is the monolithic tandem solar cell, where each subcell is grown directly on the underlying subcell. The subcells can be interconnected or contacted using standard integrated circuit processing techniques or interconnected using monolithically integrated tunnel junctions. Three-terminal arrangements are also possible but have not been researched or used extensively. A summary of the best results for tandem cells obtained to date is shown in Table II. The GaInP/GaAs tandem cell (shown on page 25) is the only multijunction device on the market today. Invented in 1984 at the National Renewable Energy Laboratory and developed over the years at NREL and other industrial labs, it has proven to be both highly efficient[1] and very adaptable to several applications.

The efficiency of two-terminal monolithically interconnected tandem solar cells is a sensitive function of the subcell band gaps. While the tandem V_{oc} is the sum of the subcell V_{oc}s, the J_{sc} is limited by the smallest subcell J_{sc}. For a given bottom subcell (usually determined by the choice of the crystalline substrate) the high conversion efficiency occurs for some optimum top cell E_g, which depends on the solar spectrum. If the top cell E_g is too large, it does not absorb enough of the solar spectrum and the tandem cell current is limited by the photocurrent generated in the top cell. If the top cell E_g is too small, its J_{sc} is high, but it also limits the amount of light getting to the bottom cell. In this case the tandem cell current is limited by the lower bottom cell J_{sc}. When the top cell E_g is less than the optimum E_g, one can "tune" the tandem cell current to its optimum by reducing the thickness of the top cell[2]. The optimal top cell thickness depends on the solar spectrum and the electronic quality of the subcells. Furthermore, for space solar cells these tandem cells can be tuned to yield more radiation resistant cells. For example, by simply thinning the GaInP top cell, GaInP/GaAs tandems can be made almost as radiation resistant as single junction InP solar cells.

Terrestrial Applications

The current world-wide terrestrial market is currently about 84 MW per year, mostly for remote stand-alone applications. These include water pumping, cathodic protection, communications, lighting and small appliances and power for remote villages. "Flat plate modules" of solar cells are ideal for these stand alone applications. When high reliablity, low maintenance, portability, and clean noiseless operation are important, PV is clearly superior to other stand-alone power generators. As the manufacturing costs decline and the cost of fossil fuels rises, the market is expected to expand from these stand-alone applications to what is termed "grid support", including large-scale central power generation,

Cell Material/Structure	Efficiency	Affiliation
GaAs/GaInP heterojunction*	25.7%	NREL
InP homojunction*	21.9	Spire Corp.
Si homojunctions	24.0	University of New South Wales
CuInSe/CdS+	17.7	NREL
CdTe/CdS†	15.8	University of South Florida
amorphous Si	12.7	Sanyo

*crystalline
†polycrystalline

Table I. Record single-junction solar cell efficiencies. AM1.5 global spectrum, 1000 W/m², 25°C.

Cell Materials/Structure	AM0	AM1.5G	Affiliation
GaInP/GaAs, 2-terminal		30.3%	Japan Energy Corp.
GaInP/GaAs, 2-terminal	25.7%	29.5	NREL
GaInP/GaAs/Ge, 2-terminal	25.7		Spectrolab
AlGaAs/GaAs, 2-terminal		27.6	Varian
GaAs/Si, 3-terminal	19.9		Nagoya Institute Technology
GaAs/CuInSe2 (thin film), 4-terminal		25.8	Kopin/Boeing

Table II. Record multijunction cell efficiencies measured at 25°C.

transmission and distribution support, and peak-demand management.

A promising approach for such large-scale applications in suitably cloud-free locales is the use of large-area mirrors or lenses to concentrate light onto a small solar cell. This "concentrator" technology reduces the cost of the solar cell relative to the total system cost by the degree to which the light is concentrated, a factor typically in the range of 20X to 1000X, making the use of highly efficient but expensive cells (tandem cells are especially suitable for this application) economically plausible. Very high system efficiencies can thus be obtained. For example, the generation of 1000 MW using a 10%-efficient flat-plate solar cell technology would require a total cell or aperture area of about 10,000,000 m^2 or about 4 mi^2. This real estate area is reduced by more than half with the use of concentrators which operate at greater than 20% efficiency. But more importantly the active cell area required for 1000MW is reduced by a factor equal to the concentration ratio(aperture area to cell area). Hence a 1 GW, 1000X concentrator system requires less than 5000 m^2 of cell area. Currently, both Tecstar and Spectrolab have annual capacities close to this number!

Photovoltaics - The Power of Choice

It sounds like science fiction - a clean, quiet, and inexhaustible energy source. But it's a reality today, and the rapid advances in compound semiconductor technology are helping to make it happen.

References

[1] K. A. Bertness, S. R. Kurtz, D. J. Friedman, A. E. Kibbler, C. Kramer, and J. M. Olson, *29.5%-Efficient GaInP/GaAs Tandem Solar Cells*, Appl Phys Lett 65, 989-991 (1994).

[2] S. R. Kurtz, P. Faine, and J. M. Olson, *Modeling of two-junction, series-connected tandem solar cells using top-cell thickness as an adjustable parameter*, Journal of Applied Physics 68, 1890 (1990).

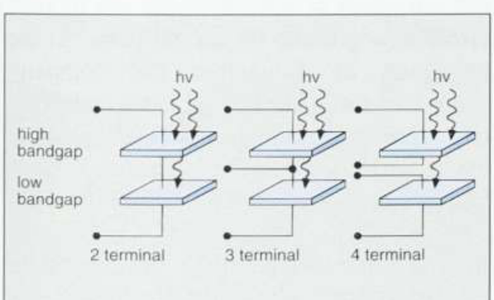

Figure 4. Possible terminal configurations for two-junction solar cells.

Fantastic Plastic, Part One:

Polymer-Based Displays

Polymer electronics could give conventional display technologies a run for their money - one day

An example of a polymer LED dot matrix display produced by CDT.

MICHAEL KENWARD

The future lies in plastics. This was the advice to the young hero in *The Graduate*, the movie that launched the career of Dustin Hoffman in 1967. It is also now the view of a growing number of people making electronic displays. Just a few years ago light emitting polymers (LEPs) were little more than a scientific curiosity. But now, in the wake of rapid scientific progress, researchers now see a bright future for displays built around relatively large organic molecules. Solve the scientific problems, and polymers offer distinct advantages over semiconductors.

Lifetimes

The most significant attraction of polymers is that they are easier to process. They do not need billion dollar foundries. Instead polymer processors can turn to techniques developed by the plastics industry, which turns out parts by the million at a cost of cents. Polymers can be spin coated from solution at room temperature. Polymers are also light and flexible and can be incorporated into novel designs. Liquid crystal or plasma displays require thin film processing on two glass plates. LEPs, on the other hand, can be fabricated on one sheet of glass or plastic. This greatly simplifies processing and reduces cost. In addition, the fabrication process is, at least in theory, infinitely scaleable. And the ability to manufacture devices on flexible plastic substrates will make it possible to create "conformable" displays - displays that match the shape of the product, rather than the other way round.

Polymer-based displays may even challenge compound semiconductors some day. This magazine recently ran an article detailing how full colour LED-based displays are constructed by assembling pixels from groups of discrete LEDs. (*CS* 2(3), p. 32). But it is hoped that polymer technology will someday allow the formation of large area flat panel displays which are essentially monolithic - one large "device", with the pixelization formed by sophisticated patterning of the electrodes.

But before anyone can exploit the advantages in processing and design that polymers offer, the materials have to match the performance of modern semiconductors. In particular, they have to achieve the lifetimes that are expected of semiconductor components. The lifetime issue is "still under debate for polymeric systems," says Dr Heinz von Seggern, who is responsible for research on polymer electroluminescent systems at Siemens. The target is 10,000 hours. There have been reports of lifetimes of several thousand hours, and earlier this year Kodak reported lifetimes of 6000 hours for an organic light emitter.

The European Connection

Polymers have already proved to be effective as diodes, LEDs and field-effect transistors (FETs). Not only have lifetimes risen, brightness is also on the increase. And polymer LEDs, the focus of much of the current activity, can now deliver light at a range of wavelengths.

The technology of polymer electronics has reached the stage where it has escaped from the academic laboratory and is attracting the interest of mainstream electronics companies. Perhaps more telling, venture capital is flowing into start up companies set up specifically to turn the science into money making technology. And European electronics companies may have the early lead. Perhaps helped by the proximity of one of the world's leading research teams in the subject, at Cambridge University in England, both Siemens, and Philips maintain an R&D effort in the subject.

Both companies have targeted displays as the first applications for polymer electronics. At Siemens, for example, the aim of the company's research effort is not to devise new materials, but to turn those coming out of research into working devices. "We are trying to use organic materials in electronic displays," says von Seggern. Potential uses include backlighting for the keys on mobile telephones, for example, or liquid crystal devices (LCDs). The driving force here, says von Seggern, is the move to attach displays to just about any piece of electronic equipment. "The display will become a very important item in the electronics business," he explains. Every electronic instrument will have some sort of display of its status. LEPs are attractive for such applications, especially in comparison to LCDs. "The nice thing about the electroluminescent materials for LEDs is that they are self emitting," he continues. They also have the edge over conventional back lit LCDs, which are hard to see from an angle.

Philips Components is also interested in polymers for displays. The company's corporate laboratory in Eindhoven has run its own research programme for several years. At the beginning of September the company announced that it has entered into a collaborative agreement with Cambridge Display Technology (CDT). The agreement gives Philips non exclusive access to CDT's patented light emitting polymer (LEP) technology. In their joint announcement, the companies said that "The initial target for the coming years is to replace the existing backlights for LCDs in applications where space, low voltage and low power consumption are at a premium, such as in mobile telephones." In the next phase Philips hopes to develop displays for application in consumer products that currently depend on LEDs or LCDs, such as Personal Digital Assistants (PDAs), CD players, electric razors, alarm clocks, radios and, ultimately, television sets.

CDT, the company that is helping Philips to achieve these ambitions, is a rare venture for Europe. It is the creation of a leading academic research team, led by Richard Friend and Andrew Holmes, both of Cambridge University. They were part of the team that first reported light emitting polymers in a scientific paper published in 1990[1].

The focus of the research at Cambridge is a family of materials known as conjugated polymers. In particular, they work with a compound known as PPV (poly p-phenylenevinylene). Conjugated polymers have a delocalised pi-electron system along the polymer backbone. This electron system gives the materials their semiconducting properties by supporting electron and hole transport along the polymer chain. (See "How Do They Work?", page 32.)

LEDs and Lasers

The Cambridge University team found that they could persuade PPV to emit yellow-green light by sandwiching it between two electrodes. At first the material was just an academic curiosity. Its efficiency at turning electricity into light was tiny, less than 0.01 per cent. By changing the chemical composition of the polymer and the structure of the device, they have pushed this to 5 per cent, which brings it into the range of conventional LEDs. These improvements have come about by borrowing device engineering techniques learnt during the improvement in efficiencies of traditional compound semiconductor LEDs. While most of the work to-date has been in the yellowish-green (around 550 nm), red and blue light emitters have also been produced.

Most recently the Cambridge group has reported that it created microcavities from PPV[2]. In this the researchers demonstrated optically pumped laser activity in PPV. The scientists admit that they have a long way to go to make it easier to inject charge into PPV in these systems. However, they believe "the quality of present polymers has reached a point where they can be considered as electrically pumped lasers for highly demanding device applications".

Commercialization

CDT's role in the development is to exploit the academic research commercially. The company, set up in 1992, currently employs around 20 people, three quarters of them involved in research. CDT's strategy is to enter into licensing agreements with Philips and other companies access that wish to gain to its patented technologies. "For CDT to be successful, it is essential that we globalise LEP technology," says Chapchal. "This means that we must license the major consumer display manufacturers and chemical companies. As global leaders in this market, I am delighted that Philips is our first consumer licensee. Partnership is key to the commercial exploitation of LEP technology and lies at the core of our business strategy."

There had been some hope that CDT would set up a full-scale manufacturing effort in Britain. It now appears, however, that this will not happen. Instead, CDT has opted to fill the role of a "centre of excellence" for LEP technology, concentrating on developing the technology and then transferring it to established manufacturers.

CDT believes that over time, LEP technology could replace the cathode ray tube. "The potential for light-emitting polymers is immense," says the company. It is aiming to carve out a share of a market forecast to exceed $42 billion by the year 2000. With the right polymer properties, it should be relatively simple to produce large display screens. Devices will consist of just three or four layers on a substrate, with two electrodes sandwiching two polymer layers. Pixels are created by patterning the electrodes.

In May, CDT gave what it described as "the world's first public demonstration" of a prototype LEP dot matrix display at the Society for Information Display meeting in San Diego. This came hot on the heels of the world first's public demonstration of LEPs as backlighting for LCDs at the Flat Information Displays Conference in San Jose, California in December 1995. The company has also reported that it had achieved lifetimes of over 9000 hours (determined by how long it took for the brightness to fall by 50 per cent). It should be noted, however, that the "record setter" was designed specifically for longevity, and was not a particularly bright device.

While the ultimate target is the flat screen graphics displays market, to begin with CDT plans to concentrate on mobile communications, personal data assistants (PDAs), and head-up displays, including virtual reality. The state of play with LEPs is hardly likely to cause any short-term concerns for semiconductors. On the other hand, recent progress has been rapid. And the growing interest of some of the major electronics companies means that it would be unwise to ignore the technology.

References:

[1] *Nature, vol 347, p 539.*

[2] *Nature, vol 382, p 695.*

In our next issue:

"Fantastic Plastic, Part Two" reviews the status of polymer laser diodes.

Polymer LEDs and Displays:

How Do They Work?

Just about everyone knows that plastics can serve as insulators. Less well known is the fact that for more than 30 years there has been steadily growing interest in exploiting the electrical properties of polymers. The class of plastic materials for which semiconductor characteristics can be observed are conjugated polymers. These are polymers which possess what is known as a "delocalized pi-electron system" along the polymer backbone. This concept is illustrated in Figure 1. In essence, whereas a typical carbon molecule has four electron bonds, the conjugated polymers have two or three, leaving spare electrons that can join a cloud of electrons above and below the polymer chain. These clouds of electrons support positive and negative charge carriers - holes and electrons - with high mobilites along the polymer chain. The semiconductor properties of conjugated polymers arise from the overlap of pz orbitals. If the overlap is over several sites, the formation of well delocalized pi (bonding state) valence and pi* (anti-bonding state) conduction bands occurs, with a defined bandgap. The bonding valance band state and the anti-bonding conduction band state are analogous with III-V semiconductors, and they provide the recipe for semiconductor behavior.

Like compound semiconductors, conjugated polymers provide opportunities for "bandgap engineering" through the use of heterostructures. In III-V materials one achieves this by forming different compositions of ternary and/or quaternary compounds from a limited range of possible materials. The largest constraint in this area is the need for lattice matching, to avoid debilitating defect density levels. The situation is somewhat easier in the polymer case, because many materials can be made through varying polymer chemistry (e.g. the addition of sidegroups to shift the band-gap). In addition, the heterostructure is effectively amorphous, and the defects tend to have energy states outside the bandgap. Also there are no dangling bonds, and the interfaces are, therefore, not as sensitive to the environment, which simplifies the growth process.

Figure 2 shows a schematic of a polymer heterostructure which is a reasonably efficient light emitter, and Figure 3 shows a schematic of a simple device structure based on it. It has been 5 years since the first reports of LEPs with internal quantum efficiencies of 0.01% were made; in that time, efficiencies have improved by about 4 orders of magnitude. This progress has been made, in part, by taking advantage of the lessons learnt in III-V device development. In particular, the use of a heterostructure that allows carrier confinement at the polymer/polymer interface is significant. This increases the likelihood of electron/hole capture to form an exciton that can radiatively recombine. Other significant improvements arise from making the electron/hole injection barriers similar - this can be done through both the choice of the injection electrode material and by using a polymer material which has a higher or lower electron affinity. In the example shown in Figure 2 the cyanoPPV group has a higher electron affinity, and therefore pushes down the barrier to electron injection. In other words, using conventional semiconductor language, it acts as an n-type layer. Recombination of holes and electrons occurs across the interface, with the emission occurring in the cyanoPPV layer, because of its lower bandgap. Thus the diode shown in Figure 2 would produce orange-red light, instead of the green emission that would occur if the active layer were made from PPV.

The principal disadvantages of conjugated polymers are lifetime and mobility. Mobilities are low due to the largely amorphous nature of conjugated polymer films. Fortunately, this is not a constraint in the formation of diode devices, but solutions such as more ordered deposition or doping will need to be applied if transistor applications are to be pursued. More important in the short term is the issue of lifetime. Much work has taken place over the last 50 years to improve the resistance of everyday polymers to photooxidation, principally through the use of additives to prevent discoloration. It should come as no surprise that similar problems exist with conjugated polymers: the tendency to oxidization is greatly increased by the presence of excited states, and the presence of excited states is, of course, the key to creating the material's electronic properties in the first place. Storage lifetimes of at least 5 years and operating lifetimes of >20,000 hours are typically required. To meet these goals, significant activity is taking place to both develop materials that are more resistant to chemical degradation such as oxidation and through improved encapsulation.

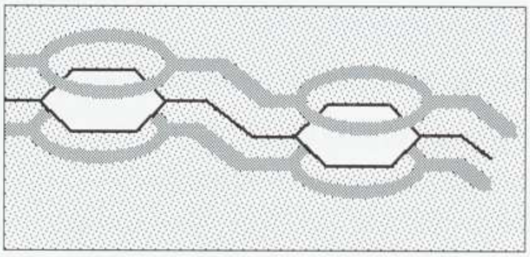

Figure 1. Conceptual drawing of a conjugated polymer, showing that the overlap of Pz orbitals leads to the formation of a delocalized pi electron cloud above and below the polymer chain. (The electron clouds are represented by the gray lines; the polymer chain is represented by the black line.)

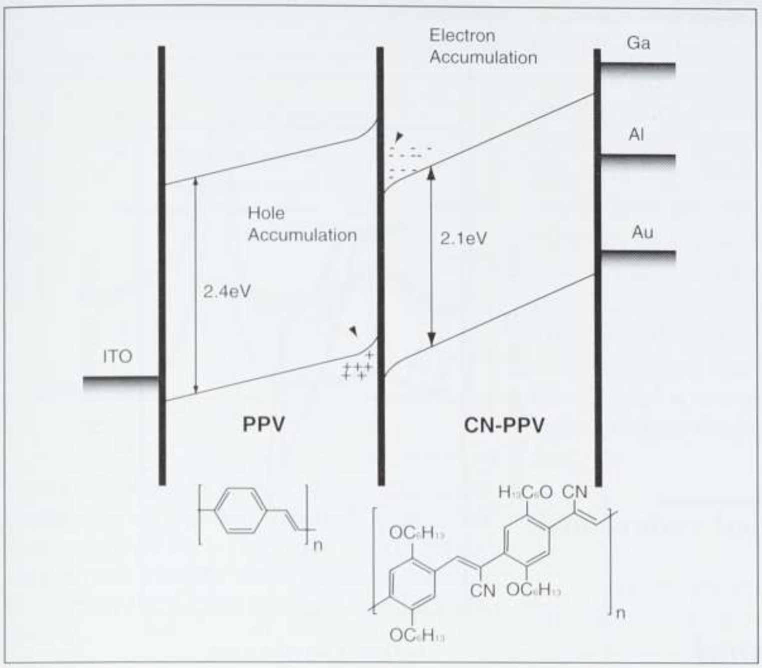

Figure 2. Heterostructures can be formed in polymer materials, allowing bandgap engineering not unlike that which is familiar to anyone working in compound semiconductors. In the example shown above the PPV layer is p-type, and the cyanoPPV layer is n-type.

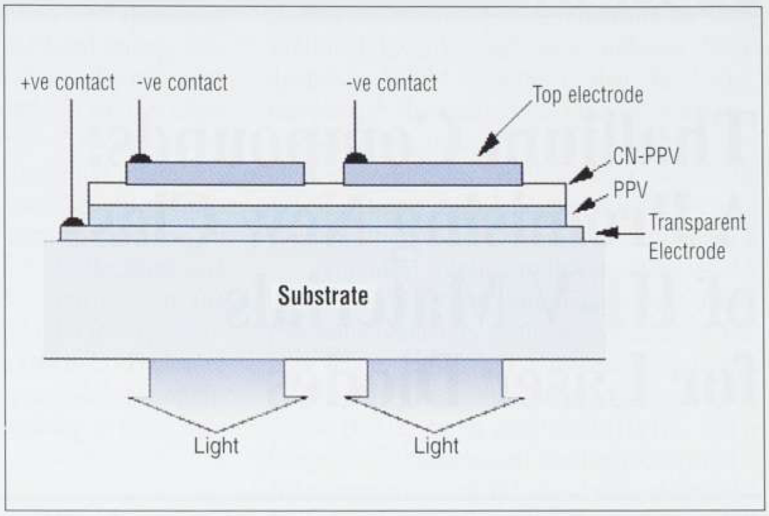

Figure 3. A cross section of a typical polymer-based light emitting diode. In traditional, i.e. compound semiconductor, technology, each pixel is formed by using discrete devices of the desired color(s). Polymer technology holds the promise of allowing large area flat panel displays which are essentially a single device, with the pixels being formed by patterning the electrodes. At present, however, the applications which appear to be within reach are backlighting of instrument panels, and dot matrix-type displays which require only simple patterning.

Thallium Compounds: A Promising New Class of III-V Materials for Laser Diodes

The use of quaternaries containing thallium as active layers might extend the range of InP-based laser diodes to 10 microns and beyond

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Indium phosphide-based lasers are extremely important for fiber optic communications, because they are ideally suited for operation at the 1.3 and 1.55 micron wavelengths. But InP materials are not often considered for longer wavelength applications. Instead, the development of this area is currently a contest between three major approaches: IV-VI materials such as PbSe, PbTe, and related materials (known as lead salts or lead chalcogenides); III-V antimonide heterostructures; and III-V quantum cascade lasers.

Our research at Osaka University and NTT leads us to believe that there is a fourth contender for infrared lasers: III-V compounds containing thallium. Specifically, we recently proposed[1] the use of $Tl_zIn_{1-z-y}Ga_yP$ as an active layer for laser diodes covering the 0.92 micron to 10 micron wavelength range, and we also demonstrated the first successful epitaxial growth of this compound. We also believe that in addition to extending the useful operation of InP-based lasers into the far infrared, the thallium compounds show potential for temperature independent operation at 1.55 micron, making them highly desirable for wavelength division multiplexing (WDM) as a method to increase transport capacity in optical fiber communications systems.

Expected Properties of TlInGaP

The expected relationship between band-gap energy and lattice constant for the TlInGaP system is shown in Figure 1. This table is based on theoretical results for TlInP published by van Schilfgaarde et al.[2] and the data for InGaP. The data for the other III-V compound materials are also plotted in the figure for reference. As can be seen by the vertical solid line in this figure, TlInGaP can be easily lattice-matched to an InP substrate. Furthermore, the lattice-matched alloys can cover the band-gap energy from 1.42 eV (InP, 0K) to lower than 0.1 eV (TlGaP). A direct band-gap is expected over the whole lattice-matched composition range. This energy range corresponds to the wavelength range from 0.92 micron (InP) to over 10 micron (TlGaP) at room temperature. The addition of Al and As can further extend the energy/wavelength range. This materials system can also be lattice-matched to a GaAs substrate,

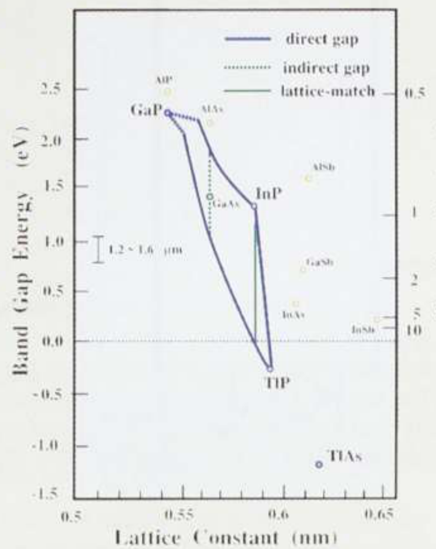

Figure 1. Band-gap energy versus lattice constant for TlInGaP. Compositions for the lattice-matching to InP and to GaAs are indicated by the vertical solid line and the vertical dashed line, respectively.

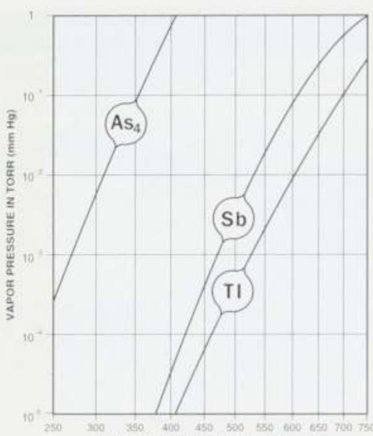

Figure 2. Vapor pressure curves for a selection of materials which are commonly used in MBE. Thallium can be evaporated in a conventional MBE system using a standard effusion cell.

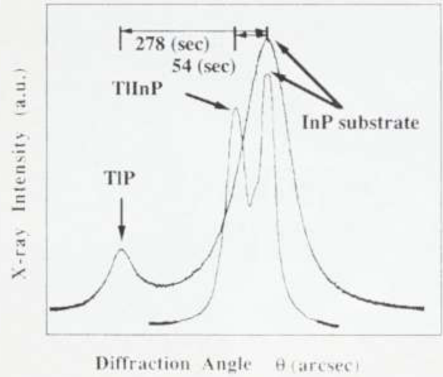

Figure 3. Double crystal X-ray diffraction rocking curves for TlP/InP and TlInP/InP. Peaks from TlP and TlInP are clearly observed.

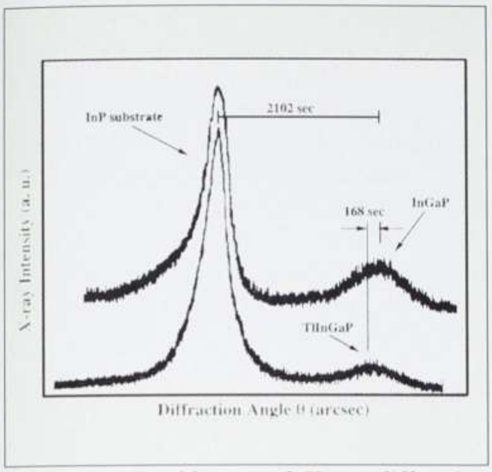

Figure 4. Double crystal X-ray diffraction rocking curves for the TlInGaP quaternary layer grown on InP. The curve for the InGaP layer grown with the same In and Ga fluxes but without the Tl flux is also shown for comparison.

where the band-gap energy ranges from 0.65 micron (InGaP) to about 1.24 micron (TlGaP). In Figure 1, TlInGaP alloys lattice-matched to GaAs are indicated by the vertical dashed line.

The TlInGaP system has only one Group V constituent. Considering the common anion rule which is widely accepted in the AlGaAs/GaAs system leads to the expectation that TlInGaP has the Type-I band lineup, featuring wider conduction band discontinuity that that of the valence band. If so, this characteristic can avoid some of the problems found in the III-V antimonide materials (which have the Type-II band lineup). It also enhances this system's attractiveness as an optical material, because both electrons and holes can be effectively confined in the TlInGaP active layer, and high radiative transition efficiency can be expected. Therefore this material seems very promising for applications to laser diodes operating at more than 2 microns.

Temperature Independence

Another interesting characteristic of TlInGaP is that the alloy consists of a semiconductor (InGaP) and a semimetal (TlP). Therefore, it is expected to exhibit a temperature-independent band-gap energy. This is of great potential importance for fiber optic applications. Wavelength division multiplexing (WDM) is considered to be a most attractive and promising way of increasing transport capacity in optical fiber communication systems, and has been widely studied at the 1.55 micron region. One problem in using the conventional InGaAsP/InP semiconductor laser diodes in WDM systems is that the lasing wavelength fluctuates with ambient temperature variation, because the band gap depends on temperature. Therefore, laser diodes in WDM systems must be equipped with Peltier elements that work to stabilize temperature.

The ideal solution to this problem would be the use of temperature-independent band-gap semiconductors as the active layer of the laser diode. HgCdTe is considered as a possible solution. That alloy consists of a semiconductor (CdTe) and a semimetal (HgTe), and a temperature-independent band-gap energy at a Hg composition of 0.4 has been observed.[3] This characteristic is believed to be caused by the reverse temperature dependence of band-gap (overlap) energy between semiconductor and semimetal. Of course, the use of HgCdTe has many practical disadvantages, but we believe that we will find the same desirable temperature independence in TlInGaP at a TlIn composition ratio of approximately 1:1 (about 0.7 - 0.8 eV) for the lattice-matched condition. We also expect that the temperature independent band-gap energy can be further tuned by forming multiquantum well structures or by adding Al or As.

Notes on Other Thallium Compounds

TlInGaP on GaAs

The compound TlInGaP can be grown lattice-matched to GaAs, and therefore is favorable to obtain the band gap of less than 1.43 eV, probably down to 1 eV. This characteristic will provide a large variety of designs for GaAs-based electronic devices. In the growth of TlGaP, the composition for the smallest band gap within this alloy, we have observed phase separation. This is in contrast to the TlInGaP on InP where no phase separation was observed. However, the observed phase separation is that into the TlGaP closely lattice-matched to GaAs and the TlGaP of TlP-like or GaP-like composition depending on the flux ratio of Tl and Ga during growth. Therefore, it is possible to obtain non-phase separated TlGaP by calibrating Tl and Ga fluxes so as to obtain exactly lattice-matched composition.

TlInGaAs on InP

Like the compound TlInGaP, which is discussed at length in the main article, the related compound TlInGaAs can be lattice-matched to InP and can be used for the optical devices in the wavelength range of 2 micron to over 10 micron. Two types of heterostructures are considered; TlInGaAs/InP and TlInGaAs/InGaAlAs. The advantage of the second type of heterostructure is that it includes only one group V element. Therefore it can be easily grown by using a conventional solid-source MBE system. (An off-setting disadvantage is the use of Al, which usually requires higher growth temperatures to obtain good quality in the Al-containing layers.) The primary reason why the TlInGaAs alloy system might be of interest over TlInGaP is that the same band gap energy can be obtained even for the use of smaller Tl composition. Thus it might be favorable from the view point of toxicity of Tl. However, the phase separation behavior must be studied: it is now under investigation in our group.

TlInGaAs on InAs

TlInGaAs cannot be lattice-matched to GaAs. However, it can be lattice-matched to the less common substrate InAs. The wavelength range it covers is beyond 3.5 microns. TlInGaAs on InAs may be of interest as a detector material; however, we can also cover this wavelength range using TlInGaP and TlInGaAs on InP substrates. Furthermore, in the case of TlInGaAs on InAs we have found that we cannot get suitable heterostructures for laser diodes and InAs is too weak in mechanical strength. Therefore, at the moment, this alloy system on InAs is not so interesting.

H. Asahi

Epitaxial Growth

A very nice feature of the TlInGaP system, for the experimentalist's point of view, is that it is relatively easy to grow, and we have succeeded, for the first time, in growing TlInP and TlInGaP epitaxial layers on InP substrates. In our work, all growths were performed in a gas-source molecular beam epitaxy system (GSMBE) using elemental Tl (5N), In (7N) and Ga (7N) as the Group III sources, and PH_3 as the Group V source. The melting point of TlP is expected to be lower than those of InP and GaP. The optimum growth temperature is, therefore, estimated to be lower than that of InP. This may mean that growth by MOVPE would be difficult, because the low growth temperature will lead the problem of insufficient decomposition of PH3. On the other had, in GSMBE the precracking of PH3 in the cracker cell solves this problem. The use of solid source phosphorus is also an option.

The vapor pressure of Tl is similar to that of Sb and other materials which are commonly used in MBE. See Figure 2. This means that a standard effusion cell can be used as the evaporator. One problem with Tl is that it is easily oxidized; another problem is that it is toxic (more so than arsenic). Thus many common sense precautions must be taken in the laboratory.

Experimental Results

Figure 3 shows the double crystal X-ray diffraction rocking curves for TlP/InP and TlInP/InP samples. In addition to the peak from InP, those from TlP and TlInP are clearly visible. TlInP alloys with various Tl compositions were also grown by varying Tl flux during growth, demonstrating that the entire range of compositions can be grown. Figure 4 shows the rocking curve for the TlInGaP quaternary layer grown on InP. The curve for InGaP grown with the same In and Ga fluxes, but without the Tl flux, is shown for comparison. The peaks from InP, TlInGaP and InGaP are observed and the shift to the lower diffraction angle is clearly observed for the TlInGaP peak. From the diffraction peaks of InGaP and TlInGaP, their compositions were calculated to be $In_{0.79}Ga_{0.21}P$ and $Tl_{0.073}In_{0.732}Ga_{0.195}P$. These values roughly agree with the expected ones, although detailed studies of composition control will be needed in the future.

Summary

We have proposed a new III-V compound, $Tl_zIn_{1-z-y}Ga_yP$ as an active layer for laser diodes covering the 0.92 micron to 10 micron wavelength range, and we have demonstrated the first successful epitaxial growth of this compound. While there is obviously much work to be done, we believe that this material system shows great promise not only for extending the useful operation of InP-based lasers into the far infrared, but also for enabling communications lasers capable of temperature insensitive operation. And while there are other materials systems which are being explored for these same reasons, we hope that we will be able to show that the thallium compounds provide a more manufacturing-friendly approach.

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2 M. van Schilfgaarde, A B. Shen, S. Krishmanurthy and A. Sher; Appl. Phys. Lett. 85 (1994) 2714.

3 D. Long; Energy Bands in Semiconductors (Wiley, New York, 1968).

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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Research Review

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

Optoelectronic Devices

Recent Developments in High Modulation Bandwidth Multi-Quantum Well Lasers

A variety of factors can influence the maximum frequency at which diode lasers can be modulated. Intrinsic limitations include nonlinear gain from spectral hole burning, carrier heating, carrier capture and transport processes. Usually, the maximum intrinsic modulation frequency is not realized due to extrinsic effects such as electrical parasitics and lateral multi-moding. There have been several reports in both InP-based and GaAs-based lasers of *intrinsic* modulation bandwidths of 40 GHz or more, but actually *measured* bandwidths have not been this high until now. A recent result, 40 GHz 3-dB modulation bandwidth under cw operation, represents the highest modulation bandwidth yet measured for any semiconductor laser. An important aspect of this result is that the measured bandwidth equals the intrinsic bandwidth, *i.e.*, extrinsic effects have been reduced to exceptionally low levels. Optimization of the device structure and of the MBE growth of the GaAs-based materials were important in achieving this result. The device design included four undoped, highly strained $In_{0.35}Ga_{0.65}As$ quantum well active layers and short (130 μm) cavities etched with chemically assisted ion beam etching. Significantly improved devices resulted from the replacement of uniform AlGaAs cladding layers with binary superlattices. The binary superlattices allowed the use of lower growth temperatures, which reduces the formation of point defects in the active layer. Work performed at the Fraunhofer IAF [Freiburg, Germany]. See S. Weisser, et al., IEEE Photonics Technology Letters, 8(5), 608 [May, 1996].

A second report also uses this standard design of high speed lasers, *i.e.*, multiple wells and as much strain as possible in the wells. However the second work uses a material system that is more flexible than AlGaAs/(In)GaAs. Compressively strained InGaAs wells on GaAs substrates were used again as in the above approach, but in this work tensile-strained GaAsP barriers replaced the conventional unstrained GaAs barriers. A high intrinsic bandwidth of 59 GHz was reported. Modulation response measured up to 20 GHz extrapolate to a 3-dB bandwidth of 25 GHz. Work performed at Bell Laboratories [Murray Hill, NJ USA]. See H. Han, et al., IEEE Photonics Technology Letters, 8(9), 1133 [September, 1996].

A different approach for high speed lasers involves the use of tunnelling injection. In conventional lasers, carriers are injected into the active region at energies higher than those of the lasing states. The carriers must relax in energy before the lasing states can be populated. Tunnelling injection lasers, however, inject the carriers directly into the lasing states. Carrier heating and gain compression are reduced by this approach. A tunneling injection InGaAs/GaAs multi-quantum well laser has been reported with an intrinsic modulation bandwidth of 84 GHz. Actual modulation response measured up to 24 GHz extrapolates to a 3-dB bandwidth of 45 GHz. The use of strain compensating barriers was found to increase the intrinsic modulation bandwidth to 100 GHz. Work performed at the University of Michigan [Ann Arbor, MI USA]. See X. Zhang, et al., Electronics Letters, 32(18), 1715, [29 August 1996].

See page 16 for a review of the highlights of semiconductor laser research in 1996.

Compound Semiconductor Materials

Reduction of Low-Energy Ion Damage with LT-GaAs Cap Layer

Low energy ion damage occurring in dry etching processes can extend more than 100 nm into the substrate, even for ion energies as low as 300 eV. Experiments have confirmed that low-energy ion channeling and defect diffusion during bombardment play an important role in the deep ion damage. The present article shows that a thin 210Å annealed low-temperature (LT) grown GaAs cap layer can protect underlying layers from ion damage when subjected to three minute argon ion beam exposures at biases of 500 and 600V (beam current 50 μA/cm2). The study uses two nominally identical multiple quantum well samples, grown by MBE on GaAs (100) substrates, that differ only in their cap layer structures; whereas one sample is grown with a 210 Å LT-GaAs layer grown at 250°C, the control sample is capped with 210Å of GaAs grown at 600°C. After growth, the LT-GaAs capped sample was cleaved into pieces and annealed for 30 seconds at various temperatures (with a GaAs cap wafer). LT-GaAs capped samples, together with control samples, were then exposed to the Ar+ ion beams in an RBIBE system. Low-temperature (1.4 K) photoluminescence measurements showed a marked improvement in the quantum well luminescent efficiency for the LT-GaAs capped samples, indicating that the annealed LT-GaAs layer can reduce the penetration depth of ion damage. This post-growth annealing condition leads to the formation of As precipitates with a diameter of 55Å, and a maximum interfacial area of ~ 2.1 x 10^5 cm^5. The data appear to indicate that As clusters play a role in de-channeling ions that would otherwise result in deep sub-surface damage, especially since the best PL efficiency improvement occurs under conditions favoring at the maximal As cluster cross-section. Work done at the University of California, Santa Barbara. See Chen et al, "Improvement in Low-Energy Ion-Induced Damage with a Low Temperature GaAs Capping Layer," Appl. Phys. Lett., Vol. 69, No. 12, pp. 1728-1730, 16 September 1996.

Mid-IR InAs/GaSb/AlSb Quantum Cascade Electroluminescence

Quantum cascade (QC) structures based on the InAs/GaSb/AlSb heterostructure system have been designed with the intent to circumvent the fast phonon scattering loss in "conventional" type I QC mid-IR laser structures by making use of the broken-gap discontinuity at InAs/GaSb interfaces. These new QC device structures should display high radiative efficiencies because of an expected reduction of phonon relaxation during an interband process. Twenty-period InAs/GaSb/AlSb QC structures were grown by MBE on n-type InAs substrates and displayed an electroluminescent peak at 3.64 μm at 80 K while driven with a 50% duty cycle at 10 kHz. Mid-IR electroluminescence, although broadened, was observed up to room temperature. The output power, which was almost constant above 200 K, was found to depend weakly on temperature and exhibited a fourfold improvement as the devices are cooled from 300 to 80 K. Work done at the Space Vacuum Epitaxy Center, University of Houston. See Yang et al, "Mid-IR Interband Cascade Electroluminescence in Type-II Quantum Wells" Electron. Lett., Vol. 32, No. 17, pp. 1621-1622, 15 August 1996.

Reduced Threading Dislocations in Highly Mismatched Systems

Epitaxial growth of highly-mismatched III-V systems generally produces a high density of threading dislocations in the epilayers (typically > 10^7 cm^{-2}), often caused because the misfit dislocations are not purely edge-type but rather are mixed 60° dislocations with out of plane Burgers components. InAs and GaP are characterized by an 11% lattice mismatch. When InAs was grown by MBE directly on (100) GaP substrates at a temperature of 350°C, the character of the resulting misfit dislocation network and of the propagating defects could be controlled through the incorporation ratio of the group V and III elements. For an As-stable growth, the RHEED pattern became spotty after the deposition of 2MLs of InAs, whereas for the In-stable growth the RHEED pattern remained streaky with a (4 x 2) reconstruction, even after the deposition of 250 Å of material with a beam flux As4/In ratio of 5. TEM measurements confirmed 3D islanding and subsequent island coalescence in the As-stable sample (with clusters of defects reaching the sample surface). On the other hand, the In-stable sample showed a smooth surface with a peak-to-valley ratio of 5-7 Å (compared to 120-150 Å under As-stable conditions), and no threading dislocations were detected. HRTEM measurements indicated that pure edge dislocations with in-plane Burgers vectors and a spacing of 41 Å are present in the In-stable sample, corresponding to an 85% strain relaxation of the InAs epilayer. Work done at Purdue University, West Lafayette. See Chang et al, "Incoherent Interface of InAs Grown Directly on GaP(001)," Appl. Phys. Lett., Vol. 69, No. 7, pp. 981-983, 12 August 1996.

GaInNAs/GaAs Long-Wavelength Laser

No, it's not a "typo," you read it right: recent work has explored the potential benefits of a Group III/arsenic/nitrogen compound. Interest in this area is driven in part by the fact that GaInNAs/InGaAsP/InP long-wavelength lasers generally display a low characteristic temperature due to the weak carrier confinement provided by their small conduction band discontinuity. GaInNAs has been proposed to overcome this problem because the new alloy, which can be grown on GaAs substrates, is expected to show a conduction band discontinuity as high as 0.5 eV. A GaInNAs/GaAs SQW laser structure was grown at 500°C on (100) n-GaAs substrates by gas-source MBE and by using a nitrogen radical as the nitrogen source. The laser active layers consist of a 70Å $Ga_{0.75}In_{0.25}N_{0.005}As_{0.95}$ quantum well sandwiched between 750Å GaAs guiding layers. $Al_{0.3}Ga_{0.7}As$ cladding layers were used to obtain superior electron and optical confinement. The GaInNAs SQW laser operated in CW mode at 77 K, and displayed a threshold current density of 1.1 kA/cm² with an emission wavelength of 1.113 μm. Although laser action at room temperature was not achieved, the electroluminescence wavelength was 1.20 μm at that temperature. Longer wavelengths should be achievable by increasing the nitrogen content in the quantum well. Work done at the Hitachi Central Research Laboratories, Tokyo. See Nakahara et al, "Continuous-Wave Operation of Long-Wavelength GaInNAs/GaAs Quantum-Well Laser," Electron. Lett., Vol. 32, No. 17, pp. 1585-1586, 15 August 1996.

Silicon Incorporation in (111)A GaAs Grown by MBE

Silicon is a widely used donor in GaAs grown by MBE on (100) substrates but its incorporation on a (111)A growth surface can vary strongly with the growth conditions. With the current interest in growth on non-(100) oriented GaAs substrates, it has become important to better understand the Si incorporation process on various growth surfaces.

A systematic study of the effect of growth conditions (over growth temperatures and As4:Ga flux ratios) on Si incorporation in GaAs layers grown on GaAs (111)A substrates was recently conducted. Infrared local vibrational mode (LVM) spectroscopy confirmed that Si atoms can be incorporated in either the Ga or As sublattices, therefore yielding donor or acceptor substitutional impurities, depending on the growth conditions. Growths were performed at substrate temperatures ranging from 460 to 620°C, with a Si effusion cell temperature fixed at 1150°C to provide a flux of 1.3 x 10^{10} atoms-cm^{-2}-s^{-1}, corresponding to a bulk doping level of 1.2 x 10^{18} cm^{-3} in GaAs grown at 0.4 μm/h. Layers grown simultaneously on GaAs (100) showed no compensation with an electron concentration of $n = 1.2 \times 10^{18}$ cm^{-3}. The (111)A layers were non-compensated p type when grown at high-substrate temperatures and low As4:Ga flux ratios, but they became increasingly compensated as the flux ratio was increased or the growth temperature decreased. For low growth temperatures and high As4:Ga flux ratios, the layers turned out un-compensated *n*-type.

The incorporation behavior of Si could be understood in terms the excess arsenic present at the growth surface. Because the (111)A GaAs face is inherently Ga-rich, Si tends to incorporate on the As (acceptor) sites unless a high arsenic concentration is present at the surface to compete for the As sublattice sites. A good correlation between the carrier concentration and type can be obtained by plotting *n* or *p* as a function of the *effective* As_4:Ga flux ratio defined as the As_4:Ga ratio multiplied by the As_4 sticking coefficient.

Work done at the Imperial College, London (United Kingdom). K. Sato et al, "Silicon Incorporation Behavior in GaAs Grown on GaAs (111)A by Molecular Beam Epitaxy," J. of Crystal Growth, Vol. 165, pp. 345-350, July 1996.

Electronic Circuits and Devices

GaN-Based MODFETs

With a large bandgap of 3.4 eV, high electron saturation velocity, and the availability of heterostructures suitable for the fabrication of high electron mobility transistors, the $A_{lx}Ga_{1-x}N$ material system is a good candidate for high power microwave applications.

Researchers at the University of California [Santa Barbara, CA] have fabricated GaN-based HFET structures for microwave power applications. Grown by MOCVD, two different HFET structures were investigated - an unintentionally doped MODFET (UID-MODFET) and a Si doped MODFET (SID-MODFET). The HFET channels were grown on C-plane sapphire substrates after a 200 Å GaN nucleation layer. Channel thicknesses were 4000 Å for the UID-MODFET and 3000 Å for the SID-MODFET. The heterojunction was formed with a 300 Å $Al_{0.15}Ga_{0.85}N$ layer, where this layer was undoped in the case of the UID-MODFET, while for the SID-MODFET, consisted of a 30 Å UID spacer above the channel, a 150 Å donor layer with a Si doping density of $3x10^{18}$ cm^{-3}, and a 120 Å UID cap. The resulting MODFET structure exhibited a record room temperature mobility of 1500 cm^2/V-s with a carrier concentration of $7.9x10^{12}$ cm^{-2}. Record high breakdown voltages of up to 340 and 230 V were obtained for 1.5 μm gate length devices using the UID-MODFET and SID-MODFET structures, respectively. These devices exhibited transconductances up to 140 mS/mm and channel currents of up to 400 mA/mm. Due to high contact and access resistances, the knee voltage of the device was typically 7V.

The first reported microwave power measurements for GaN FET's were performed on these devices. For devices with gate lengths of 1.0 μm and widths of 500 mm, a peak current of 340 mA/mm and a peak transconductance of 120 mS/mm were obtained along with an f_t of 6 GHz and f_{max} of 15 GHz at a source-drain voltage of 20 V. Microwave power measurements were performed at 2 GHz at a source drain voltage of 26 V and a drain current of 66 mA. Under class A operation, an output power density of 1.1 W/mm with a power added efficiency of 18.6% was obtained. This low PAE is due to the large knee voltage of the transistor, which is a consequence of the relatively high-contact and access resistances which are directly related to GaN's much lower mobility than that of other lower bandgap III-V semiconductors. It is believed that if the device is properly cooled and biased up to 50 V, that it would produce power at 2.8 W/mm, while increasing the channel current up to 500 mA/mm would further raise the power ability to 4W/mm. These power levels would be comparable to the best obtained with SiC-based MESFET's.

See "Y.-F. Wu et al, IEEE Electron Device Letters, 17(9), 455 [September 1996] and Y.-F Wu et al, Applied Physics Letters, 69(10), 1438 [2 September 1996].

Heterostructure-Emitter and Heterostructure-Base Transistor

Intentionally strained layers have been incorporated in HEMT structures for many years, typically in the channel and Schottky layers in order to improve device performance. However, it is only recently that strained layers are being incorporated in HBT structures. A GaAs-based heterostructure-emitter and heterostructure-base transistor (HEHBT) have recently been reported in which the emitter-base junction consists of a GaAs-GaAs p-n homojunction in order to reduce the device offset voltage, with a separate $Al_{0.45}Ga_{0.55}As$ confinement layer placed between the emitter and cap contact in order to prevent holes from being injected into the emitter. In addition, emitter injection efficiency is enhanced with the placement of a 100 Å p^+ $In_{0.2}Ga_{0.8}As$ strained layer at the emitter-base junction to further enhance the confinement of holes. The inclusion of the InGaAs layer improved DC gain from 135 to 280, while lowering the offset voltage from 300 mV to 100 mV. Work performed at the National Cheng-Kung University [Tainan, Taiwan, ROC]. See J.H. Tsai et al, Electronics Letters, 32(18), 1720 [29 August 1996].

1-W SiGe Power HBT's

Si-based devices continue to improve in RF performance, competing aggressively with GaAs-based devices in the mobile communication marketplace over the frequency range of 900 MHz to 1.9 GHz. SiGe power HBTs intended for 1.9 GHz applications, using either 10 or 60 2.25x15 mm^2 emitter fingers, were grown by a combined CVD/MBE process, in which the MBE is utilized in the growth of a 26% Ge content SiGe base which is boron doped at $4x10^{19}$ cm^{-3}. The devices exhibited a collector-emitter breakdown voltage of 4.5 V, along with f_t and f_{max} values of 16 and 11 GHz, respectively, at a collector current of 400 mA and a V_{CE} of 3V. Class A load pull measurements at 1.9 GHz demonstrated a PAE of 44% at 1 W output power for the 60-stripe transistor. In addition, a ten-finger driver HBT exhibited a PAE of 72% at 900 MHz for class A/B operation. Work performed at Daimler-Benz AG Research Center [Ulm, Germany], TEMIC Telefunken Microelectronic [Heilbronn, Germany] and ATN Microwave [Billerica, MA]. See A. Schuppen et al, IEEE Microwave and Guided Wave Letters, 6(9), 341 [September 1996].

94 GHz InGaAs/InAlAs/InP Power HEMT Amplifier

High efficiency solid-state power amplifiers at W-band are a critical component for many advanced system applications, including smart munitions and advanced phased array radars. A high efficiency W-band power MMIC using passivated 0.15μm gate length InGaAs/InAlAs/InP HEMTs, incorporating a double-doped channel structure which exhibits a sheet carrier concentration of $4.0x10^{12}$ cm^{-2} and a room temperature mobility of 9000 cm^2/v-s, were grown by MBE. A single stage HEMT MMIC amplifier with 320 mm gate width demonstrated a maximum PAE of 23% with 40 mW output power and 4.9 dB power gain at 94 GHz. When biased for higher output power, 54 mW output power with 20% PAE was achieved at 94 GHz. This combination of output power and PAE represent the best characteristics for a fixtured amplifier at this frequency to date. Work performed at TRW [Redondo Beach, CA]. See R. Lai et al, IEEE Microwave and Guided Wave Letters, 6(10), 366 [October 1996].

GaInP Channel MESFET's

Due to the large bandgap of GaInP (1.92 eV), it is well suited as a channel material for high breakdown applications in GaAs-based devices. In addition, when used as a channel material, precise etch stopping on the GaInP can be achieved during gate recess etching due to the availability of highly selective wet etches between GaAs and GaInP. GaInP channel MESFETs utilizing 1.5 μm gate lengths with channel thicknesses of 1000 Å and doped at $6x10^{17}$ cm^{-3}, were grown by GSMBE. A high gate-to-drain breakdown voltage of 42 V was obtained along with a maximum current density of 320 mS/mm. These devices exhibited an f_{max} of 30 GHz and f_t of 9.3 GHz. Work performed at the National Taiwan University [Taipei, Taiwan, ROC]. See Y.S. Lin et al, IEEE Electron Device Letters, 17(9), 452 [September 1996].

HBT - FET Integration

The monolithic integration of HBTs with HEMTs offers greater flexibility in circuit capability and design, by being able to utilize the high current driving capability, high switching speed and low 1/f noise characteristics of HBT's, while still being able to take advantage of the high input impedance and low noise characteristics of FET's. The monolithic integration of an AlGaAs/GaAs HBT and a GaAs junction-gate floated electron channel field effect transistor (J-FECFET) using a selective MOCVD process is described. 1.0 μm gate length FET's exhibited a transconductance of 102 mS/mm and an f_t and f_{max} of 10.7 and 27.3 GHz respectively, while the HBT exhibited a current gain of 21 at a collector current density of 50 kA/cm^2. Work performed at the Korea Advanced Institute of Science and Technology [Taejon, Korea], and LG Semicon Co. [Cheongju, Korea]. See H. Shin et al, IEEE Microwave and Guided Wave Letters, 6(9), 317 [September 1996].

Reversal of Fortune

MARIE MEYER

One of the most pleasant things about the Compound Semiconductor Portfolio this year has been that, despite its ups and downs, it has managed to consistently outperform both the NASDAQ Composite and the Semiconductor Sector Index. See Figure 1, which charts results through the end of August. In September and October, however, that trend was reversed. While the two market indices were up several notches, the Portfolio actually declined by almost 6% - see Figure 2. However, it is still up 20% since the first of the year, mainly because four of the seven stocks - Anadigics, ATMI, TriQuint and Vitesse - are up an impressive 55%. The best of all is Vitesse, which is up a whopping 150% since January.

The Weak Performers

All of which raises the question: what is holding the other three companies back? On October 1, 1996 **Alpha Industries Inc. [AMEX: AHA]** announced that for the second quarter of fiscal 1997 (ended September 29) it expects to report a net loss of $0.45 to $0.49 per share. Alpha noted that because it "no longer anticipates that fiscal 1997's operations will be profitable, the net loss also includes the reversal of a $600,000 ($0.06 per share) tax benefit recorded in the first quarter." Alpha had previously forecasted "break-even" results for the second quarter of fiscal 1997. Analysts at Oppenheimer, a major brokerage, downgraded their recommendation of the stock from "but" to "market performance" status on the basis of this news.

Much of Alpha's troubles appear to stem from its ceramics-filter subsidiary, Trans-Tech Inc. A large portion of the second quarter loss - $0.19 per share (or $1.9 million) - is related to inventory write-down and loss on a filter order which incurred when a major customer redesigned its end product. The company explained that "this redesign required us to scrap certain finished parts and materials ant to issue credits for returned product that was no longer required by the customer.

On a brighter note, Alpha's new president and CEO noted that orders for RF products for the cellular and PCS markets were up "significantly" over the first quarter, and that the Alpha's Microwave business was progressing well. He reported that MMIC orders for infrastructure base station products with Motorola, NorTel and Ericsson are expected to enter volume production in the next two quarters, and that Alpha had made some recent MMIC handset component design wins, including the Motorola and Ericsson dual-band PCS and cellular phones, as well as new orders for ETACS and GSM. The recent design wins are expected to lead to volume shipments and new orders beginning in the third and fourth quarters.

SDL, Inc. [NASDAQ: SDLI] was one of the best performers in the Compound Semiconductor Portfolio during the first half of 1996. In August, however, the company announced that it was struggling with lower-than-expected yields from its semiconductor laser processing line, which had forced it to turn away some new orders. SDL's share prices plummeted 33% in one day as a result, and they have not yet returned to their previous levels.

Some progress is being made in attempts to rectify the problem. For the quarter ended September 30, 1996, SDL reported revenues of $19.4 million and net income of $0.9 million, or $0.07 per share, compared to revenues of $14.1 million and net income of $1.6 million, or $0.14 per

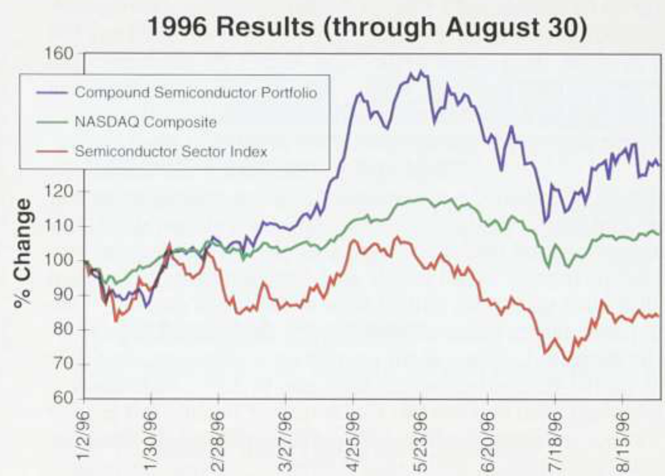

Figure 1: The going was good for the first eight months...

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	7	-49%	17 3/4	5 3/4	♦
Anadigics	ANAD	21 1/4	29 1/2	39%	35 1/4	14 7/8	34
Advanced Technology Materials	ATMI	10 3/8	12 3/8	19%	15 7/8	9 1/4	47
Cree Research	CREE	14 3/4	11 1/2	-22%	21 5/8	8 1/4	64
SDL***	SDLI	16 15/16	17	0%	32 21/64	13 1/2	♦
TriQuint Semiconductor	TQNT	14 1/4	16 7/8	18%	26 3/4	9	30
Vitesse Semiconductor	VTSS	13 1/8	22 1/8	152%	44 1/2	9 3/4	51

*Portfolio Value****, 10/31/96* *$13,581*
Change since 1/2/96 *+20%*

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

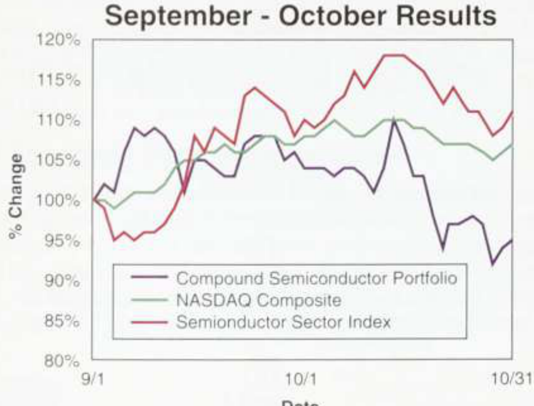

Figure 2: ...but things slowed down in September and October.

share in the third quarter of 1995. This represents a 38% increase in revenues and a 41% decrease in net income. But more importantly, Dr. Donald R. Scifres, SDL 's Chief Executive Officer, reported, "Our previously announced yield problems did impact revenues, profitability, and to a certain extent, new orders booked. However, I'm happy to report that yields are back to their historic range on two of the three product lines which experienced difficulty. The remaining problem area is 1550 nm lasers. We hope to ship limited quantities of these 1550 nm lasers in the fourth quarter." He also reported that SDL made "major" investments in new manufacturing facilities, equipment, processes and controls during the quarter, and SDL 's manufacturing operations in San Jose had received ISO 9001 certification.

It has been "good news/bad news" for **Cree Research [NASDAQ: CREE]**. First the good news: the company has announced several new contract awards and some major new business - see page 4. And for the quarter ended September 30, Cree reported record revenues of $7.4 million, and net income of $1.9 million, or $0.15 per share. And now for the bad news: but for a one-time-only license fee of $2.44 million from Cree's Japanese distributors, the company would have posted a loss for the quarter. Worse yet, Cree was hit with a shareholder lawsuit in late October (see below) that includes some serious allegations about the quality of the company's SiC-based blue LEDs. Cree maintains that the lawsuit is without merit, but given that the blue LED is intended to be the primary revenue-generator in 1997, they will need to dispel any questions surrounding the product as quickly as possible.

Cree Faces Shareholder Lawsuit

A class action lawsuit alleging securities violations and fraud was filed on behalf of shareholder of Cree Research in U.S. District Court on October 25. The complaint names Cree Research and five directors and officers of the company[1] as the defendants, and claims that an unrealistically optimistic forecast, coupled with failure to disclose information about alleged defects in Cree's blue LEDs, mislead investors and artificially inflated the company's stock. The five individual defendants are accused of personally profiting from this situation by selling shares from their personal accounts in mid-May while the stock was trading at around $20; since that time the stock has lost 40%-50% of its value. In response to the filing, Cree's President and CEO Neal Hunter defended his company, saying that Cree and its management "have and will continue to be forthright with its investors in all matters". Cree describes the lawsuit as "without merit", and says that it plans a vigorous defense.

The primary allegations in the complaint revolve around statements made in Cree's 2nd quarter earnings statement, issued on February 1[2]. At that time the company reported profits of 7¢ per share for the quarter, and projected that LED production would double to 1.5 million chips in the third quarter and then quadruple to six million ships in the fourth quarter. Cree met their 3rd quarter target, which allowed them to show a modest profit of 2¢ per share for the period. However, the company was able to produce only 3 million chips in the 4th quarter, missing their goal by 50%. More seriously, the company was forced to post a loss for the quarter, because this level of production was not sufficient to offset costs. Cree attributed this negative turn of events to "a substantial amount of down-time in our epitaxial production line" during the month of June.

Cree had warned investors at the outset that their ability to meet their production goals was dependent upon addressing "repeatability issues in the manufacturing process", and in mid-April Cree issued a press release which clearly implied that the 4th quarter production levels would be around 3 million units. However, the company stopped short of formally retracting the original forecast. The plaintiffs allege that this sequence of events constitutes grounds for a lawsuit because Cree "lacked a reasonable basis" for believing it would achieve the 6 million units target.

Perhaps more seriously, the complaint also alleges that Cree's blue LEDs suffered from significant weaknesses and defects, and that the public was mislead by the defendant's failure to disclose this information. The plaintiffs claim that significant numbers of Cree's blue LEDs contained defects in the contact layers that caused the devices to burn out after 500 to 1000 hours of use. They also allege that "Cree was experiencing wide variations in the brightness and quality of the spectrum of light" emitted by the LEDs, and that "Cree regularly stated that its product was sufficiently bright to be used outdoors, when this was not the case". The cumulative effect of these problems, according to the complaint, was that a significant number of LEDs were returned to the company by dissatisfied customers, and that "these returns increased production costs and negatively impacted Cree's revenues, income and earnings". Cree denies these allegations.

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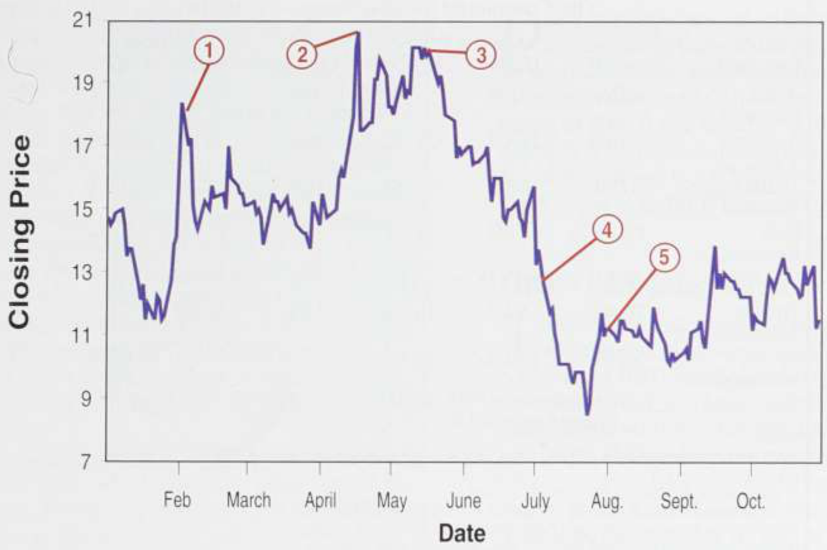
[1] *The individual defendants are: F. Neal. Hunter, Chairman of the Board, President and CEO; Calvin H. Carter, Jr., Director, Vice President and Director of Technology; James E. Dykes, Director; Michael W. Haley, Director; and Alan J. Robertson, Secretary and CFO.*

[2] *Cree operates on a fiscal year beginning July 1.*



1
February 1
Shares open at 14.125.
Cree announces 2nd Q profits of 7¢ a share and predicts that LED production will increase from 750,000 units in Q2 to 1.5 million in Q3 and 6 million in Q4.

2
April 17
Cree announces 3rd Q profits of 2¢ a share; states that shipment target has been met but implies that the forecast for Q4 needs to be scaled back to 3 million units.
Shares close at 20.625, their highest closing price of the year.

3
May 13 - May 17
Officers and directors sell 187,500 shares at 19.55 - 20.75, for total proceeds >$3.7 million.

4
July 2
Cree announces that it will likely show a loss for the 4th Q due to "a substantial amount of downtime in our epitaxial production line" during the month of June.

5
August 1
Cree reports 4th Q loss of 6¢ a share.

Chronology of some of the major events underlying the shareholder lawsuit. Cree describes the lawsuit as "without merit".

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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***

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***

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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.

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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).

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RESEARCH SCIENTIST

Universities Space Research Association (USRA) has the need of a Research Scientist to work in the Alliance for Microgravity Materials Science and Applications (AMMSA) at the NASA/Marshall Space Flight Center. This person will perform experiment research and analyses of melt and vapor growth of II-VI compound semiconductors and conduct various characterization on the grown crystals in support of Marshall Space Flight Center's ground-based and space flight experiments on the preparation and crystal growth of semiconducting compounds and alloys. The applicant should have a Ph.D. degree in physics, materials science or related field. USRA is an AAP/EEO employer. Send resume and 3 references' names/addresses no later than 1/31/97 to:

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QED Positions Available

GaAs MBE Engineer: Manage state-of-the-art production multi-wafer MBE reactors. Supervise production MBE personnel. Set growth sequences and conditions. Assist in the characterization of MBE grown material and the interpretation of data. Provide technical assistance in the area of materials and electronic devices to Sales Department and customers. Assist in the implementation of ISO 9000 quality system. Salary is competitive and commensurate with experience. Requires MS with significant experience, or Ph.D. with growth experience. Area of expertise should be Materials Science, Physics, or Electrical Engineering. Send resume to: Human Resources, Quantum Epitaxial Designs, Incorporated, 119 Technology Dr., Bethlehem, PA, 18015. Fax: (610) 861-5273.

Materials Characterization Engineer: Characterize MBE grown GaAs, and InP multi-layer semiconductor materials, with the use of X-ray diffraction, Hall, Photoluminescence, Polaron C-V profiling, and other techniques. Interpret data and assist growth personnel. Assist in the implementation of ISO 9000 quality system. Salary is competitive and commensurate with experience. 40 hours per week. Requires BS degree in Materials Science, Physics, or Electrical Engineering. Send resume to: Human Resources, Quantum Epitaxial Designs, Incorporated, 119 Technology Dr., Bethlehem, PA, 18015. Fax: (610) 861-5273.

Applications Engineer: Assist in technical interaction with customers on issues concerning MBE grown GaAs microwave material. Lead trouble shooting efforts, interpret data, and coordinate problem solving process. Position requires familiarity with GaAs based microwave devices, MBE, and GaAs material, and excellent communications skills. Salary is competitive and commensurate with experience. Requires MS with significant experience, or Ph.D. Area of expertise should be Materials Science, Physics, or Electrical Engineering. Send resume to: Human Resources, Quantum Epitaxial Designs, Incorporated, 119 Technology Dr., Bethlehem, PA, 18015. Fax: (610) 861-5273.

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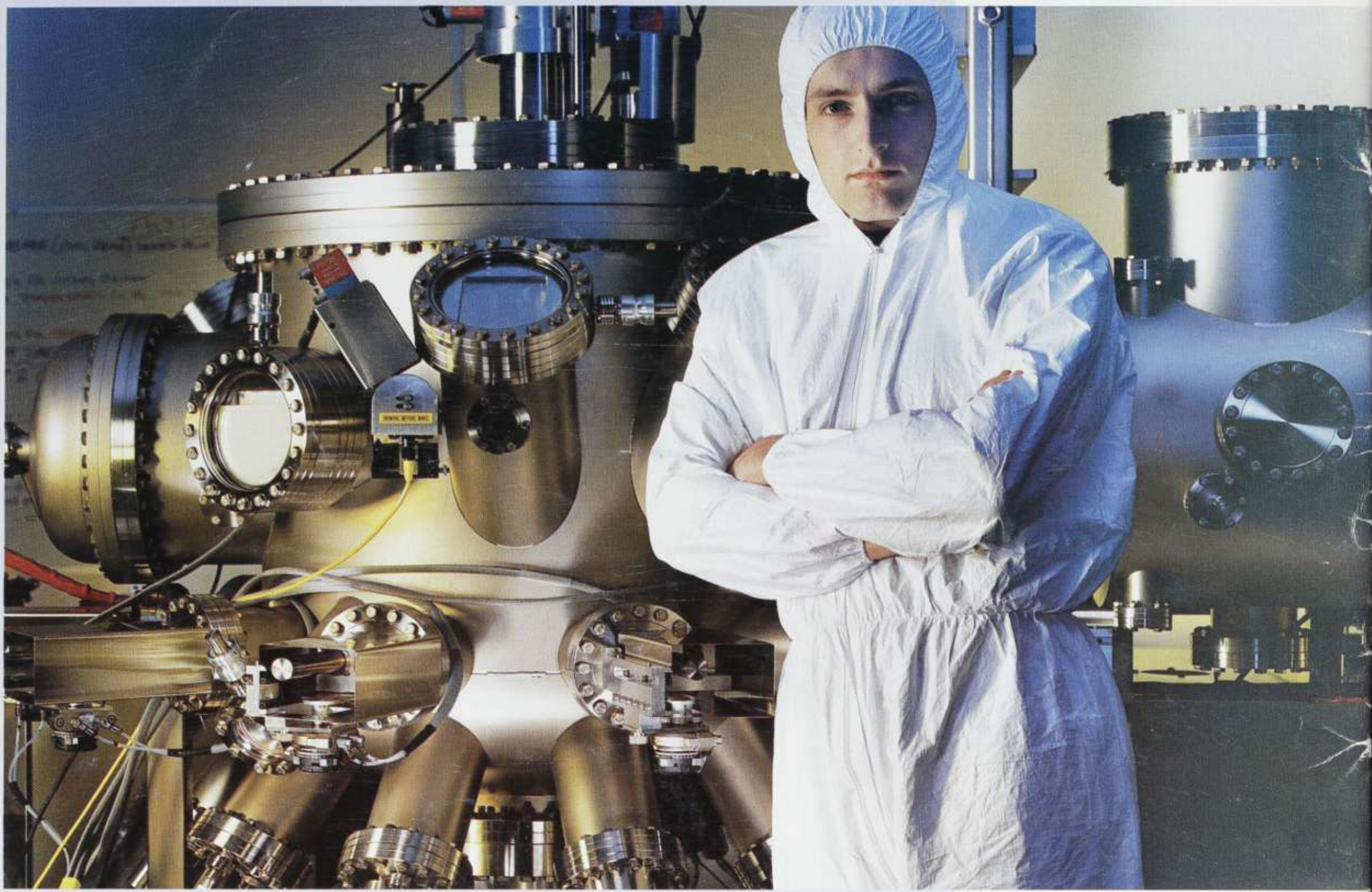

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