



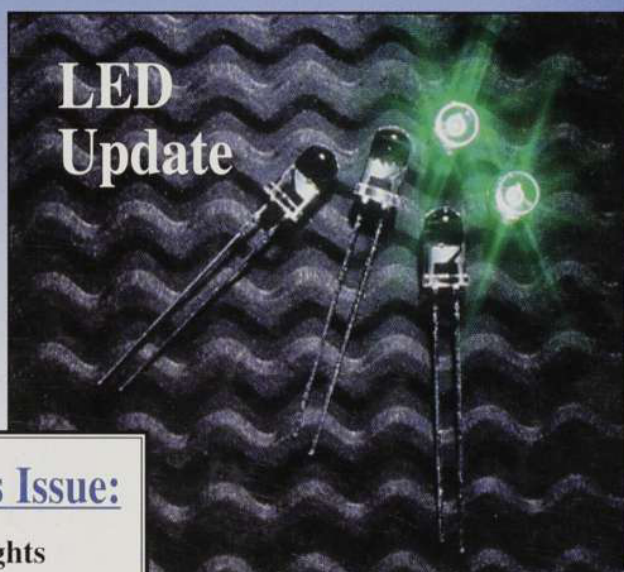
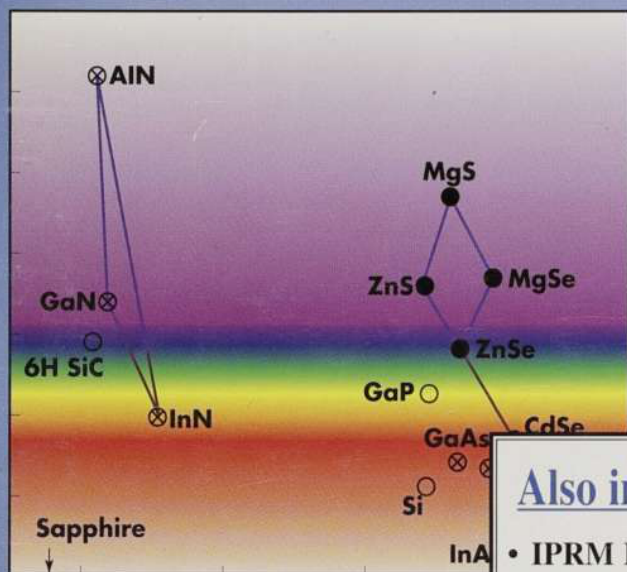
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Summer I - June, 1998

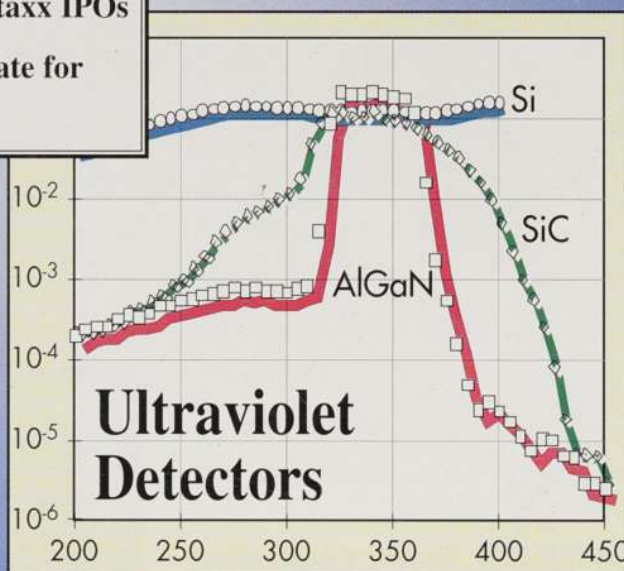
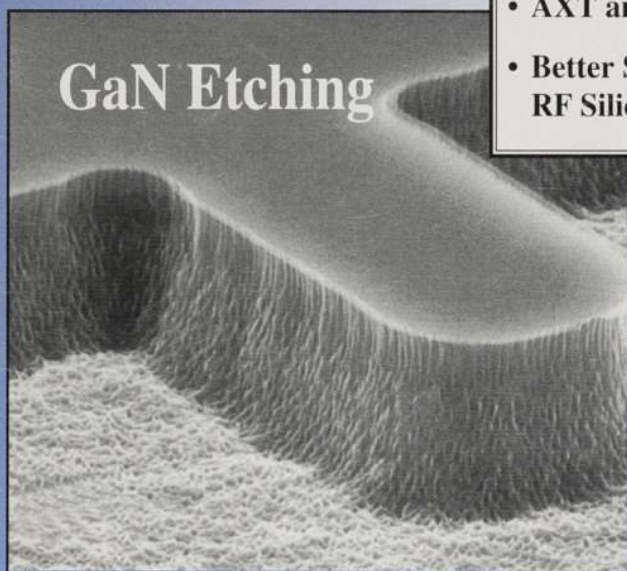
Volume 4 Number 5

WIDE BANDGAP MATERIALS



Also in this Issue:

- IPRM Highlights
- SiC Transistors
- AXT and Epitaxx IPOs
- Better Substrate for RF Silicon?



Includes Directory of Substrate Suppliers

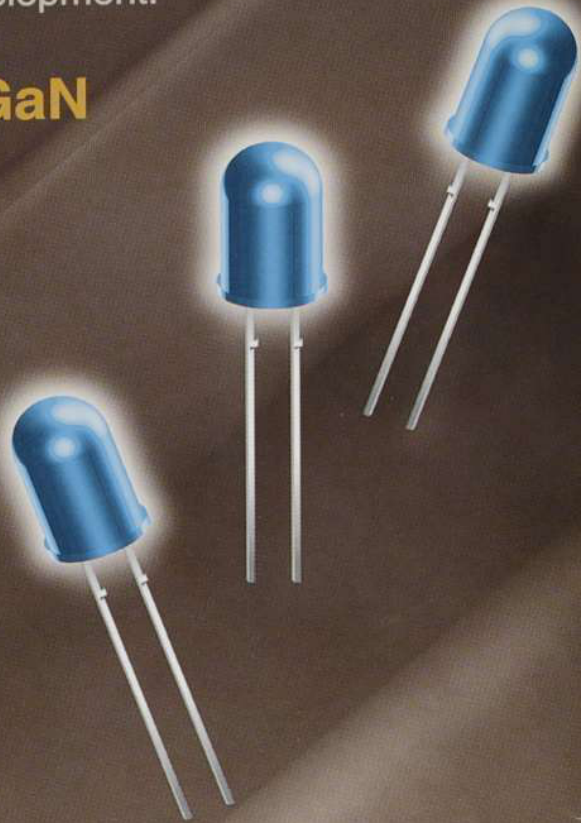
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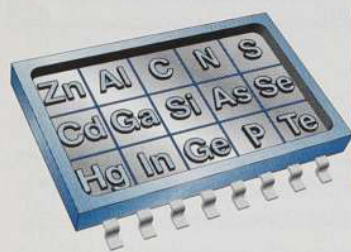
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13 Competition Spices Up the Blue LED Market

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20 SiC Transistor News

Cree is planning for microwave SiC products in 1998, and a new SiC research collaboration is launched in the UK.

22 UV Detectors at Honeywell

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25 Photo-enhanced Wet Etching of GaN

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11 Silicon Update

Researchers at Hitachi have developed a new way to transform portions of a silicon substrate into highly resistive regions. Could this make Si more competitive for RF applications?

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Compound Semiconductor Materials: GaN with low etch pit density...mixed Group V-Nitride alloys...ballistic electron distribution in HBTs

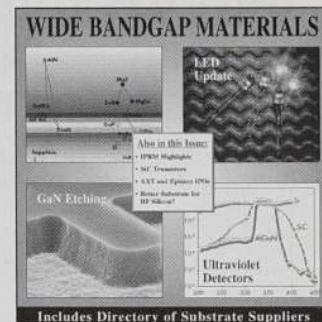
Microelectronic Devices and Circuits: 1.2V InAlGaP/InGaAs HEMTs with 65% efficiency...3.4V power HFETs with 60% efficiency...High reliability InGaP/GaAs HBTs...Silicon Germanium QWIPS

36 Directory of Compound Semiconductor Substrate Suppliers

As part of our continuing series of mini-directories, we provide a listing of 34 companies offering a wide variety of III-V and II-VI substrates, as well as SiC, Ge, sapphire and other important materials relevant to the compound semiconductor industry.

43 Portfolio

IPOs from American Xtal Technology and Epitaxx, plus recent news from several other publicly traded companies.



Wide bandgap materials are the theme for this issue. Shown on the cover: upper right, Hewlett-Packard's new green InGaN LEDs; lower right, responsivity data for various types of photodiodes from Honeywell; lower left, demonstration of sidewall etching of GaN from the University of Illinois. Coverage begins on page 13.

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A Truly Insulating Si Substrate - page 11

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Coherent Ramps Up Laser Diode Production

Coherent describes themselves as "the world's largest manufacturer of lasers", with 1997 sales in excess of \$390 million. Obviously, the majority of that is not semiconductor lasers - they offer a wide variety of laser products, as summarized on the next page. But laser diodes are becoming a more important part of Coherent's product portfolio. Sandra Todd, Director of Marketing for the Coherent Semiconductor Group, reports that shipments of laser diodes to both external customers and other divisions of Coherent are increasing very rapidly - sometimes even doubling from quarter-to-quarter.

Coherent's progress toward volume production of laser diodes began in 1995 with the acquisition of some proprietary technology from Uniphase. In 1996, Coherent paid \$16 million to acquire 80% of Tutcore [Tampere, Finland], a company experienced in the production of epi wafers for lasers and other optoelectronic devices. And then last year the company opened a new laser diode manufacturing facility at its Santa Clara headquarters.

Coherent's focus is on high-power devices, and, according to Todd, "the future of high power laser diodes is in materials processing and medical applications". Coherent is a proponent of using InGaAsP for high-power applications. Some comparison studies of AlGaAs and this "Al-free" material show improved performance of InGaAsP in areas such as resistance to dark-line defects, sudden failures, and gradual degradation. Coherent says that the absence of aluminum, which typically experiences oxidation problems during wafer processing, and the availability of highly selective wet chemical etchants make the processing of InGaAsP much simpler than AlGaAs.

The company says it has developed and patented new facet-coating techniques which significantly increase COD (catastrophic optical damage) levels and improve lifetimes. In addition, the company has been working on proprietary high-efficiency fiber-coupling techniques. All of this has been incorporated into the introduction of several new products. These include:

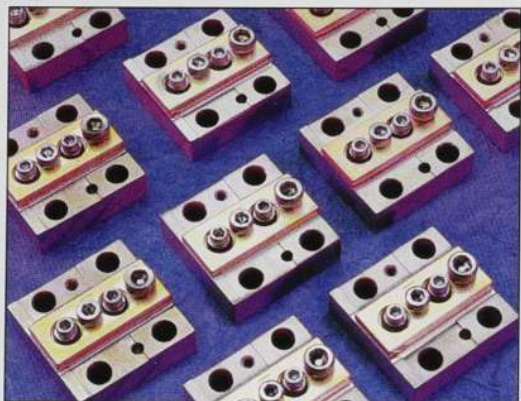
- 40W 808 nm Bars

Available from stock in 800 nm to 820 nm wavelengths. These bars are 1cm linear arrays mounted on conduction-cooled packages. The company says they do not require a special operating environment, and thus can be easily integrated into existing applications.

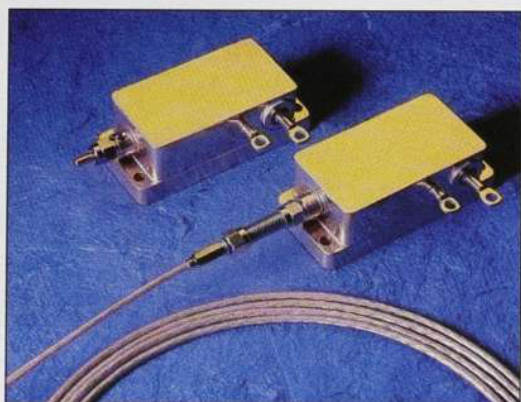
- Fiber-Coupled, Single-Stripe Laser Diodes

Available in 670 nm, 810 nm and 830 nm wavelengths. The company says its proprietary packaging gives these devices a smaller package volume than the competition. This type of device is being widely deployed in the reprographics industry. Other applications include medical diagnostics and illumination. The typical package offers >80% coupling efficiency from a single-stripe laser diode and has a beam divergence of <0.15 N.A.

cont. on page 6



Coherent



Coherent

40W 808nm laser diode bars (top) and 30W fiber array packaged bars (bottom) recently introduced by Coherent's Semiconductor Group.

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• 30W Fiber Array Packaged (FAP) Bars

Coherent says that its Fiber Array Packaged (FAP™) diodes provide easy integration, and they are "the simplest and easiest way to deliver up to 30W of laser output." Applications include material processing, marking, and laser pumping at 808 nm. Also available is the new FAP-System™, which is a turn-key 30W system which includes controls for the operating temperature of the laser diode, as well as current and pulse width.

In addition, Coherent is shipping 500 mW, 670 nm laser diodes with a 100 µm stripe, and recently introduced a higher brightness device that produces 350 mW from a 50 µm stripe. According to the company, this is 2 to 4 times the brightness of other commercially available diodes at this wavelength. These devices have been tested extensively in various operating conditions. Lifetests showed over 8,000 hours of continuous operation at 25°C with no failures.

One of the most well-known applications for red lasers is DVD pick-ups, but Todd says that Coherent is eschewing that highly competitive market in favor of higher power applications. Of particular interest is photodynamic therapy, which uses laser light to activate drug in the bloodstream. Only a few photodynamic drugs have been approved for use so far, and they require use of 1-2 W lasers in the 630 - 650 nm range.

Todd also reports that Coherent is not actively planning any telecommunications-related products at this time, in order to allow it to focus on its existing market.

For the quarter ended March 28, 1998, Coherent reported record sales of \$105.9 million, up 16% over the year-ago period. Net income, which was \$6.8 million, was 23% lower than the same quarter last year. This was attributed to lower gross profit as a percentage of sales due to manufacturing problems associated with yield issues on key purchased components, and higher research and development spending. Separate figures for the Semiconductor Group are not available.

Coherent at a Glance

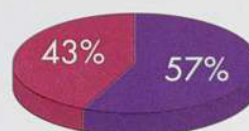
Corporate Headquarters: Santa Clara, CA
1997 Revenues: \$391 million
Employees: 2100
NASDAQ Symbol: COHR

Operations

- **Coherent Medical** (Palo Alto, CA) — Lasers for aesthetic procedures, select for urology, orthopedics, ophthalmology
- **Coherent Laser Group** (Santa Clara, CA) — CW Ion lasers and tunable/dye lasers, CO₂ lasers, pulsed solid-state lasers (Nd:YAG), ultrafast modelocked Ti:S lasers
- **Coherent Auburn Instruments** (Auburn, CA) — Optics and related equipment as well as laser measurement instruments and laser cooling systems
- **Lambda Physik GmbH** (Göttingen, Germany) — Excimer lasers, pulsed diode-pumped solid-state lasers, pulsed tunable systems (190 nm - 5 µm)
- **CFX Communications Systems** (Northboro, MA) — High-powered broadband transmission product line based on solid-state lasers
- **Coherent Semiconductor Group** (Santa Clara CA) — High power IR and red laser diodes for materials processing and medical applications

Coherent 1997 Sales Revenue

Medical
\$170M



Electro-Optical
\$221M

Electro-Optical includes all operations other than the Coherent Medical division.

Kopin to Acquire Korean Opto Producer

Kopin Corporation has announced an agreement to acquire a majority equity interest in Kowon Technology Co., Ltd., of Seoul, Korea, a producer of optoelectronic products. The equity investment by Kopin is expected to be approximately \$2,000,000.

Founded in January 1998, Kowon recently purchased the assets and business of the GaAs optoelectronics division of Sammi Steel Company of Korea, which formerly produced optoelectronic products for the Korean domestic and export markets. Kowon's products, mostly LEDs, are used primarily in consumer electronics products.

Dr. John C. C. Fan, president and CEO of Kopin, stated, "We

are delighted to have made this investment in Kowon, a company with strong manufacturing capabilities in the GaAs optoelectronics market. We believe that Kowon has the potential to grow rapidly in their target markets."

Dr. Jhang W. Lee, president of Kowon said, "We are very pleased with the opportunity to join forces with Kopin. Kopin's reputation as a world leader in gallium arsenide and other advanced semiconductor technology was a significant factor in our decision. We are looking forward to working with Kopin on new value added products for our existing and growing customer base." Prior to founding Kowon, Dr. Lee was the CEO of Sammi Technology Co., a subsidiary of Sammi Steel.

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Vixel Spins Off VCSEL Operation

Cielo Communications of Broomfield, Colorado has announced that it is introducing five new short- and long-wavelength optical transceivers based on VCSELs. Cielo is a new company in a familiar location - the former Bandgap facility in Broomfield, CO. Cielo was formed earlier this year by being spun out of its former parent, Vixel Corporation.

Vixel was founded in 1991 to commercialize VCSEL technology. In 1994 it acquired the former Bandgap epiwafer facility. In 1996 it acquired the Western Digital Connectivity Solutions Group, a company which specialized in Fibre Channel products. The company's headquarters were relocated to the Seattle, Washington area, where the Fibre Channel efforts were based. The Broomfield operation continued to work on VCSEL development and Gigabit Ethernet products, and these are the areas which Cielo will continue to pursue, while Vixel focuses exclusively on Fiber Channel. At this time, Vixel is not planning to use VCSELs in any of its products, but a company spokesperson said they may revisit VCSEL technology at a later date when it is more mature.

Expansion, Patent Deal at Tecstar

Space solar cell manufacturer Tecstar Inc. recently announced that it has added an additional 10,000 square feet of manufacturing space at its Applied Solar Division's plant in City Of Industry, CA. This brings the total footage offering full solar array deployment and test capabilities to more than 31,000 square feet.

Tecstar recently brought its 13th MOCVD reactor on-line. Their current GaAs solar cell capacity is now 350 kW per year.

Tecstar also announced last month that it had signed a patent agreement with NREL (The National Renewable Energy Laboratory, located in Golden, CO) for new solar cell technology which could allow satellite on-board power to be increased by as much as 50%. The agreement covers two U.S. patents. Tecstar has adapted NREL's GaInP dual-junction technology for growth on germanium substrates to reduce costs. According to Tecstar, the new cells will also have a longer useful life and are more rad-hard.

OSA Announces 1998 Award Winners

The 1998 Optical Society of America (OSA) award winners include three well-known individuals from the compound semiconductor field.

George Craford of Hewlett-Packard has been awarded the Nick Holyonyak, Jr. Award for contributions to optics based on semiconductor materials. He is being recognized for "the research and development of visible-wavelength LED materials and devices, including the first yellow LED and the high-brightness, transparent-substrate, red-orange-yellow InAlGaP LED that exceeds in performance the incandescent lamp". Craford joined HP in 1979; currently, he is the R&D manager in the Optoelectronics Division.

Kenichi Iga has been awarded the John Tyndall Award for contributions to fiber optics technology. He is being recognized for "the development of surface emitting lasers and planar microlens arrays for parallel optoelectronics". Iga is the director of the Precision and Intelligence Laboratory at the Tokyo Institute of Technology. He is presently researching surface emitting lasers and microoptic systems, mostly on 2-D array devices. In 1997-1980 Iga was a visiting technical staff member at Bell Laboratories, and was engaged in GaInAsP/InP technology for single-mode lasers and integrated optics.

Amnon Yariv has been awarded the Esther Hoffman Beller Award for contributions to optical science education. He is being recognized "for educating a significant number of current leaders in optics/optoelectronics, and for authoring seminal textbooks, thus enable early and now-ubiquitous adoption of optics into undergraduate and graduate curricula". Yariv is a Professor of Applied Physics at CalTech. Yariv took part in the discover of a number of early solid-state laser systems, and the invention of the distributed feedback laser. His present research efforts are in the areas of nonlinear optics, semiconductor lasers, and periodic optical waveguides.

The awards will be presented at the OSA Annual Meeting in October in Baltimore, MD.

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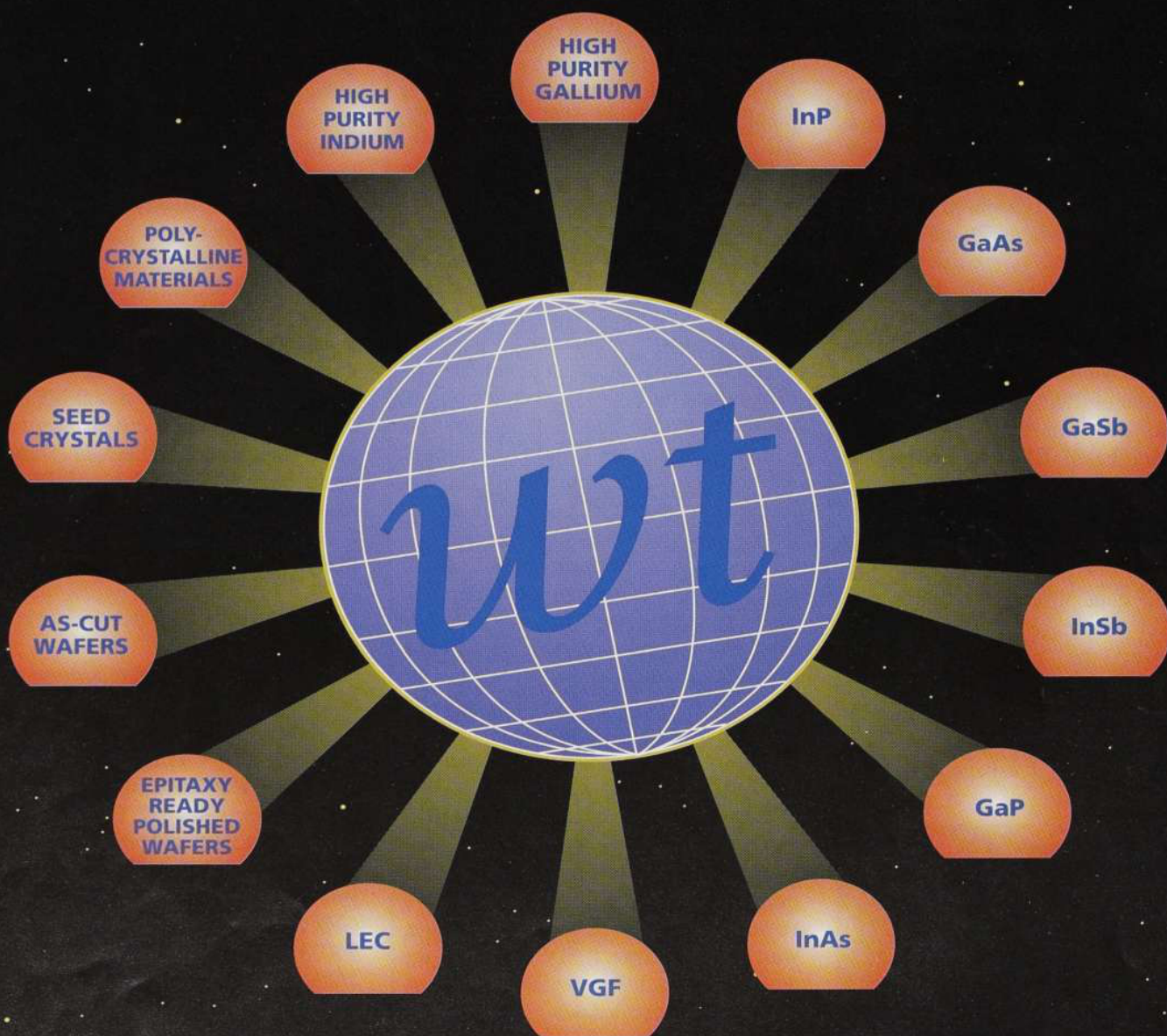
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IPRM Highlights

As usual, the InP and Related Materials Conference, held May 11 - 15 at Tsukuba, Japan, was the place to be for the latest research results, ranging from electronic devices to optoelectronics applications, as well as including fundamental materials work, and novel applications. This year's conference included 220 papers with a record attendance in excess of 450.

Electronic Devices

Dwight Streit of TRW reported on efforts to move InP-based electronics out of the realm of military-only applications and into true commercial production. TRW's InP-based HBTs which will be slated for commercial and space and defense applications, have baseline characteristics of $f_{\max}$ and f_t of 140 and 88 GHz, respectively, at a current density of 60 kA/cm² and collector bias of 2 V.

A key advantage which these HBTs offer over the more conventional AlGaAs/GaAs HBTs, is that the use of an InGaAs base results in a device turn on voltage of 0.7 V, as compared to GaAs HBTs with a turn on voltage of 1.3 V -

making InP-based HBTs well suited for low voltage, battery operated applications. When utilized in the all-important commercial wireless regime from 800-2400 MHz, InP-based HBT power amplifiers exhibited 50% PAE at 950 MHz and 1.5 V collector bias, and 68% PAE and 20 dB gain at 1.9 GHz with 2.7 V bias.

For devices of a more experimental nature, R. Pulella and coworkers from the **University of California at Santa Barbara** reported on InP-based HBTs utilizing their transferred substrate approach which allows minimum geometries of both the emitter and collector, and therefore reduce junction capacitances which result in peak f_t and $f_{\max}$ values of 220 and 470 GHz, respectively. Using this technology, an ECL static frequency divider operating at a clock frequency of 48 GHz with a power dissipation of 380 mW from a -5 V supply was fabricated. These devices utilize 0.6x8 μm^2 emitters. Their analysis indicates that scaling down the emitters to 0.2 μm should produce digital ICs operating at clock rates > 80 GHz. Other circuit results included those presented by I. Adesida and coworkers from the **University of Illinois** on their enhancement/depletion (E/D) HEMT process in the fabrication of a DCFL 23-stage ring oscillator which exhibited a propagation delay of 16.72 ps/stage and a power-delay product of 0.322 fJ/stage, which is the lowest PDP reported for devices in the InP material system. A divide by 4 prescaler was also fabricated which worked up to 6 GHz with a power dissipation of only 5.37 mW/stage.

While the method of growth for InP-based electronic devices is done almost exclusively by MBE, Dan Docter and coworkers at the **Hughes Research Laboratories**, reported on the MOVPE growth of InAlAs/InGaAs HEMTs. By growing in a regime which produced a minimum background charge in the HEMT of less than $9 \times 10^9 \text{ cm}^{-2}$, the resulting Hall measurements showed mobilities

of 10,500 cm²/Vsec for channel charges up to $4 \times 10^{12} \text{ cm}^{-2}$. Gate-lengths of 0.15 μm were used in the fabrication of HEMTs which exhibited an f_t of 108 GHz along with a minimum NF of 1.3 dB and gain of 10 dB at 26 GHz operation, demonstrating that MOVPE growth can be applied to low cost production of InAlAs/InGaAs HEMTs for RF and low noise applications.

By utilizing a two-step gate recess process in order to suppress the parasitic resistance which can occur due to side-etching around the gate periphery during the gate recess process, Tetsuya Suemitsu and coworkers reported on NTT's 0.1 μm InAlAs/InGaAs enhancement-mode HEMT process. The devices exhibited a positive threshold voltage of 49 mV, a transconductance of 912 mS/mm, and an f_t and $f_{\max}$ of 208 and 460 GHz, respectively.

Photonic Devices

There were several reports on monolithic integrated optoelectronic receivers.

Kursad Kiziloglu and coworkers from the **Hughes Research Laboratories** reported on a receiver which utilized an HBT, HEMT and a pin diode fabricated from the base-collector region of the HBT. A flat transimpedance gain of 6 kohm with a bandwidth of 2.5 GHz was observed for a supply voltage of 2.8-3.0 V. At a 10⁻⁹ BER, a sensitivity of -18.5 dBm was observed for 7 Gb/s operation.

Utilizing a HEMT and a top illuminated pin photodiode grown by MOCVD, I. Adesida from the **University of Illinois**, reported on a three stage transimpedance amplifier. With a BER of 10⁻⁹, the packaged photoreceiver showed a sensitivity of -17.7 dBm at 10 Gb/s and -15.8 dBm at 12 Gb/s. And D. Huber and coworkers from the **Swiss Federal Institute of Technology** reported on a pin/HBT photoreceiver which exhibited a bandwidth of 23 GHz, along with a tran-

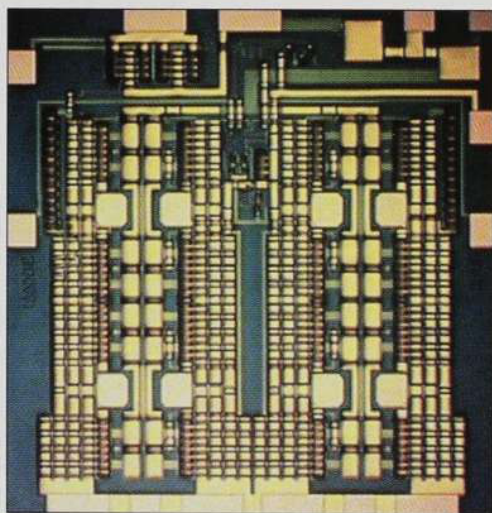


Photo of an InP-based 1.9 GHz power amplifier, fabricated by TRW. PAE of 68% and 20dB gain from such devices was reported at this year's IPRM.

impedance-bandwidth product of 12 THz/ohm - one of the highest values reported to date.

A wide range of laser work was reported. This included results presented by M. Kondow from **Hitachi** on GaInNAs/GaAs lasers pseudomorphically grown on GaAs substrates which are suitable for 1.3-1.55 μm operation. With the very deep QWs which can be obtained in this material system, an improvement in high temperature operation is expected as compared to the more conventional InGaAsP long wavelength lasers which experience poor high temperature behavior due to shallow QWs. VCSELs were fabricated for 1.18 μm operation which exhibited a threshold current density of 3.8 kA/cm² (threshold current of 61 mA) and an output power 5 mW. Using the more conventional GaInAsP/InP material system, M. Fujita and coworkers from **Yokohama National University** reported on cw lasing in a GaInAsP/InP microdisk injection laser at room temperature for the first time. Record low threshold current of 150 microamp was obtained at 1.63 μm operation.

One of the major difficulties in fabricating InP-based VCSELs is due to the small index of refraction changes between InP-based alloys, making the fabrication of high reflectivity mirrors nearly impossible. To circumvent this limitation, H. Gebretsadik and coworkers at the **University of Illinois** first grew a 45.5 period InP/InGaAsP DBR, the laser active region, and a thin InAlAs layer all of which were patterned and then etched to form 2 μm high and 20-40 μm diameter mesas. Subsequently, during a second growth, a short 5 period AlGaAs/GaAs DBR is grown defect-free on top of the mesa where a larger degree of strain can be accommodated as a result of growing on the patterned substrate. In a different approach to solve the same problem, S. Rapp and coworkers from the **Swedish Royal Institute of Technology** use a fused AlGaAs/GaAs top DBR, resulting in a VCSEL operating in pulsed mode at temperatures up to 40°C. And C. Starck and coworkers from Alcatel Alsthom grew a metamorphic GaAs/AlGaAs top DBR, without any prior mesa etching, and obtained lasing in pulsed mode.

SILICON UPDATE

A Truly Insulating Silicon Substrate

ROBERT A. METZGER



We all know that one of the strongest selling points in using III-V technology for RF applications is the availability of a highly insulating substrate. Unlike silicon substrates, which at best can be made resistive into the mid 10^3 ohm-cm range, both GaAs and InP substrates can be fabricated with resistances in the 10^6 - 10^8 ohm-cm range. This characteristic helps reduce parallel current pathways through the substrate and allows the fabrication of high quality passive elements which are not degraded through RF coupling to a conductive substrate.

Researchers at Hitachi [Tokyo, Japan] have put a new twist on this silicon limitation, implementing a relatively simple processing step which effectively transforms portions of the silicon substrate into highly resistive regions. Utilizing an SOI substrate which has 70 nm of silicon atop 300 nm of SiO₂, a 0.1 μm CMOS process featuring dual poly-Si gates in which both the source/drain region and the gate electrode are selectively coated with tungsten, is implemented. The resulting T-shaped gate structure exhibits a low resistance of 1.8 ohm/square, making it suitable for high frequency operation. This CMOS process exhibited an f_t of 40 and 25 GHz for NMOS and PMOS structures, respectively, at a current density of 3×10^{-2} mA/ μm .

The use of SOI substrates improves device leakage by eliminating conductive electrical paths due to the SiO₂ beneath the device, but does nothing to improve the parasitic and RF degradation due to RF coupling to the silicon substrate beneath the buried oxide. This roadblock is eliminated by etching away of the silicon beneath the buried oxide to form suspended device structures. The etching of the silicon substrate is done after the final passivation step in a three layer metallization process, through small openings which are fabricated to

expose the silicon substrate beneath the buried oxide. By dry etching in SF₆, a high selectivity is obtained between silicon and SiO₂, such that large cavities with 100 μm depths are formed beneath both the CMOS circuits as well as the spiral inductors used in this process.

Control samples fabricated for comparison, in which the silicon substrate was not selectively removed, were also fabricated. Spiral inductors on the suspended circuitry exhibited a Q of 10 at 5 GHz, as compared to a value of 4 for the control samples. The self resonance of the inductors was also measured, in which F_r for the suspended and conventional inductors were 19.6 and 8.7 GHz, respectively.

One potential drawback of the suspended structure is its susceptibility to short channel effects, since the high potential of the drain region penetrates through the air gap (with its small dielectric constant) beneath the device, which lowers the source barrier and degrades device performance. However, very little degradation was observed for 0.15 μm gate length devices, as compared to long channel devices, in which the subthreshold slope increased slightly from 67 and 63 mV/decade for long channel NMOS and PMOS devices, respectively, to 75 and 79 mV/decade, respectively, for the short channel devices. Simulations show that only minimal degradation takes place because the gate potential prevents the lateral spread of the drain potential through the buried oxide and effectively shields the source region.

This process opens the way for good RF performance through the commercially critical frequency regions up to 2.4 GHz, utilizing a silicon ULSI process - potentially allowing the fabrication of single chip radios incorporating both the front end and baseband portions, and not requiring any step down to IF frequencies. This is a technology that the III-V community certainly needs to keep a watch on.

New GaN MOCVD System Supplier Established in Korea

Hanvac Corporation recently announced that it is offering for sale a new MOCVD system for the growth of GaN and related materials. Hanvac was formed in 1995 by a group of researchers from KRISS (the Korea Research Institute of Standards and Science). The company reports that it has been manufacturing vacuum systems since 1995, but only began offering MOCVD systems earlier this year. The first of these systems, which carry the trade name "Solomon", is currently in use at Optel in Korea for developmental-scale production of blue LEDs. The company says it will offer the systems for export outside of Korea.

Aixtron First Quarter Results

For the first quarter of 1998, MOVPE system manufacturer Aixtron reported revenues of DM 28M (US\$ 15.8M) and net income DM 3M (US \$1.7M). The geographic distribution of revenues was 44% North America, 37% Asia, and 19% Europe. The company reports that orders valued at DM 13.8M (US \$7.8M) were booked in the quarter, and that 21 MOVPE reactors were shipped in the quarter and 28 more are in production.

The company says it is not concerned about the Asian financial turmoil having a negative impact on its business. They cite a number of factors, including relatively low exposure to most the severely troubled "tiger economies", a healthy current backlog from Japanese and Taiwanese companies (equaling 57% of current orders), and a diversified customer base, with no single company accounting for more than 5% of turnover.

Aixtron is forecasting revenues of over DM 103M (US \$58.3M) and income of DM 10M (US\$ 5.6M) for 1998.



QED Develops Higher Mobility PHEMT Growth Process

Quantum Epitaxial Designs reports that it has developed a proprietary MBE growth process that, when applied to the growth of power PHEMT structures, delivers significantly higher 2DEG mobility for a given channel charge. Associated with the enhanced mobility is an increased electron saturated velocity. Therefore, in addition to an enhanced extrinsic transconductance through reduced access resistance, this material enables higher frequency and higher power density devices and circuits.

According to Scott Massie, QED Vice President of Operations, the new growth process shows significant increases in the PHEMT figure of merit (defined as the product of the 2DEG concentration and associated Hall mobility at 77K). He says "We achieved these improvements on multiple customers' structures and have demonstrated successful transfer of this technology between MBE reactors."

According to the company, the performance observed in the enhanced mobility power PHEMT material makes it an excellent material choice for device applications ranging from 1.9 GHz up to millimeter-wave frequencies.

Briefly...

Emcore SiC Production System to Siemens...Emcore has launched a new SiC MOCVD system designed for SiC growth. The company reports that the first of these new systems, which can handle up to 6 x 2" wafers, was recently delivered to the SiC research group at the Siemens AG Corporate Technology laboratory in Erlangen, Germany.

Bio-Rad Wins Export Award...Bio-Rad Micromeritics has won the U.K.'s 1998 Queen's Award for Export Achievement. The award is being given to the company for semiconductor characterization and process monitoring equipment.

Hitachi Cable Expands GaAs Epiwafer, SI Substrate Production...Hitachi Cable recently announced that it has more than doubled its GaAs epiwafer production capacity at its Takasago Works in Ibaraki

prefecture. Capacity now exceeds 7000 4" wafers a month. The company says it also recently increased its production capacity for semi-insulating 4" GaAs substrates, to correspond to the continuing industry-wide transition from 3" to 4" GaAs substrates. They are also adding on capacity for producing 5" and 6" GaAs wafers.

Oxford Etching System for Alpha...

Oxford Plasma Technology recently announced the sale of two Plasmalab 90 Plus systems for batch etching of GaAs through wafer vias to Alpha Industries. The company also reported that 1997 was its best year ever for sales of plasma etching and deposition equipment, and that they are forecasting further increases in 1998.

Epiwafer Expansion at Epitronics...

Epitronics recently announced that evaluation samples of production process-qualified epitaxial wafers from its new Aixtron 2400/2600 G3 MOCVD tool were now available to selected customers. According to the company, this is the first GaAs epitaxial machine with full cassette-to-cassette automated wafer handling capability. The automated wafer handling is expected to improve both wafer throughput and yield as compared to that obtained using manual handling.

Plasma-Therm Etcher To Motorola...

Plasma-Therm recently announced sale of a Versalock plasma processing system to Motorola for use in high volume compound semiconductor fabrication. The system uses Inductively Coupled Plasma (ICP) technology.

Acquisitions...

On May 5 Air Products and Chemicals announced that it had completed its purchase of Solkatronic Chemicals from Solvay America... Materials manufacturer Eagle-Picher Industries has been acquired by Granaria Holdings BV, a Dutch investment firm, for \$700M...Philips Analytical has completed the acquisition of semiconductor metrology equipment manufacturer Plasmos GmbH of Munich Germany. Terms were not disclosed.

Competition Spices Up Blue LED Market

As more companies are getting into the business of making blue and green LEDs, market leader Nichia is trying to push out the range of wavelengths that can be covered by InGaN active layer devices

MARIE MEYER

LEDs are undoubtedly the biggest application for wide bandgap materials, in terms of both unit volume and revenue. The market for GaN-based blue and green LEDs is currently valued at around \$200 million/year, but it is growing at 40 - 50% per year.

As the market is growing, so is the competition. More companies are entering the field, and prices are eroding rapidly as blue and (to a lesser extent) green LEDs become less of a novelty and more of a commodity. But Nichia Chemical, always the innovator, recently introduced a new wrinkle by revealing that it had made significant progress toward extending the wavelength that can be covered by

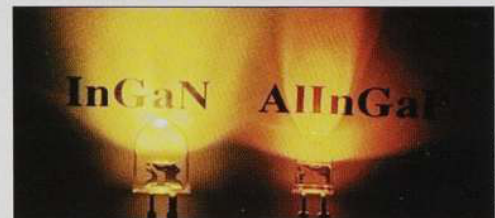
InGaN-active layer devices out to the amber region. Currently, almost all high-brightness red, orange and amber LEDs, are made from AlInGaP; however, the efficiency of this material system drops when moving from red toward the shorter wavelengths.

Nichia's amber LEDs have a luminous efficiency of 10 lm/W at a wavelength of 594nm. This compares well with AlInGaP-on-GaAs LEDs from Hewlett-Packard, but is not as good as HP's highest brightness commercial models, especially its AlInGaP-on-GaP models. See Table One, page 16.

At a current of 20mA, the InGaN amber LED had an external quantum effi-



Hewlett-Packard



Nichia Chemical

Top: Examples of Hewlett-Packard's new green LEDs; Bottom: An InGaN-based amber LED from Nichia, compared to a more conventional AlInGaP device.

ciency of 3.3%, and an output power of 1.4mW. One very interesting aspect of the Nichia demonstration is that the output power remains almost constant as the temperature was increased from RT to 80°C. In contrast, the output power of the AlInGaP LED decreased dramatically under these same conditions. See Figure One.

The one area where the InGaN LED was clearly inferior to the AlInGaP model was its spectral purity. Its FWHM was 50nm, compared to 17nm for the HP LED. See Figure 2. Shuji Nakamura, head of R&D at Nichia, conjectures that this may be due to fluctuations in the composition of the InGaN active layer. Nakamura reports that the structure of the amber LED is basically the same as that used in Nichia's blue and green LEDs, only with more In in the active layer.

Nakamura believes that the amber InGaN can be produced more cheaply than AlInGaP LEDs, because of the less expensive starting materials (especially the sapphire substrate) and the absence of toxic materials. He also thinks that red InGaN LEDs are feasible. Development work on the amber LEDs is now essentially finished, and the company is now getting the process ready for mass production. Nakamura says the devices will be available as soon as production capacity allows.

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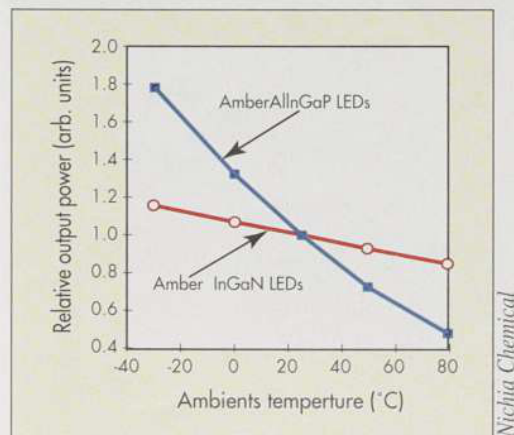


Figure One: Output power of InGaN and AlInGaP amber LEDs as a function of the ambient temperature.

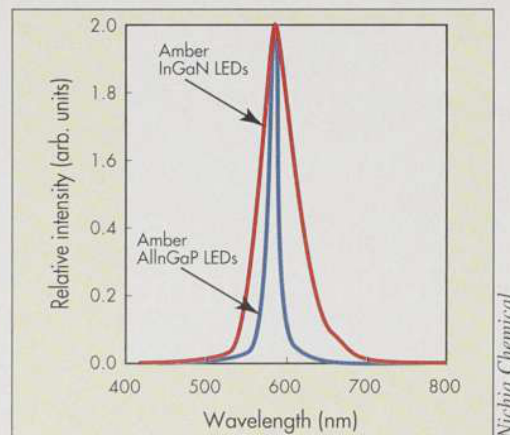


Figure Two: The emission spectra of InGaN and AlInGaP amber LEDs at a forward current of 20 mA.

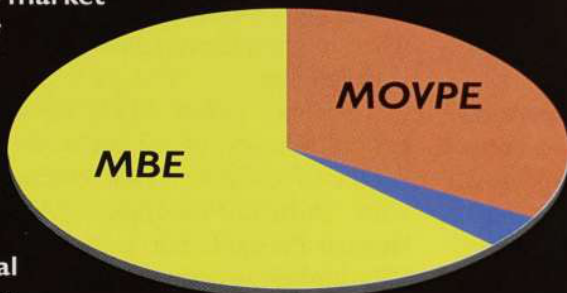
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HP First Over the Rainbow

If Nichia can develop red LEDs, they'll be able to offer the full palette of visible wavelengths. HP is already in this enviable position, having announced the availability of 505nm and 525nm green InGaN LEDs in mid-May. They join HP's previously announced 473nm InGaN blue LEDs and, of course, its wide range of AlInGaP-based LEDs in longer wavelengths.

HP is just the third company to offer green InGaN LEDs (the other two are Toyoda Gosei and Nichia). The 505nm LEDs are suitable for use in U.S. traffic signals. They provide intensities of up to 2.3 cd. The 525 nm lamps are more of a "true green", of the type that might be used in displays.

HP will soon be introducing a family of 5-mm oval lamps in 470nm blue and 525nm green, as well as AlInGaP red (626nm and 630nm). This product family, which will be lensed so that the radiation patterns are matched, is intended for

use in full-color outdoor signs and related applications such as arena scoreboards.

Displays remain the most popular application for blue and green LEDs. (See photo). Traffic signals look like a good future prospect. LED signals consume 85% less energy than incandescent lamps, and they also require less maintenance. But for now, the prices of green LEDs are still too high. A 12" red LED signal currently costs \$135, and pays for itself in 30 months, says Mike Friedman of ElectroTech, a manufacturer of traffic signals. But that same signal in green would cost more than \$400, making it a less attractive investment. But Friedman predicts lower prices now that there is more competition and greater production capacity. "We expect the price to drop by half over the next 24 months" he says.

Some cost reductions have already been seen. HP is introducing the green LEDs at \$0.75 per piece; in comparison, its blue LEDs were priced at \$1.40 piece when introduced last fall. HP's Northe Osbrink says that the price reductions are

due to increased capacity and the higher volume. HP's current capacity for GaN-based LEDs is ~3 million units/month, with plans to increase to ~9 million units/month in early 1999. In comparison, Nichia's current capacity is said to be ~15 million units/month.

More from Japan

The other companies in the "old guard" of blue LED manufacturing aren't standing still. Toyoda Gosei recently expanded its product line to include green LEDs as well as blue and green LEDs in low-profile surface-mount packages. They also report that they will be revamping their product line again this summer. Some - but not all - of HP's blue and green LEDs are believed to be fabricated on epiwafers purchased from Toyoda Gosei.

Matsushita has recently begun selling 1.4 cd blue LEDs in the U.S. under the Panasonic brand name. In addition, Stanley and Rohm are believed to be planning to enter the market. Both companies are already well-established in the Japanese optoelectronic components market - in fact, Stanley is one of the world's largest LED manufacturers.

cont. on page 18

Table One:

InGaN Amber LEDs as Good as AlInGaP? HP Responds

	Nichia InGaN [1]	Hewlett Packard AlInGaP on GaAs [2]	HewlettPackard AlInGaP on GaP [3]
Dominant Wavelength (nm)	594	591	595
Electroluminescence FWHM (nm)	50	17	17
Efficiency (lm/A)	33	44	86
Efficiency (lm/W)	10	22	40
External Quantum Efficiency (%)	3.3	5.0	10.5
Power Out (mW)	1.4	1.9	4.4
Wallplug Efficiency (%)	2.1	5.2	10.2
V _f	3.3	2.0	2.15

[1] Data reported in Jpn. J. Appl. Phys. 37 Pt. 2 (5A), L479-481 (1998).

[2] Data reported in Appl. Phys. Lett. 61 (9), 1045-1047 (1992).

[3] Data reported in Proceedings of the IEEE, 85 (11) 1752-1764 (1997).

Table One: Characteristics of the InGaN amber LEDs recently reported by Nichia, compared to two AlInGaP LEDs from Hewlett-Packard. All values were measured at 20 mA at room temperature (-25°C). The values in *italic* are approximate. The amber LED characterized in the third column uses a GaAs substrate which absorbs a portion of the emitted light, negatively impacting the overall performance of the LED. But the LED characterized in the fourth column has a GaP substrate that is transparent to the emitted light, resulting in improved performance.

According to HP, the data given here for their AlInGaP LEDs reflects the characteristics of products which are in current production. Nevertheless, the Nichia result remains impressive, given the relative immaturity of InGaN technology in comparison to the more established III-V materials.



"LEDs are what I want, what I really, really, want"...The Spice Girls are just one of the pop groups who are using gigantic LED video displays manufactured by Saco Smartvision of Montreal. Each of these displays requires around half a million LEDs - not surprisingly. Saco is thought to be Nichia's biggest customer. Shown here is Ginger Spice on a 19' x 14' display - no word yet on whether she'll be getting one of her own for her solo career.

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PbZrTiO
SrBaTi(N)
SrTiO
YBaCuO
Si
SiGe
Cu
W
Pd
TiN

Cree & Siemens

Since its inception, Cree Research has been the only company to offer LEDs based on SiC substrates. Their first products, in the early 1990's, were 10 mcd indirect bandgap SiC-only LEDs. They subsequently introduced direct bandgap GaN-on-SiC devices which were 40 - 100 times brighter.

The reasons why SiC should be superior to sapphire as a substrate for GaN growth are numerous. For starters, it is a conductor, not an insulator. The three other most important factors are 1) a lattice mismatch with GaN of just 3%, whereas the sapphire-GaN mismatch is 15%; 2) higher thermal conductivity; and 3) natural cleavage planes.

However, these theoretical advantages are just now being turned into competitive advantages in the marketplace. Part of the reason for the delay is that the very large majority of the worldwide R&D on blue emitters has been based on sapphire substrates ever since Nakamura demonstrated that this was a feasible approach in 1993 with the first 1 cd blue LED. In his recent book, "The Blue Laser Diode", Nakamura seemed to acknowledge that SiC was probably a superior choice for a substrate, but he has never employed it in his work because of what he described as its "extraordinary" expense.

This has left Cree to go it alone. And while their products are still not as bright as GaN-on-sapphire LEDs, and they don't have the same spectral purity (see Table Two), the company says that important

new developments are on their way.

Cree recently overhauled its LED production, switching over to a new vertical device structure which should be much cheaper to produce. For the first time, blue LEDs can be fabricated with top and bottom contacts, like GaAs- or GaP-based LEDs. This is an advantage provided by the conducting SiC substrate. In earlier generations of devices, Cree found it necessary to use an insulating buffer layer to get the desired brightness from the InGaN active layer. Thus an unusual metal contact running down the edge of the LED chip was required to make the contact. But in the new conductive buffer layer (CBL) structure, Cree has managed to dope the buffer layer sufficiently to enable the vertical structure. According to Chuck Swoboda, Chief Operating Officer at Cree, the CBL LED requires only half as many processing steps as the older LED models, enabling significant cost reductions and productivity gains. The chip is also brighter, because it has a larger emitting area, and because it is more efficient. The CBL is 53% brighter than the previous product, which has been discontinued.

The company says that its market strategy is to be the low-cost leader. Prices are currently ~\$0.25 per piece, which is 2 - 4 times lower than their competition. According to Cree CEO Neal Hunter, the company is pushing toward even lower prices, because they believe that significant new markets cannot be opened up until the price approaches \$0.10. Examples of new applications that might be available at this price point

include printers and scanners.

The successful transition to the CBL process was an important milestone in Cree's effort to reduce costs. With that complete, according to Hunter, the company will begin focusing on higher brightness products and other colors. Cree plans to introduce both a brighter blue LED and their first green LED this fall.

And Cree won't be the only GaN-on-SiC producer any longer. Siemens recently began manufacturing its own blue LEDs under license from Cree, using the CBL process. Siemens is currently Cree's largest customer. Together they landed this summer's coolest application for LEDs - a blue backlight for the instrument panel on the newly reintroduced Volkswagen Beetle. Cree believes that their use of SiC enabled them to meet the low price required for this application, because of the small chip size and vertical device structure.

Siemens will launch volume production of a white LED within the next few months. This product is based on the LUCOLED (luminescence conversion LEDs) technology developed at Fraunhofer IAF in Freiburg, Germany. The LUCOLED combines a blue LED with an organic dye or an inorganic phosphor, emitting at longer wavelengths, to synthesize white light by additive color mixing. A wide range of colors can be produced by changing the dye or phosphor. See photo, below.

The Siemens white light LEDs will be offered in surface mount packages, targeting automotive applications first.

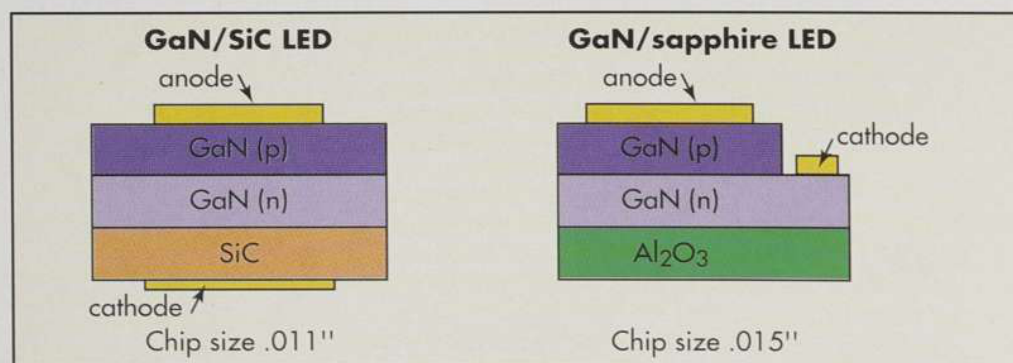


Figure Two: GaN-on-SiC blue LEDs (left) can be made using a vertical device structure like those used in GaAs- and GaP-based LEDs. Sapphire-based LEDs (right) are unique in that they use an insulating substrate (SiC, GaAs and GaP are all conductors). As a result, they require an extra wire bond and specialized equipment to accommodate the extra top contact.



Examples of LUCOLEDs (luminescence conversion LEDs) developed at the Fraunhofer IAF.

Uniroyal

The next new entrant will likely be Uniroyal Technology Corporation (Sarasota, FL), which has a joint venture with Emcore aimed at manufacturing InGaN-on-sapphire blue and green LEDs. A new subsidiary, Uniroyal Optoelectronics, has been formed for this purpose. The company expects sales of epitaxial wafers and chips for LEDs will begin in the third quarter of this year.

According to Bob Soran, Chief Operating Officer at Uniroyal, the company is in the final stages of selecting a site for setting up a new manufacturing facility for the Optoelectronics division. Uniroyal has licensed the process for making the LEDs from Emcore on a non-exclusive basis. As we reported in our last issue (CS 4(4), p. 13), Emcore claims to be the largest supplier of MOCVD reactors for high volume blue LED production, and they are also a merchant sup-

plier of blue LED wafers. The process currently yields a wavelength of 470nm, a FWHM of 30nm, and >1 mW radiant flux. This would put them at the low end of the scale in terms of brightness. But improvements are said to be in the works. Uniroyal says their sales strategy is to offer a quality product at competitive prices.

Uniroyal has not yet decided whether the packaging of the devices will be done

in-house or whether it will be contracted out, but they have indicated that they are considering doing a mixture of both.

Uniroyal Technology, a spin-off from Uniroyal Tire, manufactures plastic products and specialty chemical and polymer products, with 1997 sales of \$208 million. This is their first foray into the semiconductor business.

Perhaps GaN based LEDs are just the thing to "spice up" their product line.

Table Two: LED Specifications

Company	Color / Wavelength	FWHM	Luminous Intensity	Radiant Flux
Cree	Blue / 430nm	65nm	[1]	1.15 mW
HP	Blue / 473nm	35nm	1.1 cd	4.0 mW
	Green / 502nm	35nm	2.1 cd	3.5 mW
Nichia	Blue / 470nm	30nm	2 cd	3.0 mW
	Green / 525nm	40nm	6 cd	2.0 mW
Toyoda Gosei	Blue / 470nm	45nm	5.0 cd	[2]
	Green / 525nm	35nm	1.5 cd	[2]
Uniroyal	Blue / 470nm	30nm	[1]	1 mW

Notes: [1] Product is unpackaged, company does not specify luminous intensity. [2] Data not available.

Company datasheets



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SiC Transistor News

Cree Planning for Microwave SiC Products in 1998

Cree Research recently announced its intention to introduce microwave SiC MESFET products for the commercial market in 1999. The first target market will be power supplies for cellular base stations.

In March Cree announced the demonstration of a SiC MESFET with an output power of 53 W at 3.0 GHz. This result was achieved from a single chip with a die area of 3 mm² - a first-of-its-kind achievement.

Silicon-based microwave products capable of operating at higher power levels are already available, but these are typically multiple chip packages. SiC should be able to offer output power levels substantially higher than other solid-state products now on the market.

In 1996, total sales of cellular base station transistors were \$279M, according to Dataquest. At present, transistors are estimated to be 30 - 40% of the cost of a base station. Previously, most of these were fabricated from bipolar Si. But as the higher frequency PCS services are being rolled out, there has been a shift to LDMOS (laterally diffused metal-oxide-semiconductor) chips above 1 GHz, as they provide better linearity and gain.

According to Neal Hunter, president and CEO of Cree, SiC MESFETs will be able to provide better gain and linearity than LDMOS, and they will deliver 5 times the power at a given frequency. Cree hopes to supply a power amplifier which can deliver up to 400W using a few as four transistors. This could be an important factor, as base stations are expected to be smaller in size in the future due to tighter integration of component technology.

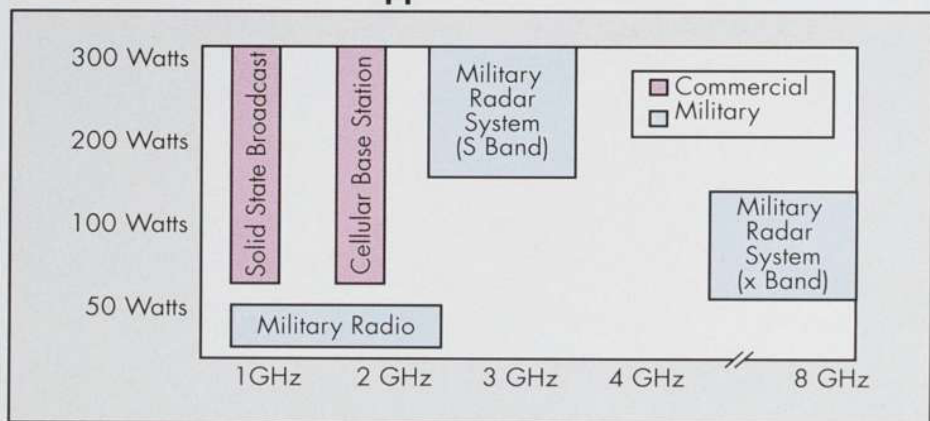
Cree's analysis of their advantages in terms of cost for the base station applications are shown in Table One. Table Two illustrates some of the other applications that are under consideration. Hunter says the company is working on a 50 watt product for X-Band radar that can deliver up to 50W for less than \$5/W, and than it can replace GaAs MMICs that deliver 10W for \$20 - \$30/W.

Table One: Base Station Transistors

Material	Est. Cost Per Watt of Power	Est. Transistors per Base Station
GaAs	\$3	20
LDMOS	\$1	10
SiC	\$0.75	4

Cree Research

Table Two: Microwave Applications



Cree Research

UK SiC Research Collaboration

A major collaboration has been launched in the United Kingdom to develop SiC technology. Project SCEPTRE (Silicon Carbide Electronics for High Temperature High Power Applications) has been funded for £1.3M (US\$2.1M) over 3 years.

The UK Engineering and Physical Sciences Research Council (EPSRC) has awarded £900k (\$1.47M) to the project, including £600k (\$981k) to Newcastle University for a national center of excellence for SiC research. Other EPSRC funded work is being carried out at University College Swansea and the University of Surrey, and several industrial participants will also fund their own work within the collaborative effort. The partners are DERA Electronics Sector (Malvern), Mitel Semiconductor (formerly GEC Plessey Semiconductors), GEC Alsthom Engineering Research Center, AEA Technology, Semelab, and GEC Marconi Materials Technology (GMMT) at Towcester. Existing internal programmes on SiC and packaging technology at DERA and AEA bring the total SiC activity in the UK to around £1 million (\$1.64M) per annum.

The overall aim of the program is to demonstrate generic processing techniques for SiC using devices as drivers for each technology area. Basic processing techniques, such as contacting, etching and passivation developed at Newcastle University and DERA will be used in the fabrication of power Schottky diodes and power MESFETs. Target ratings are 1kV and 10A for vertical power switching structures and 100W CW S-band performance for a lateral MESFET.

Complementary work, based at AEA Technology, GMMT and Semelab is investigating packaging for high temperature and high power applications. GEC Alsthom Engineering Research Center are constructing a SiC system demonstrator to utilize the device and packaging technology of the project.

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Ultraviolet Detectors at Honeywell

WEI YANG, THOMAS NOHAVA AND SUBASH KRISHNANKUTTY

HONEYWELL TECHNOLOGY CENTER
PLYMOUTH, MN

Honeywell Inc. has been in the business of making controls for over a hundred years - the company was founded in 1885 with the invention of the automatic thermostat control for home heating. Today's Honeywell is a global leader in control technology, with sales in excess of \$8 billion in 1997.

The Honeywell Technology Center (HTC) has worked with AlGaIn-based materials and UV detectors for close to two decades, including the investigation of GaN photoconductors and GaN/AlGaIn heterojunction photodiodes and phototransistors. HTC is currently making these devices available for internal Honeywell use, and flame sensors incorporating HTC's GaN photodiodes are being field-tested by various Honeywell divisions (see Figure 1).

$\text{Al}_x\text{Ga}_{1-x}\text{N}$ films across the alloy range have been grown by MOCVD on sapphire substrates at HTC. The optical transmission data from films with varying values of x demonstrates a sharp cut-off (or absorption edge) in each case, corresponding to the bandgap energy of the alloy. The cut-off wavelength decreases as the Al

content of the layer increases, varying from 365 nm for GaN ($x=0$, bandgap ~ 3.4 eV) to 200 nm for AlN ($x=1$, bandgap ~ 6.2 eV).

Photoconductors

When light of a suitable wavelength impinges on a photoconductor, the formation of electron-hole pairs changes the resistance. Photoconductive detectors with high internal gain based on this principle have been developed at HTC for flame sensing applications. The devices are fabricated from a single GaN layer grown on a sapphire substrate using an AlN buffer layer. The top metal electrode has a familiar interdigitated pattern.

High internal gain of greater than 10^5

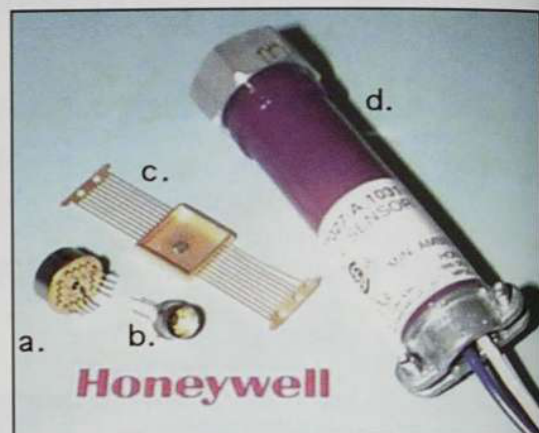


Figure 1. Honeywell's UV Detector Technology - (a) Photodiode (b) Photoconductor (c) Phototransistor and (d) Flame Sensor for burners/boilers incorporating (a).

has been measured from these devices. Despite this desirable property, photoconductors suffer from well known drawbacks, including high dark currents, DC drift, slow response time, and occasionally spurious photoresponse at long wavelengths. This makes them less useful for applications where DC operation is required or where response time is an issue. Such applications can be suitably addressed with photodiodes and phototransistors.

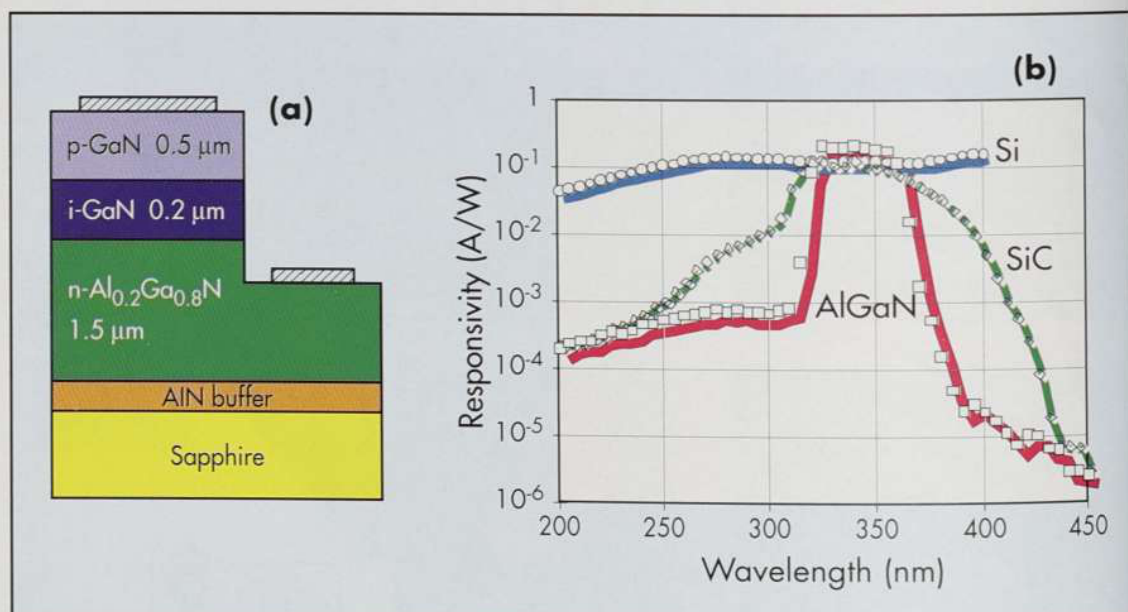


Figure 2. (a) Schematic of a back illuminated p-i-n GaN/AlGaIn heterojunction photodiode and (b) responsivity of the device compared to SiC (Cree) and Si (UDT) devices.

We acknowledge the generous support of the USAF Wright Laboratories, the Defense Advanced Research Project Agency (DARPA), and the Homes and Buildings Control Division of Honeywell. We also acknowledge stimulating discussions with Paul Ruden at the University of Minnesota.

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Photodiodes

Photodiodes are two-terminal devices designed to respond to light absorption. In a p-n junction photodiode, electron-hole pairs generated in, or within one diffusion length of, the depletion region create a photocurrent. The dimensions of the insulating layer in a p-i-n device can be designed to wholly contain the depletion region, allowing the sensitivity and frequency response to be optimized. Typically, photodiodes have gain at or below unity, unless operated in avalanche mode. If gain is required, it must be supplied externally, using a suitable amplifier.

GaN/AlGaIn heterojunction photodiodes have been developed at HTC under both internal contracts for flame sensing applications and external US Government contracts for missile warning applications. In addition to the sharp absorption edge provided by the GaN detector, it is also possible to include a wider bandgap region to provide a short wavelength cut-off, narrowing the spectral responsivity of the device.

Typical p-i-n device structures (figure 2) are grown on sapphire. This substrate is transparent to UV light, allowing the device to be rear-illuminated without having to worry about reflection from or absorption by the top metal contacts. The wider bandgap n-Al_{0.2}Ga_{0.8}N layer ($n = 2 \times 10^{18} \text{ cm}^{-3}$) provides a short wavelength cutoff, at around 325 nm in the example shown. The UV-absorbing layer is ~0.2 μm undoped GaN, and the device is capped with 0.5 μm GaN doped at $p = 2 \times 10^{17} \text{ cm}^{-3}$.

These devices have an external quantum efficiency in excess of 80%, and a peak responsivity of around 0.2 A/W at 360 nm (see Figure 2b). They feature a very low dark current (approximately 2 pA) near zero bias, and a high R_0A product of approximately $10^{10} \Omega \text{ cm}^2$. The AlGaIn device has a very sharp response compared to a commercially available Cree SiC photodiode, as a result of the direct and indirect bandgaps in

AlGaIn and SiC respectively.

By increasing the Al mole fraction in the constituent layers, it is possible to shift the response band of the device into the solar blind region, or into a UV band of specific significance for flame sensing and combustion control. HTC has fabricated devices with the same structure as in figure 3, but with 35% Al in the bottom n-AlGaIn layer, shifting the short wavelength cut-off down to 290 nm. A practical limit is presently reached at about 45% Al, due to the difficulty in doping high Al content layers. Ongoing work will add Al to the p- and i- layers (at a lower composition than the n- layer), thereby reducing the long wavelength cut-off.

Although extensive temperature testing has not been carried out, the devices should operate at up to ~200°C, provided that cheap, temperature-resistant electronic components are also available.

Phototransistors

Three terminal, bipolar phototransistors offering high internal gain have also been demonstrated at HTC. Like the photodiode, the device (figure 3a) is rear-illuminated through the sapphire substrate. An n-AlGaIn layer acts as the collector and also provides a cut-off at short wavelengths. The light is mostly absorbed in the undoped i-AlGaIn layer, and the field

in this region separates the photo-generated electron-hole pairs. Holes drift to the base (p-AlGaIn layer) and electrons drift to the collector. Hole accumulation in the base causes lowering of the p-AlGaIn barrier, and increasing electron injection from the Si-doped n-AlGaIn emitter layer. The gain of the device is determined by the electron transit time across the base, and the excess carrier lifetime in the base.

We have measured gains of up to 10^5 at a bandwidth of 5 Hz, and 10^8 rejection of visible wavelengths (at 400 nm) on our AlGaIn phototransistors as seen in Figure 3b. In this device, the photocurrent will persist as long as the holes in the base create a forward bias across the base-emitter junction. The device can be reset by flooding the base with electrons, thereby inducing electron-hole recombination. This is achieved by applying a large voltage across the collector.

Conclusions

HTC has successfully demonstrated GaN- and AlGaIn-based photoconductors, photodiodes and phototransistors. These devices appear to be well suited to several applications, including flame sensing, missile warning, and as aids in flight landing systems. GaN and related materials will likely be an important component of many Honeywell products in the future.

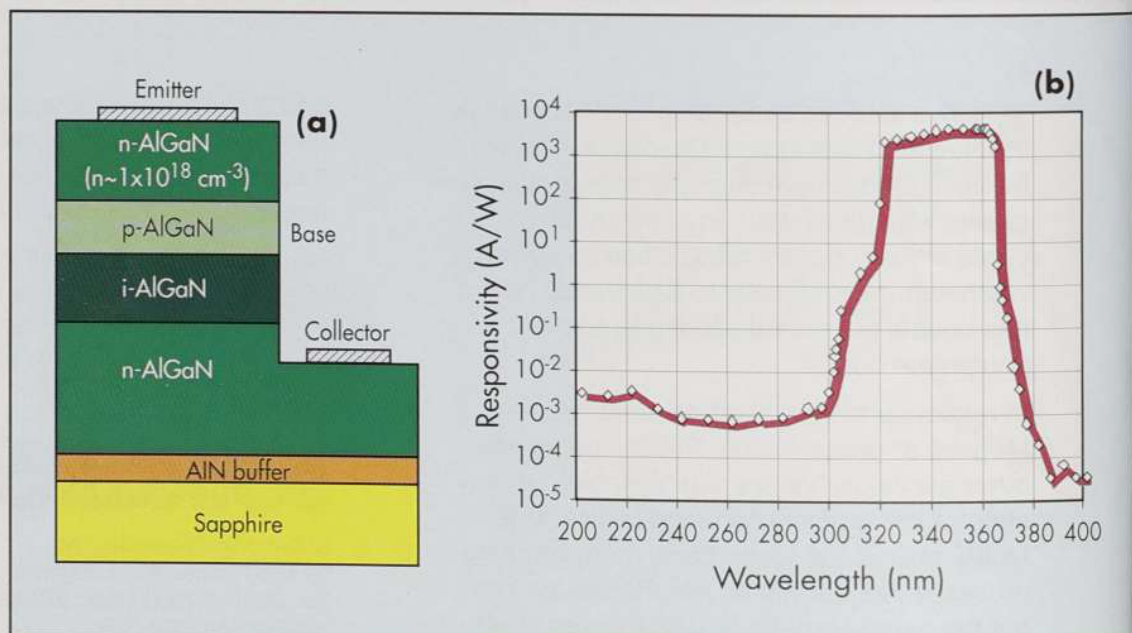


Figure 3. HTC's n-p-n AlGaIn heterojunction bipolar phototransistor (a) schematic structure (b) responsivity characteristics.

Photo-enhanced Wet Etching of GaN

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The group-III nitride materials pose significant new challenges in terms of semiconductor device fabrication. A fundamental step in the realization of any semiconductor device is the transfer of patterns into the surface of the semiconductor by etching. The wide bandgaps of the group-III nitrides reflect the high bonding strength of these crystals, and this physical characteristic is also manifested in the exceptional resistance of the group-III nitrides to chemical attack by wet etching solutions. Conventional dry etching techniques such

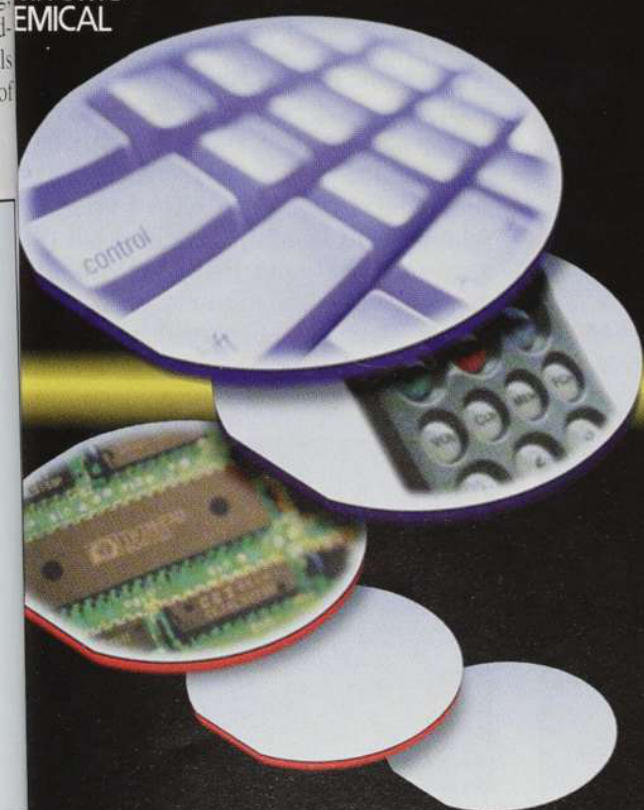
as reactive ion etching are effective for patterning nitride films, though etch rates are generally appreciably lower than for other III-V materials.¹

The development of viable wet etching methods is of great interest due to their inherent simplicity and the minimal experimental apparatus they require. In addition, wet etching introduces negligible damage to the etched surfaces, and can frequently provide very high etch selectivity between materials of differing composition. Several reports in the early 1970s described wet etching of low qual-

ity GaN crystals in phosphoric acid solutions. More recently, however, a survey of common acid and base solutions produced no discernable etching of high-quality GaN films.² Among the group-III nitrides, appreciable etching has been obtained only for AlN films in KOH and AZ400K developer solutions.

The etching of semiconductors is electrochemical in nature and can be enhanced by the application of a bias between the sample and a counter-electrode in solution. Anodic etching of GaN was first demonstrated by Pankove³

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using an NaOH solution. Pankove observed that the etching efficiency was greatly enhanced by using a jet spray of electrolyte which mechanically removed insoluble gallium hydroxide reaction products that formed during the etching. Very recently, Ohkubo⁴ noted that the electrolytic etching of Pankove could be improved upon by reducing the level of dissolved oxygen in the etching solution. This minimized the formation of gallium hydroxide on the etched surfaces and enabled etching without the physical spray-etch component. Etch rates were still quite low, however, on the order of only 0.7 $\mu\text{m}/\text{hour}$.

Photo-enhanced Wet Etching

The wet etching rates of GaN are significantly enhanced by illuminating the semiconductor with ultraviolet radiation during etching. Minsky et al⁵ first demonstrated photo-electrochemical (PEC) etching of GaN by using HeCd laser (325 nm) illumination with KOH and HCl solutions. Subsequent experiments by several groups have investigated the PEC etch characteristics of GaN using Hg arc lamp illumination and aqueous solutions of KOH^{6-8,10} and H_3PO_4 ¹¹ and buffered aqueous solutions of tartaric acid in ethylene glycol.⁹ Photo-enhanced wet etch rates as high as 400 nm/min have been achieved in n-type GaN films. To date, no wet etching has been demonstrated for p-type GaN films.

The mechanism behind photo-enhanced wet etching lies in the photo-generation of electron-hole pairs at the semiconductor surface. (Note that the wide bandgap of GaN necessitates the use

of ultraviolet radiation with wavelengths below 365 nm). The population of thermally generated holes in GaN at room temperature is quite low, and the absorbed radiation can greatly increase the supply of holes available to participate in the anodic etching reaction. A concentration of holes at the semiconductor surface allows conversion of surface atoms into higher oxidation states, with their subsequent dissolution into an aqueous solution. From another point of view, the absorption of the ultraviolet radiation 'weakens' the surface bonds by promoting electrons out of bonding states, and thereby increases the susceptibility of the crystal to attack by the electrolyte.

Experimental Setup

Figure 1 shows a schematic of the experimental setup used to conduct PEC etching in our laboratory.⁶ The GaN sample is clipped to a teflon base by a Ni washer, which makes electrical contact to the sample. A Pt wire is used as a counter-electrode, and, in general, no bias is applied between the GaN sample (anode) and the Pt cathode. The ability to etch without applying a bias greatly simplifies the procedure, since it is not necessary to electrically isolate the electrical contact to the sample from the electrolyte. An unfiltered Hg arc lamp illuminates the sample with typical light intensity of 10 mW/cm² measured at 365 nm. The GaN samples were grown by MOCVD on sapphire and SiC substrates, and doped n-type ($n \sim 1 \times 10^{18} \text{ cm}^{-3}$). For an etch mask, the GaN samples were patterned with 100 nm Ti, which can be removed following the etch process in HF solution. Aqueous

KOH solutions were utilized with solution concentrations varying between 0.01-0.04 M. As demonstrated below, the GaN etch characteristics are strongly dependent on the KOH solution concentration.^{6-8, 12}

Rapid and Anisotropic Etching

Figure 2 (a) shows an n-type GaN sample that was etched using a solution of 0.04 M KOH to a depth of 2 μm .⁶ The etched surfaces are reasonably smooth, and the etch process exhibits high anisotropy. Unlike conventional wet etching methods, in which etch profiles are generally isotropic or crystallographic, photo-enhanced wet etching processes can attain a high degree of anisotropy from the collimation of the incident radiation. The Ti metal mask is opaque to the UV illumination, and therefore minimal etching occurs in the 'dark' regions of the sample beneath the metal etch mask. Figure 2 (b) demonstrates the exceptional etch verticality that is attainable. This sample was etched through the entire 3.5 μm film thickness and then over-etched until the sidewalls became vertical.

The PEC wet etch process offers a very high degree of etch selectivity between the GaN and the metal etch mask, allowing very deep etches to be carried out using only a very thin masking layer of metal. The n-type GaN film shown in Figure 3 was etched using a solution of 0.04 M KOH to a depth of approximately 12 μm . Following etching, the 100 nm Ti metal mask remained completely intact. This suggests that the PEC etch technique would be suitable for very deep etches of several tens of microns or

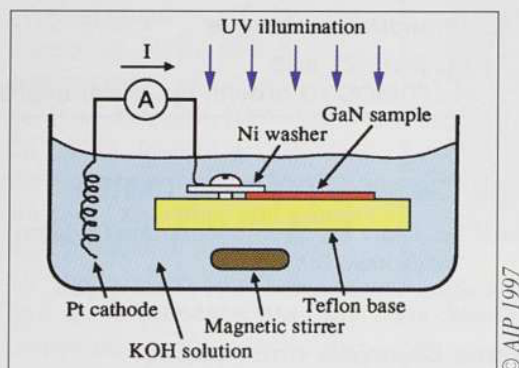


Fig. 1 Experimental apparatus for PEC etching. [from Ref 6]

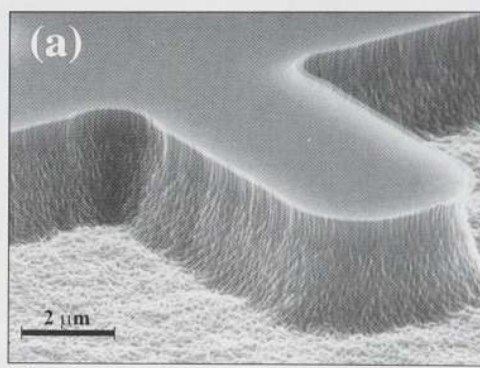
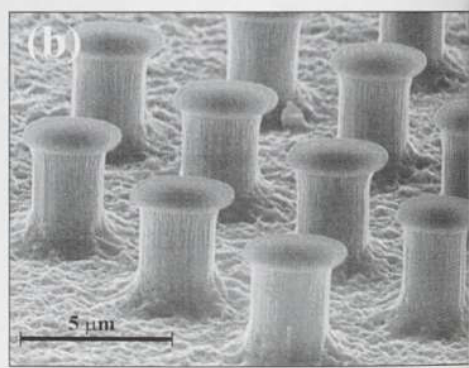


Fig. 2 (a) and (b) Typical photoenhanced wet etch profiles in n-type GaN using 0.04 M KOH. The exceptionally high anisotropy seen in (b) was obtained after extended etching.



more. Conventional dry etch techniques for GaN depend upon a very strong physical etch component, which limits the degree of etch selectivity that can be achieved. To produce comparable etch depths by dry etching would require an exceptionally thick and durable etch mask. One notable exception is the low energy electron enhanced etching (LE4) dry etching method,¹ which uses low energy electrons to stimulate the etching and is also highly selective.

Dislocation Decoration

Wet etching solutions are frequently useful for revealing crystal defects such as dislocations. Estimates of dislocation densities in crystals are often made by counting etch pit densities after a surface has been 'decorated' by a selective etchant that forms etch pits at dislocation sites. We have observed that under specific etching conditions, the PEC etching of GaN is highly sensitive to the crystal microstructure.¹² The n-type GaN samples shown in Figure 4 were etched using a solution of 0.02 M KOH. Figure 4 (a) shows the GaN surface after 300 nm of etching.

The etched surfaces exhibit remarkable 'whisker-like' features that stand normal to the surface. Transmission electron microscope (TEM) analysis of the etched features indicates a clear correlation with threading dislocations within the crystal. The distribution of the whiskers seen in Figure 4 (a) appears to delineate the grain boundaries present in the film. Contrary to conventional wisdom, the dislocations are found to suppress the PEC etching of

the crystal, resulting in the formation of etched filaments around the dislocations. The 'grasslike' surface seen in Figure 4 (b) was formed after an extended period of etching. The etched filaments seen in this image have diameters between 10-50 nm and lengths of 1 μm or more. The high density of whiskers is comparable to the film dislocation density of approximately $10^9 - 10^{10} \text{ cm}^{-2}$.

Smooth Etching

Below solution concentrations of 0.01 M KOH, another remarkable transition in the surface morphology takes place.⁷ The 'grass' morphology disappears and the etched surfaces become exceptionally smooth as shown in Figure 5. The RMS etched surface roughness is determined by atomic force microscopy (AFM) to be less than 1.5 nm. Etch rates under these conditions are diffusion-limited. At higher solution concentrations, etch rates show a linear dependence on light intensity, but at low concentrations the etch rates are limited by the diffusion

of reactants to the sample surface. Under these conditions, the etching kinetics are much less sensitive to local material variations due to crystal defects, allowing the smooth etch morphologies to be obtained.

Dopant-selective Etching

The inability to PEC etch p-type GaN remains an important hurdle to overcome in order to expand the useful range of wet etching applications. The difficulty in photo-etching p-type semiconductors arises from the nature of the surface depletion region generally exhibited by p-type materials.⁸ The depletion of holes from p-type surfaces due to surface states results in a near-surface electric field which sweeps photo-generated holes away from the surface into the bulk. For this reason, it is difficult to produce a high concentration of photo-generated holes at p-type surfaces in order to carry out anodic etching. A variety of approaches remain to be investigated, such as the utilization of reductive etch chemistries for p-type GaN.

However, this dopant-selective etching behavior is useful for a number of novel etching applications. We have explored the PEC etching of GaN p-n homostructures consisting of 400 nm p-type GaN ($p \sim 3 \times 10^{17} \text{ cm}^{-3}$) grown on top of 1 μm n-type GaN ($n \sim 1 \times 10^{18} \text{ cm}^{-3}$).⁸ Patterns were first etched into the sample shown in Figure 6 (a) using chemically assisted ion beam etching (CAIBE). This dry etch extended through the top p-type GaN layer and into the underlying n-type GaN layer. The p-type layer is visible in Figure 6 (a) as a light-colored band. A

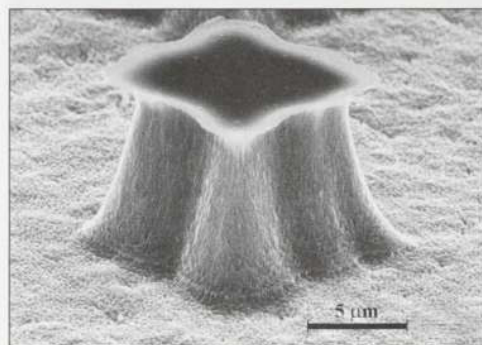


Fig. 3 Etching of thick n-type GaN films is readily accomplished by PEC etching. This 12 μm deep etch was carried out using a 100 nm thick Ti metal mask.

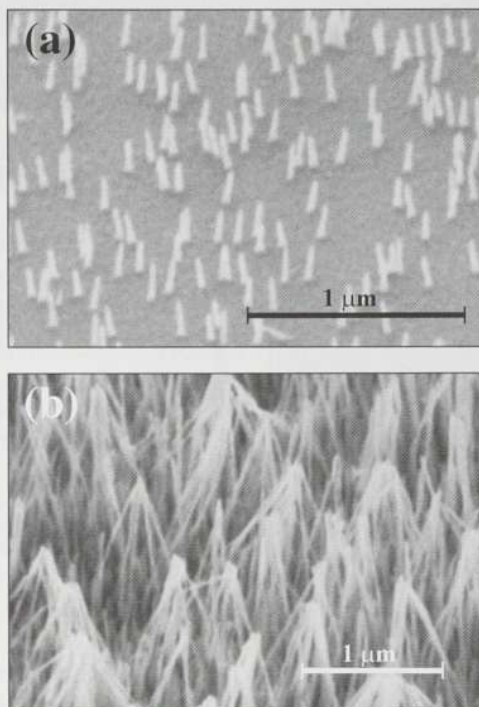


Fig. 4 The PEC etch process can be used to reveal threading dislocations in n-type GaN films. The 300 nm high 'whiskers' seen in (a) were formed by etching and show the distribution of dislocations at grain boundaries. After extended etching, the whiskers lengthen to form the 'grasslike' morphology seen in (b).

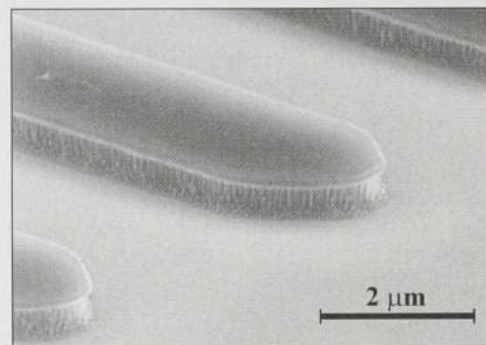


Fig. 5 Smoothly etched n-type GaN surface obtained under diffusion-limited etch conditions. AFM indicates an RMS etch roughness of less than 1.5 nm. [from Ref 7]

PEC etch step was then used to selectively remove the buried n-type GaN layer, leading to the observed undercut etch characteristics seen in Figure 6 (b). The undercutting extended laterally beneath the p-type layer more than 10 μm .

In addition to controlled undercutting of layer structures, another important application of selective etches is to allow the use of etch-stop layers. It should be possible, for example, to etch through an n-type GaN film and automatically stop etching on a buried p-type layer. Selective etches are useful tools in the fabrication of such devices as heterojunction bipolar transistors (HBTs), field effect transistors (FETs), and photodetectors.

The group-III nitrides clearly show great promise for present and future device applications ranging from optical emitters and detectors to high temperature and high power electronics. Important inroads have been made into the wet etching of these materials, and these new methods should be useful additions to the processing technologies for device fabrication.

This research was supported by NSF Grant No. ECS 95-21671 and DARPA Grant No. F19628-96-C-0066. The authors are grateful to Linda Romano of Xerox PARC for TEM characterization of etched samples and invaluable discussions.

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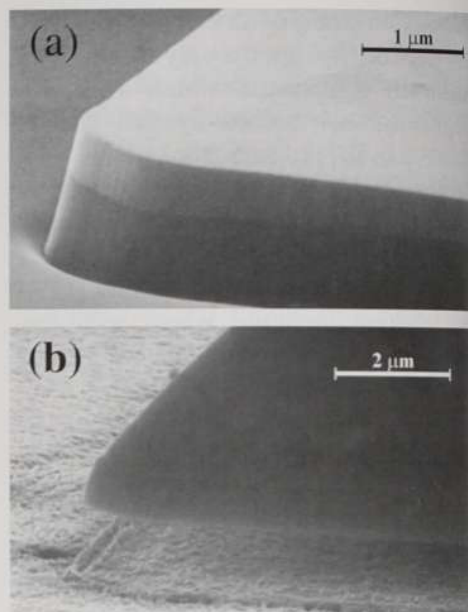


Fig. 6 (a) Etched mesa formed in a GaN p-n homostructure by chemically assisted ion beam etching (CAIBE). The 400 nm thick p-type layer is visible as the lighter band on top **(b)** Dopant-selective PEC etching was used to etch the sample seen in (a) to selectively remove the lower n-type GaN layer, resulting in deep undercutting of the top p-type film. [from Ref 8]

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Research Review

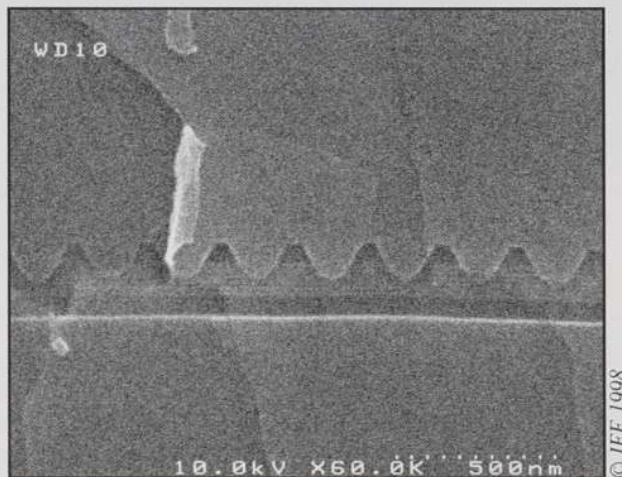
The following is a sampling of recent papers from a variety of international journals, compiled by the staff of Compound Semiconductor.

Optoelectronic Devices

700 A/cm² Threshold Current Density DFB Lasers

N. Aberkane et al, Elec. Lett., 1998, 34(5), p.464

Gain-coupled DFB lasers with periodically etched quantum wells have been shown to offer superior performance compared to standard, index-coupled DFB laser structures. The main drawback is the requirement to directly etch the active layer. This paper, from Alcatel Alsthalm, describes a method to achieve very high quality interfaces, allowing fabrication of 1.55 μm lasers with threshold current densities in the range 700-800 A/cm². The active layer, comprising 6 compressively strained InGaAsP quantum wells grown by gas-source MBE, was etched using a combination of reactive ion etching with a CH₄/H₂ gas mixture and wet etching. The absence of argon during dry etching was important in limiting damage to the active layer, and subsequent cleaning resulted in very low surface contamination. GSMBE was then used to regrow p-InP on top of the etched gratings, followed by p⁺-InGaAs. Broad area (300 x 100 μm) lasers had a calculated T₀ of ~52 K and an external quantum efficiency of 0.27 W/A.



SEM of the periodically etched MQW active layer. The grating is etched through 3 of the 6 wells.

II-VI Laser Grown on ZnSe Substrate

F. Nakanishi et al, Elec. Lett., 1998, 34(5), p.496

The highest performance ZnSe-based, II-VI blue-green lasers have been fabricated on GaAs substrates, which have a close lattice-match to ZnSe. However, the difference in thermal expansion coefficients between substrate and epilayer, and the hetero-nature of the interface, can make the reduction of defect densities very difficult. This paper, by Sumitomo Electric, reports the growth of ZnSe-based lasers on conductive ZnSe substrates. The n-type 1cm² wafers were prepared in-house using the seeded chemical vapor transport technique. After polishing and degreasing, an HF solution was used to reduce the surface ZnO layer, which was then completely removed in the MBE growth chamber by hydrogen plasma treatment. The laser structure had a single ZnCdSe QW active layer, ZnSe optical guiding layers and ZnMgSSe cladding layers. The lasing wavelength was 527.9 nm and the threshold current for CW operation was 44 mA, corresponding to a very low threshold current density for this type of laser of 222 A/cm². The slope efficiency was 0.57 mW/mA per facet. At a constant light output of 2 mW/facet, a lifetime of 74 s was measured at room temperature, representing the longest lifetime for homo-epitaxial ZnSe-based lasers. Further improvements are expected with the reduction of defects in both ZnSe substrates and epilayers.

Compound Semiconductor Materials

GaN With Low Etch Pit Density

M. Iwaya et al, Jpn. J. Appl. Phys., 1998, 37(2), p. L316

Device-quality GaN films grown at high temperature on sapphire conventionally use a low temperature buffer layer of either AlN or GaN. To attempt to reduce the generally high concentration of dislocation densities in GaN, this paper from Meijo University, Nagoya, Japan, describes alternative buffer layer growth sequences. The conventional sequence - 20 nm GaN or AlN buffer deposited at 400°C followed by GaN growth at 1050°C - resulted in an etch pit density in the low- to mid-10⁷ /cm² range. A sequence with two GaN buffers, growth of which was separated by a 10 min anneal at 1050°C, resulted in an increase in etch pit density to the low- to mid-10⁸ /cm² range. However, when two 10 nm buffer layers (either GaN or AlN) grown at 400°C were separated by a 1 μm thick high temperature GaN layer, no etch pits were observed in the GaN grown on top of the second buffer layer. The thickness of the intermediate high temperature GaN layer was not critical to the observed reduction in etch pit density.

Mixed Group V-Nitride Alloys

Fiber-optic networks rely on 1.3 μm and 1.55 μm lasers, fabricated from the InGaAsP-InP material system. However, these devices offer poor high temperature performance compared to shorter wavelength lasers on GaAs substrates. The cause is weak electron confinement by the low conduction band offset (ΔE_c) in InGaAsP-InP devices. Several approaches towards increasing ΔE_c have included using an InGaAlAs barrier, or growing InGaAsP-InGaP lasers on ternary InGaAs substrates.

Alternatively, introducing small amounts of nitrogen ($\leq 1\%$) into InGaAs creates a high ΔE_c and allows fabrication of long wavelength lasers on GaAs substrates.

1.3 μm CW Operation of a GaInNAs Laser

Room temperature CW operation of a 1.3 μm quantum-well laser with a GaInNAs active layer was recently demonstrated for the first time by researchers at Hitachi [see K. Nakahara et al, *IEEE Photon. Tech. Lett.*, 1998, 10(4), p.487]. The laser structure (see figure 1) was grown on an n-GaAs substrate by gas-source MBE, using a nitrogen radical source to introduce 1% N into the 7 nm thick, strained active layer. The QW was enclosed by GaAs guide layers and AlGaAs cladding layers. For comparison, a similar structure with an InGaAs QW was also fabricated. The GaInNAs laser had a threshold current of 108 mA, a slope efficiency of 0.16 W/A, and a lasing wavelength of 1.31 μm . The same parameters for the InGaAs laser were 28 mA, 0.25 W/A and 1.12 μm respectively. Improved material quality in the GaInNAs structure should reduce threshold current and increase slope efficiency. The same group at Hitachi has previously demonstrated 1.18 μm VCSELs incorporating a GaInNAs-GaAs active layer [CS 4(2), p.29].

InNAsP And Other Systems

Researchers at the University of California at San Diego have investigated several other material systems. A further motivation for this work is the prospect of lattice-matching various compositions (eg $\text{GaN}_{0.20}\text{As}_{0.80}$ or $\text{InN}_{0.49}\text{P}_{0.51}$) with silicon. However, introducing N into these material systems has proved relatively difficult, due to large miscibility gaps, which often result in phase separation. UCSD has grown $\text{GaN}_{0.148}\text{As}_{0.852}$ and $\text{GaN}_{0.16}\text{P}_{0.84}$ but N incorporation in InP was limited to 1%.

The bandgap of a material can be strongly affected by incorporating even small amounts of N. Figure 2 shows the effect of incorporating either N or As into InP. Introducing As increases the lattice parameter, since As is larger than P, so that $\text{InAs}_x\text{P}_{1-x}$ epitaxial layers grown on InP are compressively strained (assuming the critical thickness is not reached). The conduction band edge falls but the valence band edge rises, so the bandgap falls as the As content increases. Although N atoms are very small, resulting in tensile strain as N is added to InP, the large electronegativity of N pulls both the conduction and valence band edges down in energy, and the bandgap decreases as more N is added.

Figure 3 shows the conduction band offset (ΔE_c) between InP and various alloys. Adding As to InP introduces compressive strain and also increases ΔE_c . If N is subsequently added into the InAsP alloy, ΔE_c increases still further, but the overall strain in the system decreases. By adding N, this should allow long wavelength laser with strong electron confinement, and hence good high temperature performance.

UCSD has fabricated microdisk lasers with an $\text{InN}_{0.005}\text{As}_{0.45}\text{P}_{0.545}$ active layer, which operated at up to 70°C at a wavelength of 1.42 μm when optically pumped. [see C. Tu et al, *Proc. SPIE* vol. 3284, 1998; W. Bi et al, *IEEE Photonics Tech. Lett.*, 1997, 9(8), p.1072].

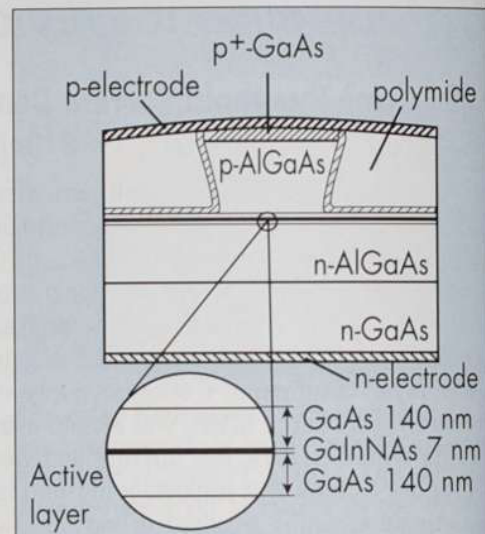


Figure 1. Cross-section of the 1.3 μm GaInNAs SQW laser.

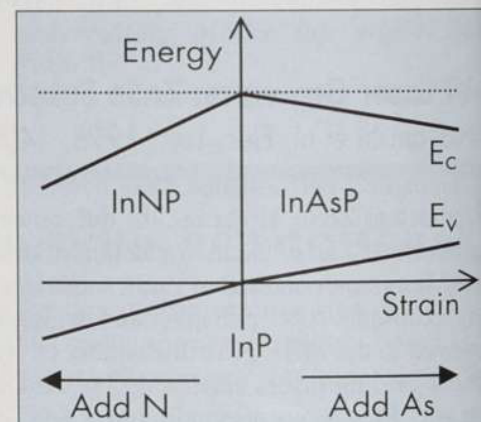


Figure 2. Band edge variation as N or As is added to InP.

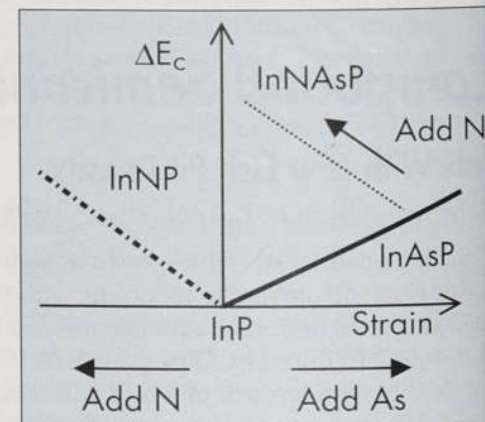
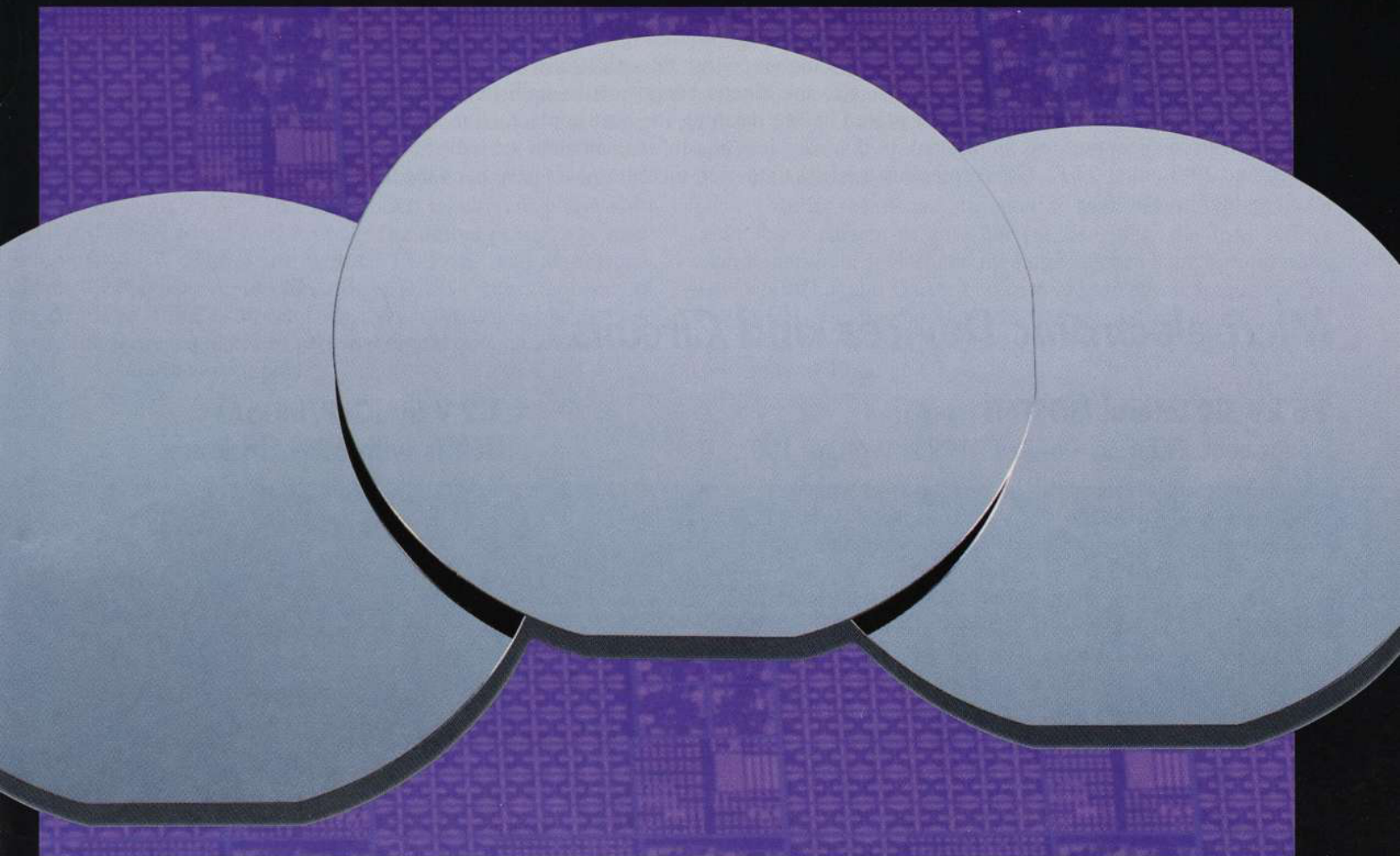


Figure 3. Conduction band offset (ΔE_c) between InP and various alloys.

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Ballistic Electron Distribution in HBTs

R. Teissier et al, Appl. Phys. Lett., 1998, 72(21), p. 2730

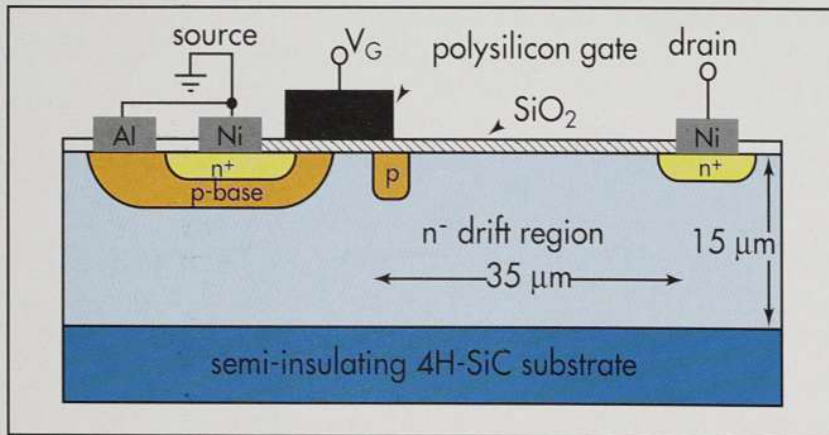
InP-based HBTs have demonstrated cut-off frequencies in excess of 200 GHz, due in part to the very fast non-equilibrium transport taking place in the base. This work, by CNRS, France, describes the use of electroluminescence (EL) measurements to give clear evidence of ballistic electron transport through the base. In an InP-based HBT, electrons are injected into the p-type InGaAs base from the n-type InP emitter. Due to the conduction band discontinuity, electrons enter the base with a high kinetic energy, forming a ballistic population which relaxes energy and momentum through scattering. Ballistic electrons that recombine with holes in the valence band are clearly observed by EL as peaks having a higher energy than electrons which recombine from the bottom of the conduction band. The separation of these two peaks indicates the kinetic energy of the ballistic electrons. As the width of the base region is increased, more and more electrons are scattered before reaching the base contact, so that the contribution to the EL spectrum from ballistic electrons becomes less significant. In this way, it is possible to calculate the ballistic length in these InP HBTs as 18 ± 6 nm at 300 K, and 29 ± 3 nm at 77 K. This represents the first time such measurements have been made at room temperature and at p-doping levels as high as $10^{19}/\text{cm}^3$.

Microelectronic Devices and Circuits

2.6 kV SiC Lateral MOSFETs

J. Spitz et al, IEEE Elec. Dev. Lett., 1998, 19(4), p. 100

SiC is an attractive material for high voltage, high power devices and can also be thermally oxidized to form device quality SiC/SiO₂ interfaces. Power devices are usually vertical devices with a blocking voltage limited in theory to about 2 kV, based on the thickness of currently available SiC epilayers. In the lateral MOSFET shown opposite, the depletion region surrounding the p-well first depletes through the n-type epilayer to the insulating substrate, then moves laterally toward the drain, and is therefore not limited by the thickness of the epilayer. The device, a doubly-diffused or D-MOSFET, features a 15 μm n-type 4H-SiC epilayer grown on an insulating substrate. The p-well is formed by boron implantation, and the n⁺ source and drain regions are then formed by nitrogen implantation. The device had a threshold voltage of 6 V and a drain to source blocking voltage of 2.6 kV, nearly double the highest previously demonstrated blocking voltage for any SiC power switching device. [Work carried out at Purdue Univ and Wright Patterson AFB]



Cross section of the 4H-SiC lateral DMOS power transistor

1.2 V InAlGaP/InGaAs HEMTs with 65% Efficiency

Y. Wang et al, Elec. Lett., 1998, 34(6), p. 594

For HEMTs to operate at very low DC supply voltages (< 3 V) while maintaining the same output power, it is necessary to either increase the total gate width (which has detrimental implications towards the yield) or to increase the drain current density. The latter is achieved by using a heterostructure containing a higher conduction band offset, which provides a higher 2-D electron gas density in the quantum well of the HEMT. This paper, from Lucent Technologies and Rutgers University, reports power results from devices featuring In_{0.5}(Al_{0.3}Ga_{0.7})_{0.5}P/GaAs heterojunctions, which show a significantly larger offset than AlGaAs/GaAs or InGaP/GaAs. The HEMTs have a double heterojunction structure with the InGaAs channel separated on both sides from In_{0.5}(Al_{0.3}Ga_{0.7})_{0.5}P layers by GaAs spacers. An f_t of 21 GHz and an f_{max} of 64 GHz were measured for $1 \times 60 \mu\text{m}$ devices, and these figures increased to 61 and 118 GHz respectively for $0.25 \mu\text{m}$ gate length devices. Power measurements were performed on $1 \mu\text{m} \times 5 \text{mm}$ devices. When operated at 850 MHz and tuned for maximum output power, PAEs of 65.2 and 68.2% were obtained under 1.2 V (the voltage of one NiCd or NiMH cell) or 2 V respectively. At 1.9 GHz, a 53% peak PAE, a 8.3 dB linear power gain and a 25 dBm saturated output power were obtained from the same device at a drain bias of 2 V.

3.4 V Power HFETs with 60% Efficiency

Y. Bito et al, Elec. Lett., 1998, 34(6), p. 600

Personal digital cellular phone requirements are moving towards small power devices with high power added efficiency (PAE) operating at 3.4 V with >1 W output power. Single-bias operation is also desirable. This work, by NEC, describes an AlGaAs/InGaAs/AlGaAs heterojunction FET operated from a single 3.4 V supply. The device structure, grown by MBE, features an undoped $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ channel between Si-doped AlGaAs layers. The 1.0 μm gate length device exhibited an on-resistance of 2.3 Ωmm and a threshold voltage of -0.25 V. An HFET with a gate width of 16 mm was examined at a source-drain voltage of 3.4 V, and with a 950 MHz $\pi/4$ -shifted quadrature phase shift keying (QPSK) signal as the input. The output power was measured at 1.42 W (31.5 dBm) with 60.1% PAE, with an adjacent channel leakage power of -48.2 dBc at an off-center frequency of 50 kHz. The HFET is a promising device for single-bias voltage operation power modules of personal digital cellular phones with a single Li-ion battery supply.

High Reliability InGaP/GaAs HBTs

N. Pan et al, IEEE Elec. Dev. Lett., 1998, 19(4), p. 115

The potential of InGaP/GaAs HBTs for numerous microwave applications is demonstrated by long term reliability and high frequency results. The devices were grown by MOCVD, using intrinsic carbon doping from the TMGa precursor to achieve p-type doping at $4 \times 10^{19} / \text{cm}^3$ in the GaAs base. Long term reliability testing was carried out on ten devices measuring $6.4 \times 10 \mu\text{m}$, with a current density of 25 kA/cm^2 and a collector-emitter voltage of 2 V. At an effective junction temperature of 264°C , all devices showed an initial current gain degradation of 7-10%, but then remained stable out to 10,000 hours with no device failures. The reliability results are attributed to high material quality, low initial base current at low current densities, the low surface recombination of InGaP, and the large valence band discontinuity between InGaP and GaAs. The current gain cutoff frequency (f_T) was 61 GHz and the maximum frequency of oscillation (f_{max}) was 103 GHz. [Work carried out by Kopin Corp., Sharp and the University of Illinois].

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Silicon Germanium QWIPs

Quantum Well Infrared Photodetectors (QWIPs) are rapidly emerging as an alternative to HgCdTe in certain long wavelength IR imaging applications [see CS 4(4), p.24]. The SiGe/Si material system presents the possibility of fabricating monolithic focal plane arrays, consisting of QWIP detectors integrated by direct epitaxial growth onto a readout circuit. Usually, QWIPs are fabricated by bump-bonding the detector array to a readout chip, and thinning the substrate.

Researchers at the UK's Defence Evaluation and Research Agency (DERA) in Malvern have demonstrated the feasibility of monolithic integration of SiGe/Si QWIPs. A small direct injection circuit was used, to represent the photocurrent integration and readout functions of a single pixel in a large array (see left figure). A standard CMOS process was used to form the circuit on a bulk Si substrate, stopping before metallization. A non-resonant SiGe/Si QWIP with 12 μm cut-off wavelength was grown by low pressure CVD and isolated on the detector site, and finally the metal interconnect was patterned over the complete circuit. To minimize the number of processing steps, a large area, thick dielectric capacitor was used, although this reduced the optical fill-factor.

The circuit was operated successfully at temperatures down to ~ 40 K, using external bias controls. The responsivity

of the QWIP was similar to that for an equivalent discrete device, and there was no degradation of either the QWIP or the CMOS transistors caused by the process integration.

Resonant Cavity Devices

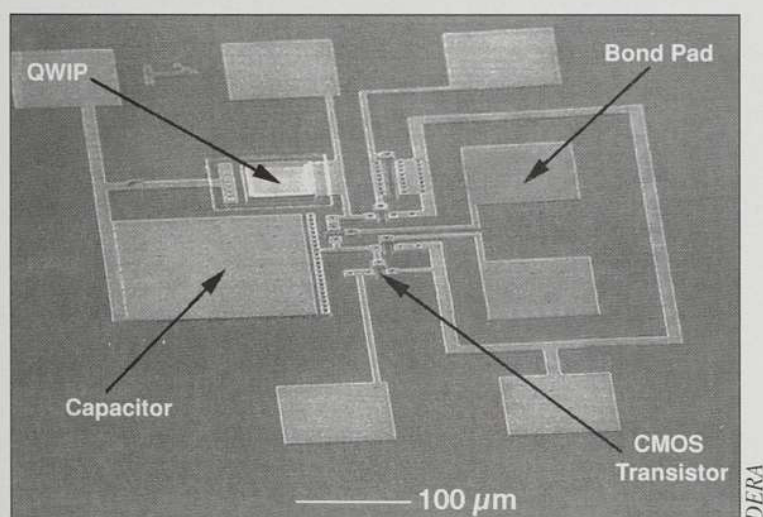
The monolithically integrated QWIP is illuminated through its top surface. By incorporating a buried reflective layer, it is possible to create a vertical resonant cavity, hence establishing a standing optical wave within the device and increasing the quantum efficiency. DERA has demonstrated individual resonant cavity devices, by growth of an IR-sensitive SiGe/Si MQW stack onto an SOI wafer containing a buried, reflective tungsten silicide layer (see right figure).

The substrate was prepared by CVD of 0.3 μm tungsten silicide ($\text{WSi}_{2.7}$) onto a silicon wafer, followed by a 1 μm oxide layer. This wafer was bonded to a handle wafer (also Si), and thinned to form a silicon-silicide-on-insulator substrate. The epitaxial layers were grown by low-pressure CVD (20 Pa) at 650°C and consisted of a 16-period QW stack surrounded by p-type silicon contact layers. The 5 nm thick $\text{Si}_{0.86}\text{Ge}_{0.14}$ wells had a sheet carrier concentration of $p \sim 1.5 \times 10^{12} \text{ cm}^{-2}$ and the Si barriers were 55 nm thick and nominally undoped.

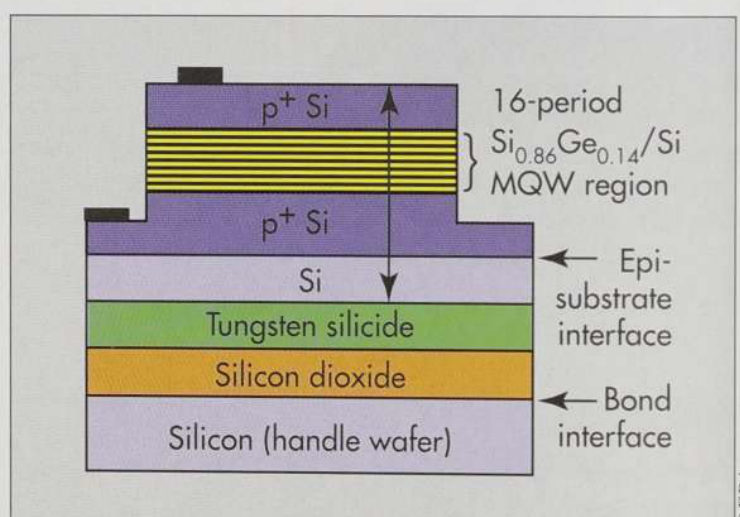
The present cavity design is not con-

sidered ideal, because the reflectance of the top silicon surface is much lower than that of the silicide layer, and also because the position of the MQW is not optimized relative to the standing optical wave. Nevertheless, a 500 K blackbody responsivity of 10 mA/W was measured in normal incidence with 0.5V bias. This value is $\sim 5\times$ higher than that for a similar single pass QWIP on a bulk Si substrate, and slightly greater than values measured for similar n-type GaAs/AlGaAs QWIPs using a 45° waveguide geometry. There was no degradation of dark current in the QWIP grown over the silicide layer when compared with a device grown on a bulk Si substrate.

SiGe/Si QWIPs can be tailored to cover both the 3-5 and 8-12 μm bands, making a monolithic dual-band technology possible with two stacked detectors. As the device is p-type, and is therefore able to absorb light normal to the surface, a specialized surface reflector is not required. To achieve the same detectivity as an equivalent GaAs/AlGaAs device, the operating temperature of the SiGe/Si QWIP must be slightly lower to produce an equal dark current. At the present stage of development, SiGe/Si QWIP arrays need to be cooled below 50 K to achieve high performance thermal imaging in the 8-12 μm band. [See R. Carline et al, IEDM Tech.Dig., 1997].



SEM photograph showing a demonstration circuit representing a single pixel in a monolithic focal plane array.



Cross-section of a SiGe/Si QWIP grown on a substrate with a buried reflective layer. The double-headed arrow shows the position of the resonant cavity.

Siemens Announces More Optocouplers

Cupertino, CA. The Optoelectronics Division of Siemens Microelectronics has extended its range of optocouplers by offering new dual channel, high speed products as well as photodarlington and phototransistors. The dual channel products (SFH6325/6326) consist of pairs of AlGaAs LEDs and integrated photodetectors, containing a photodiode and a transistor in a plastic 8-pin dual-in-line package (DIP). The dual-channel structure leads to significant space savings, and the devices operate at up to 2 MHz. The SFH6325 is for use in TTL/MOS or wide bandwidth analog applications and has a minimum current transfer ratio (CTR) of 7% at 16 mA. The SFH6326 is designed for high speed TTL/TTL applications and features a minimum CTR of 19% at the same current.

Siemens' photodarlington and phototransistor products in 4-pin plastic DIPs offer optimized board-space, surface mountability, and the choice between high gain and high speed. Photodarlington contains two transistors coupled to behave as a single transistor with very high gain. The SFH619A photodarlington has a CTR of 1000% and a low current turn-on of 1 mA, providing stable and reliable switching when a high degree of isolation between the driving and load circuits is needed. The breakdown voltage of 300 V is appropriate for electrically noisy environments. The SFH614A phototransistor has the same breakdown voltage and a CTR of 50%, enabling higher speed operation than the photodarlington, for applications such as digital logic and high frequency power supplies. The products all feature high isolation voltages of 5300 V, reverse voltage of 6 V and forward current of 60 mA.

Power MESFETs from NEC

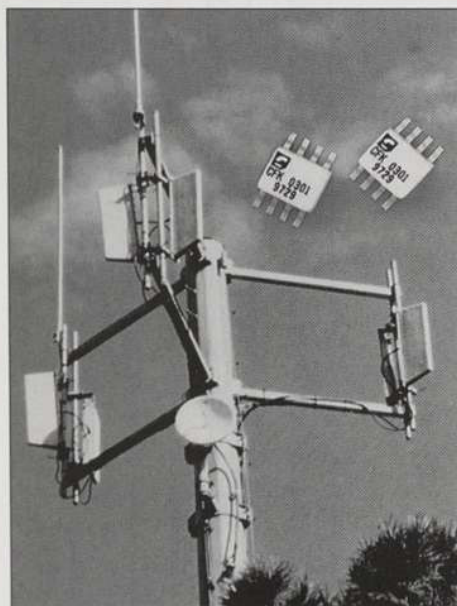
Santa Clara, CA. California Eastern Laboratories have announced the availability in the United States of two new GaAs power MESFETs from NEC, operating in the Ku-band. The 3 W and 5 W devices are specifically designed for use at 14.0-14.5 GHz in very small aperture terminal (VSAT) transmitters for satellite-based communications. The devices operate at 10 V with a typical power added efficiency of 30%. Part NEZ1414-3E operates at an output power of 3 W (34.5 dBm) with 7.5 dB linear gain, and NEZ1414-5E operates at 5 W (37.0 dBm) with 7.0 dB linear gain.



NEC's 5 W GaAs MESFET operating at 14.0-14.5 GHz, available from California Eastern Laboratories

Semiconductor Optical Amplifier from Alcatel

Nozay, France. Alcatel Optronics have introduced a second semiconductor optical amplifier product for high speed optical routing and switching in advanced telecommunication networks. The 1921SOA operates in the 1550 nm window, and is fabricated from a buried ridge stripe InGaAsP heterostructure using Alcatel's 2" wafer technology. The structure features a high internal gain in excess of 30 dB, and highly efficient fiber-to-chip coupling. An adiabatic taper is included to reduce far-field divergence, and optimized lens technology allows 2-3 dB coupling loss per facet. Applications include WDM systems, optical in-line amplification and gating for high speed optical switching.



Celeritek's dual GaAs FET product for base stations, repeaters and tower-mounted amplifiers

Celeritek Launches LNAs for Base Stations

Santa Clara, CA. Celeritek's CFK0301 is a high dynamic range, low noise product designed for balanced front-end amplifiers in communication systems. The wide bandwidth makes it applicable to both 900 MHz and 1.9 GHz communication bands. The product contains two 600 μm gate width, 0.25 μm gate length GaAs FETs in one surface-mount package. The devices are taken from adjacent areas on the processed wafer, and are phase- and gain-matched. The primary users of the product will be designers of cellular and PCS base stations, repeaters and tower-mounted amplifiers.

DIRECTORY OF SUBSTRATE SUPPLIERS

The following is our first directory of compound semiconductor substrate suppliers. Included are 34 companies offering a wide variety of III-V and II-VI substrates, as well as SiC, Ge, sapphire and other important materials.

As more and more compound semiconductor devices move into volume production, substrate size is becoming an important issue, especially in GaAs and InP. Seven of the manufacturers indicated that they are now producing 6" semi-insulating (SI) GaAs, and three companies even indicated they are producing 4"

SI InP. For semi-conducting (SC) GaAs and InP, 3" is very common, with very few companies indicating they can also do 4".

Of course, most manufacturers will argue that the crystal growth technique which they employ gives them some degree of competitive advantage, either in cost or quality, or, sometimes, both. For those of you who would like a little help in sorting out the details, we've provided a brief overview of the three major techniques, on the next page.

Please watch for a directory of compound semiconductor-related equipment suppliers in an upcoming issue.

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Abbreviations:

BG: Bridgeman
CZ: Czochralski
GF: Gradient Freeze
HB: Horizontal Bridgeman

HGF: Horizontal Gradient Freeze
LEC: Liquid Encapsulated CZ
VB: Vertical Bridgeman
VGF: Vertical Gradient Freeze

GaAs				InP	Other			Growth Techniques
SI	SC	SI	SC	III-V	II-VI	Other		
6"	3"	3"	3"			*	LEC	Largest producer of SI GaAs in the world. 6" wafers commercially available. Ready for Epi™ wafers available for specific epi processes. 3" InP available Oct. '98.
6"	4"	3"	3"	GaP		Ge	VGF	Largest U.S. producer of GaAs. Leader in commercializing VGF which results in low dislocation density low internal stress and high uniformity from boule to boule and wafer to wafer.
3"	3"	2"	2"	GaP InAs GaSb InSb	MCT ZnSe ZnS CdS CdSe CdTe	ZnO Sap- phire	CZ BG	Custom production & small batch sizes available. SI & SC GaAs, also Ga, GaSb, InAs, InSb and undoped n-type and p-type InP in all major orientations.
3"	3"						LEC	Closed (no waste) manufacturing cycle best prices compared to other substrate manufacturers.
						SiC		Offers single crystal SiC wafers and epitaxy in 1 3/8" (35mm) and 2" (50mm) diameters.
		4"	4"				LEC	Complete range of SC and SI InP products in bulk and wafer form. InP from 2" & 4" dia. with low defect density. State of the art epi-ready wafers.
3"							VB HB HGF	Utilizes three different crystal growth techniques providing wide flexibility of substrate shapes and specifications. Has been supplying GaAs substrates world-wide for over 25 years.

* SiC in development

cont. on page 39

Bulk Single Crystal Growth Techniques

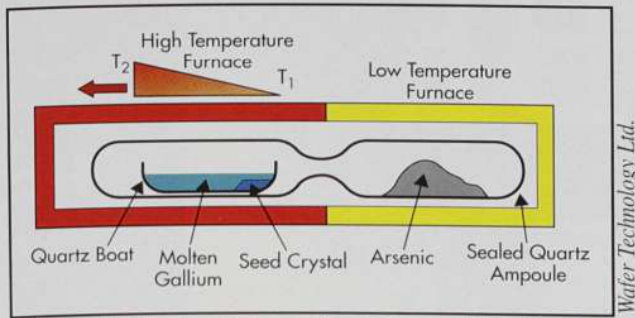


Figure 1. Horizontal gradient freeze. The thermal gradient ($T_2 > T_1$) is moved along the boat from right to left by changing furnace settings.

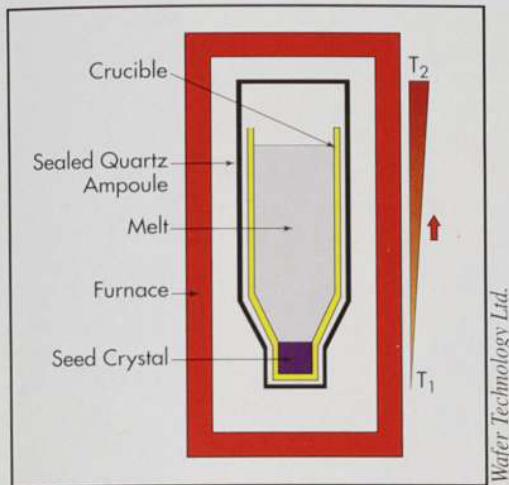


Figure 2. Vertical gradient freeze (VGF). The thermal gradient is moved upwards from the seed crystal.

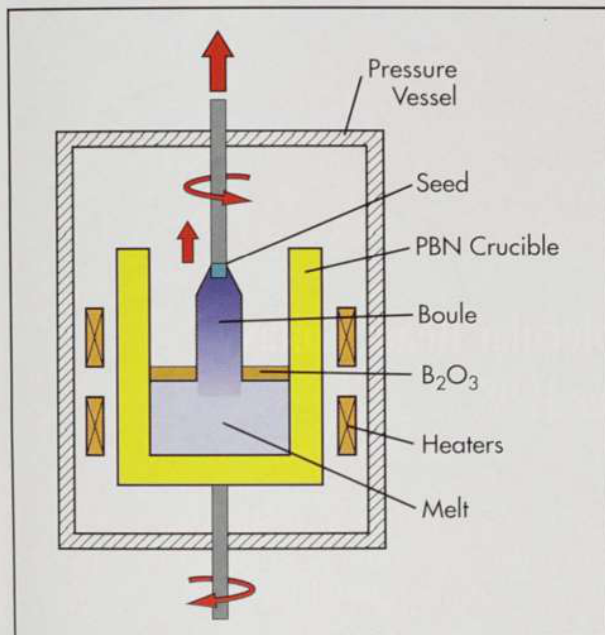


Figure 3. Liquid-encapsulated Czochralski (LEC). The seed crystal is dipped through the liquid boric oxide into the melt and slowly removed while being rotated.

Substrates for epitaxial growth of compound semiconductors or device formation by ion implantation are generally sliced from large ingots of bulk single crystal material. These boules of material are produced by two common melt growth techniques; furnace growth, in which controlled cooling of the starting materials occurs inside a sealed quartz ampoule within a furnace; and the pulling technique, in which cooling occurs as the seed is slowly withdrawn from the melt. Both techniques are normally carried out within a sealed environment to prevent non-congruent evaporation of the more volatile species (usually the group V element in the case of III-V crystals) from the melt.

Furnace Growth - Bridgeman and Gradient Freeze

The basic components for furnace growth are shown in figure 1. High purity elements are placed in a quartz boat together with a seed crystal. The boat and a quantity of excess group V element are sealed in a quartz ampoule, which is placed within a two-zone furnace. Controlled cooling of the melt in the hottest zone of the furnace, by moving a thermal gradient along the length of the boat, forms single crystal material. In the **Bridgeman** technique, the ampoule is moved through the furnace. An alternative is to use the heater elements to gradually move the temperature profile along the furnace, which is known as **gradient freeze**.

Both the Bridgeman and gradient freeze techniques can be performed in horizontal or vertical furnaces. Figure 2 shows the configuration for the **vertical gradient freeze (VGF)** technique. A crucible containing the starting materials (usually a seed crystal together with polycrystalline material) is placed within a vertical furnace, and the temperature gradient is moved upwards away from the seed crystal.

The ingot takes the size and shape of the boat or crucible, and can be subject to contamination and stress due to contact with the container. However, diameter control of the boule in VGF is very simple, and thermal gradients are small, leading to low dislocation densities.

Crystal Pulling - Czochralski

The technique originally developed by Czochralski involves slowly withdrawing a rotating seed crystal from a melt contained within a PBN crucible. The melt is formed from polycrystalline chunks, or by an in-situ reaction between the constituent elements. To prevent evaporation of the more volatile component, boric oxide (B_2O_3) is placed within the crucible. At high temperatures this forms a viscous liquid layer on top of the melt, so the technique is known as **liquid-encapsulated Czochralski (LEC)**. See figure 3.

The inert gas pressure within the sealed puller also helps to maintain stoichiometry. A pressure of 20 atmospheres is typical for GaAs growth, with higher pressures used for InP. Steep thermal gradients occur during LEC, perhaps as high as $60-80^\circ\text{C}/\text{cm}$, which introduce dislocations and can lead to cracking as the crystal cools. Accurate control of the temperature and shape of the liquid/solid interface is crucial.

Plan to Attend!

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CANNES, FRANCE**



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31 August - 04 September 1998

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SI	SC	GaAs		InP	III-V	Other		Growth Techniques	
		SI	SC			II-VI	Other		
					Ternaries			CZ LEC BG GF	Specialist in bulk ternary III-V single crystal growth research. Current emphasis is the InPAs system. Also offers specialty research and custom materials synthesis.
							Sapphire	CZ	Offers the most advanced levels of consistency and uniformity. Max. dia. 5". Manufacture of sapphire wafers for use as epitaxial substrates is a speciality.
6"	3"	3"	3"					LEC VGF	Lowest EPD in the world (VGF). Very competitive price (LEC VGF). Good electrical uniformity (LEC).
						ZnSe ZnO	Ge		Largest capacity for production of electronic grade Ge substrates. Also unique in the production of II-VI materials including ZnSe up to 3" dia. (grown by SPVT) and ZnO up to 20 mm sq. (grown by PVT)
							SiC		Supplies SiC substrates for SiC and GaN epitaxy. Also offers HVPE GaN substrates for GaN epitaxy which provide an epi ready surface requiring no nucleation or buffer layers
					InSb GaSb			CZ	Custom-grows, orients, fabricates and polishes InSb and GaSb wafers. (Ga, In) Sb and (Ga, In) (As, Sb) crystals are under development.
6"	3"							LEC	Fully ISO-9001 certified production of SI & SC GaAs. Bulk material with extremely low residual impurity concentration. Single and double side polished wafers ultra smooth wafer with minimum warp. Excellent surface quality for ion implantation and epitaxy.
4"								LEC	Supplies up to 4" SI GaAs substrates grown by LEC. Can control both resistivity and deep level by means of annealing and carbon-control technique. Can supply substrates at a low price.
6"	3"							LEC HB VGF	SI GaAs up to 6" dia. by LEC and SC GaAs up to 3" dia. by HB and VGF. For more details visit: http://www.hitachi-cable.co.jp/gaas

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GaAs				InP	Other			Growth Techniques	
SI	SC	SI	SC	III-V	II-VI	Other			
6"	3"								Reclaimed (recycled) GaAs and InP wafers. All formats and sizes including up to 6" GaAs. Single or double side polishing, extra thin or thick wafers, back-thinning of structured material and "Ready to Use" surface treatment.
		3"	3"					LEC	Innovative surface contamination analysis with the powerful TOF SIMS technique. Very low contamination level for all elements to better guarantee the surface preparation reproducibility.
		3"	3"		CdTe CdZnTe			CZ	Has succeeded in reducing the EPD of Sn- and S-doped InP substrates using a newly developed crystal growth technology. Can provide Fe-doped InP with EPD less than $1 \times 10^4 \text{ cm}^{-3}$.
				GaSb				LEC	The leading manufacturer of GaSb wafers and GaSb thermophotovoltaic cells. LEC GaSb available in 2" & 4" both n- and p-type low EPD (<1000).
					Ge			LEC	Supplies high quality single crystal Ge substrates up to 4" dia. Also available are square and rectangular shapes as well as ultra low EPD wafers.
6"	3"					Si epi- taxial wafer		LEC	The most experienced SI GaAs supplier using HPLEC systems that yield 3", 100mm and 150mm dia. wafers. Recently developed a process for SI InP wafers at 3" and 4" dia.
4"	4"	2"	2"	GaP GaSb InSb InAs	MCT CdSe CdS ZnTe ZnS	SiC Sap- phire Oxides		CZ LEC	Offers a range of cost effective products for III-V compounds including all the primary III-V substrates as well as NdGaO ₃ (101) which has only a 1.2% deviation from the GaN lattice structure.
4"	4"							LEC VGF HGF	GaAs wafers in 3" and 4" dia. are supplied. Epi-ready polish is available for all kinds of substrates.
		3"	3"		Cd Te			LEC	Provides high quality wafers with superior surface finish grown from high purity raw materials that provide excellent results for our customers.

New Products/New Literature

New Direct Replacement Magnetically Coupled Rotary Motion Feedthrough for GEN II and MOD GEN II CAR

St. Paul, MN. EPI MBE Products Group announces the introduction of a new magnetically coupled rotary motion feedthrough. This feedthrough is a direct replacement and upgrade for the original rotary motion feedthrough used on GEN II and MOD GEN II MBE Systems for substrate rotation in the continual azimuthal rotation (CAR) substrate manipulator. The new rotary motion feedthrough is fully bakeable and has an expected bearing lifetime in excess of 10 million revolutions. It has a bellows free design with replaceable ceramic bearings. Bearing replacement is easy to perform, costs a fraction of a new feedthrough, and can be scheduled into your existing maintenance program.

The new magnetically coupled CAR rotary motion feedthroughs are already in use in a number of MBE facilities.



For more information, contact:

EPI MBE Products Group

1290 Hammond Road, St. Paul, MN 55110 USA

TEL (612) 653-0488, FAX (612) 653-0725

Email: info@epimbe.com, or visit <http://www.epimbe.com>



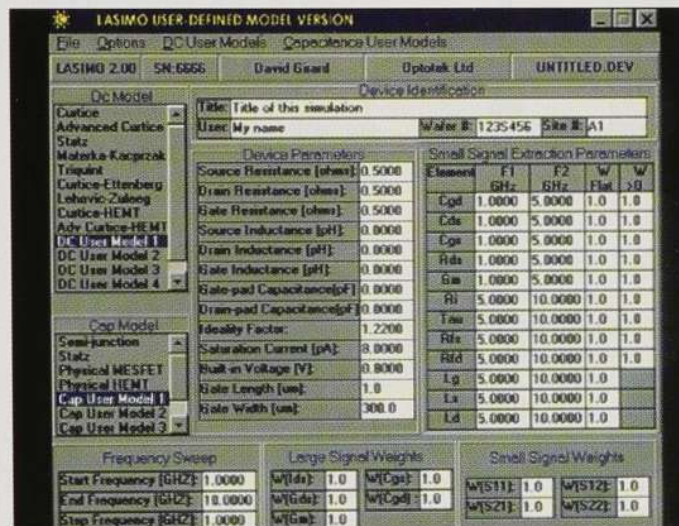
Large Signal Modeling of MESFETs & HEMTs

Kanata, Ontario, Canada. Optotek announces the availability of Version 2 of its large signal modeling software Lasimo™. The main enhancement is the introduction of user-defined large signal models.

Accurate device models are essential for the efficient use of both linear and nonlinear simulation programs. Optotek's Lasimo software facilitates the development of accurate large signal models by simplifying procedures for the extraction of MESFET and HEMT large signal models using a PC.

Lasimo 2.0 requires a 486 or Pentium PC with Windows 3.1 or above, and a minimum of 8 MB of RAM.

Lasimo is a component of Optotek's MMICAD™ CAE/CAT Suite of software solutions.



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GaAs				InP	Other			Growth Techniques	
SI	SC	SI	SC	III-V	II-VI	Other			
6"	3"	3"	3"	GaP GaSb InAs InSb		Ge Sap- phire			A leading ity subst consum versities around
6"	3"								Recyclin wafers f patented duces ul substrate in the he Valley in
6"	3"	3"	3"	GaP GaSb InAs InSb					Offers F as well wafers o Other su GaSb In able.
4"		3"	3"	GaP				LEC	We alwa isfaction S Zn an dia. Sn & 4" dia
						SiC			The only SiC subs ditions f a full qu substrate level.
6"	3"	4"	3"	InSb InAs GaSb				LEC VB VCZ	The lead InP and tributing
4"	4"			GaP				LEC VGF	Manufac substrate S-doped SC GaAs and VGF
						Sap- phire		CZ	World's phire sub
4"	3"	3"	3"	GaSb InAs InSb				LEC VGF CZ	Offers the range of ety of for Focuses with custo on-time d quality v ucts.

Going Public: AXT and Epitaxx

MARIE MEYER

American Xtal Technology (AXT) of Fremont, CA has become the most recent compound semiconductor company to go public. The company, which began trading on the NASDAQ as "AXTI" on May 21, raised \$25 million in an offering that represented around 16% of the outstanding shares.

AXT's specialty is the manufacture of GaAs substrates using the "vertical gradient freeze" (VGF) technique. The company believes that the VGF technique has significant advantages over more traditional crystal growth methods, such as liquid-encapsulated Czochralski (LEC) or horizontal Bridgman (HB). These include greater physical and chemical uniformity and fewer defects, which the company says results in substrates with lower breakage rates. AXT is one of only very few companies in the world that are using VGF, and they are likely the only company that is in high volume production.

Within the compound semiconductor community, VGF-grown semi-insulating GaAs has been generally recognized as a superior starting material for epitaxially grown structures such as lasers, HBTs and HEMTs. But, historically, VGF wafers have been more expensive, and there has been debate as to whether the benefits of using VGF wafers are so great as to justify paying a premium for them. Nevertheless, judging from the revenue and income figures in the AXT prospectus, it seems that AXT is on to something. Revenues have been growing at an annualized rate of 50% since 1994, reaching \$25 million in 1997. See Chart. And at a time when substrate producers are being squeezed by rising gallium costs and pressure from their customers to reduce profits, the company reported net income of \$3.26 million, up nearly 60% from the previous year.

GaAs substrates, both semi-insulating and semi-conducting, accounted for 94.9% AXT's 1997 revenues. But the

company is expanding its product line to include InP and Ge substrates, and they have GaP and GaN products in development. The impact of the InP and Ge wafers is already being felt: GaAs sales made up just 78.3% of 1st quarter 1998 sales.

AXT says its major customers include Emcore, Hewlett Packard, Motorola, NEC, Nortel, Siemens, Sony, Spectrolab and TRW. As we reported in our last issue, AXT, along with Litton Airtron and M/A-COM, was the beneficiary of a recently-concluded U.S. Department of Defense program aimed at improving the viability of U.S. manufacturers of semi-insulating GaAs wafers. (CS 4(4), p. 14). Prior to that program, most U.S. manufacturers had a tough time competing with the Japanese counterparts. But now the tables have been turned - at least a bit. AXT reports that 38.2% of its 1997 sales were exports, with 23.5% of them coming from Japan.

The company is in the midst of adding another 30,000 square feet to its 50,000 square foot facility in Fremont, CA to meet its anticipated production needs through 1999. AXT also recently purchased an additional 58,000 square foot facility in Fremont for future expansion.

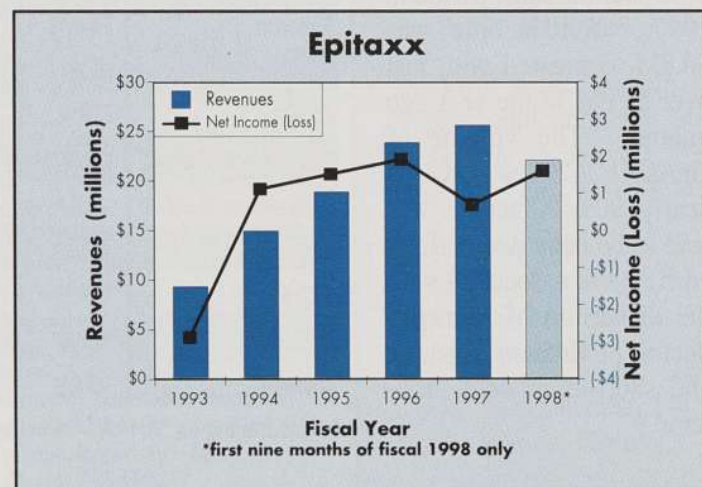
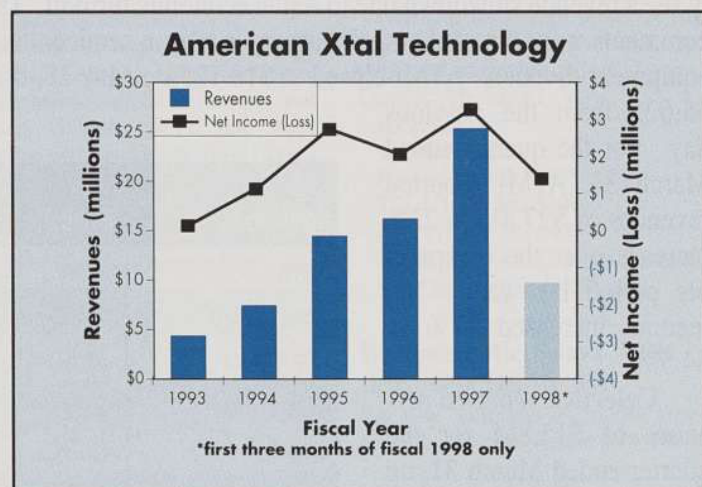
The net proceeds of the offering will be approximately \$20 million. The company intends to use \$6 mil-

lion for capital expenditures, \$4 million for product development, and \$1 million for sales and marketing, with the remainder of the net proceeds to be used for general working capital purposes.

Shares in AXT closed at \$10.625 on the first day of trading.

Who's Next?

Next out of the chute will be InGaAs detector manufacturer Epitaxx, located in West Trenton, NJ. The company announced its plans for an IPO in January; it is expected to be launched in the 2nd week of June. Epitaxx hopes to raise \$19 to 24 million for 30% of the outstanding shares. The Company was founded in 1984 and purchased in 1990 by Nippon



Sheet Glass (NSG), which is listed on the Tokyo Stock Exchange. After the IPO, NSG will continue to own the remaining 70% of the shares.

Epitaxx makes semiconductor optical detectors and receivers for fiber optics communications, with special emphasis on InGaAs-based products. Principal applications are high capacity, long-haul terrestrial and undersea fiber optic systems; digital local loop and access networks; cable television ("CATV"); high-speed computer networking; and test and measurement equipment. Major customers include Ciena, Finisar, Harmonic Lightwave, Hewlett-Packard, JDS FITELE, Lucent, Philips, Pirelli and Siemens.

Approximately \$13.7 million of the IPO proceeds will be used to repay indebtedness to NSG. The remainder will be used for general corporate purposes, including working capital and capital expenditures.

For the 1997 fiscal year, Epitaxx recorded just over \$21 million in sales, and \$0.63 million in net income. See chart.

Other News

Alpha Industries has switched to the NASDAQ Stock Market under the symbol "AHAA", effective June 2, 1998. Alpha had been trading on the American Stock Exchange under the symbol "AHA".

Shares of **ATMI** plunged after a brokerage downgraded them to "buy" from "strong buy." The firm said ATMI will likely see a revenue slowdown due to Asian economic turmoil. Their comments were directed at the company's silicon semiconductor equipment division. ATMI closed at \$18.125 on May 28, down \$5.625 from the previous day. For the quarter ended March 31, ATMI reported revenues of \$27.4M, a 22% increase over the comparable period last year. Net income increased 77% to \$4.5M.

Celeritek reported revenues of \$15.8M for the quarter ended March 31, up 36% over the same period in 1997. Net income was \$0.8M, compared with just over \$1.0M in the year ago quarter. The volume of GaAs RF IC sales increased nearly 90%. Income was said to be negatively affected by costs associated with the expansion of semiconductor production capacity and short-term yield problems.

Emcore reported revenues of \$13.8M for the quarter ended March 31, up 7% over the year ago period. Materials and device revenues increased more than 200% and represented approximately 45% of total revenues. Systems and components decreased 25%. Income was \$37,000, compared to a loss of \$3.2M in the year ago period.

Kopin reported revenue of \$5.5M for the quarter ended March 28, 1998. This represents an increase of 47% compared to the same period last year. The net loss for the quarter was \$0.6M, compared to a loss of \$2.1M in the year ago period. Product revenues for GaAs epi wafers and display products in the first were up 62%.

Ortel reported revenues of \$16.3M and a net loss of \$1.0M for the fiscal quarter ended April 30, compared to revenue and income in the year ago period of \$21.5M and \$2.3M respectively. The company attributed the loss to softness in the domestic broadband business and the effects of the Asian economic crisis.

SDL reported revenues of \$25.4M for the quarter ended March 31, compared to \$21.0M for the year ago period. Net income was a record \$2.7M, up 432% over the \$0.5 million for the same quarter in 1997.

Semiconductor Laser International (SLI) reported \$0.25M in revenue and a loss of \$1.0M for the quarter ended March 31, 1998.

Spire Corporation reported revenues of \$4.4M for the quarter ended March 31, 1998, nearly equal to the revenue reported for the year ago period. Net income was \$17,000, compared to \$150,000 for the same quarter of 1997. The company attributed the reduced earnings to increased sales and marketing activities, legal expenses and new product development costs on lower than anticipated sales.

Company	Symbol	52 - Week		Closing Price		Change	Volume (000's)	P/E Ratio
		Hi	Lo	Jan 2	May 29			
Alpha	AHA*	20 5/8	7 1/8	15 3/4	16 9/16	5.16%	90	15
Anadagics	ANAD	54 1/4	11 3/4	29 2/3	14 7/16	-51.33%	252	20
APA Optics	APAT	9 1/4	5 3/8	8 5/8	5 7/8	-31.88%	3	◆
ATMI	ATMI	42 1/4	17 1/8	23 1/8	18 1/8	-21.62%	371	24
Celeritek	CLTK	18 3/8	7 3/4	13 1/2	7 3/4	-42.59%	59	14
Cree Research	CREE	29 1/2	10 5/8	17 3/4	15 7/16	-13.03%	99	40
Emcore	EMKR	25 1/4	11	19 1/4	15 3/8	-20.13%	47	◆
Kopin	KOPN	29	13 1/4	16 2/3	18 7/8	13.25%	64	◆
Ortel	ORTL	25	10 5/8	15 3/4	14 5/8	-7.14%	132	28
RF Micro Devices	RFMD	23 3/4	9 3/4	13	12 13/16	-1.44%	72	■
SDL	SDLI	27 3/4	13 1/2	15 1/8	22	45.45%	80	◆
SLI	SLIC	6 3/4	1/2	1 3/4	1 5/32	-33.93%	186	◆
Spire	SPIR	24 3/4	4 1/2	14 5/8	6 1/2	-55.56%	22	13
TriQuint	TQNT	45 1/2	17 3/8	20 1/4	22 5/8	11.73%	147	◆
Vitesse	VTSS	28 1/2	15 7/8	17 2/3	25 5/8	45.05%	488	46

* Now trading as "AHAA" ◆ = loss in most recent 4 quarters ■ = P/E Ratio over 100

The Fifth Wide Bandgap Nitride Semiconductor Workshop

The Fifth Wide Bandgap Nitride Semiconductor Workshop will be held August 4-7, 1998 at the Adams Mark Hotel, St. Louis MO USA. Topics include: Bulk Substrates, Composite, Compliant, and Constructed Substrates, Nitride Epitaxy, Optical and Electrical Characterization of Nitride Materials, Structural and Local Characterization of Nitrides, Dopants, Alternate Sources, & Device-Related Materials Issues, Electronic Devices, and Optoelectronic Devices

Abstract Submission Deadline: July 1, 1998

Contact: Russell D. Dupuis
University of Texas
Microelectronics Research Center
PRC/MER 1.606D-R9900
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FAX: [1] 512 471 0957
Net or Web: dupuis@mail.utexas.edu

China-US Workshop on GaN

The China-US Workshop on GaN sponsored by the Chinese Department of Education and Chinese Natural Science Foundation will be held at Peking University, Beijing, China August 17-22, 1998. Individuals actively engaged or interested in GaN and related materials research and development are encouraged to attend this meeting.

Contact: Prof. H. X. Jiang
Department of Physics
Kansas State University
Manhattan, KS 66506-2601
TEL [1] 785 532 1627
FAX [1] 785 532 5636
Net or Web: Jiang@phys.ksu.edu

10th Int'l Conference on Molecular Beam Epitaxy

MBE-X will be held August 31 - September 4, 1998 in Cannes, France. This conference will cover the full spectrum of MBE-related topics, in the pleasant surroundings of the south of France.

Abstract Submission Deadline: March 15, 1998

Contact: CRHEA-CNRS Sophia Antipolis
Rue Bernard Gregory
F 06560 Valbonne France
TEL [33] 4 9395 4220
FAX [33] 4 9395 4142
NET or Web: org@mbe-x.unice.fr
http://www.crhea.unice.fr/mbe-x

6th Int'l Conf. on Terahertz Electronics

THz 98 will be held September 3-4, 1998 in Leeds, England. This conference has established itself as the primary meeting for the terahertz electronics research community. Its main goal is to

provide a forum for the exchange of information on the theory, technology and application of the emerging and interdisciplinary field of terahertz electronics, and to foster an appreciation of the capabilities and future directions of this technology.

Contact: Dr. Stavros Iezekiel
School of EEE
University of Leeds
Leeds, LS2 9JT, UK
Tel: [44] 113 233 2088
Fax: [44] 113 233 2032
Net or Web: THz98@elec-eng@leeds.ac.uk or http://www.elec-eng.leeds.ac.uk/THz98Picture

First Int'l School on Crystal Growth Technology

ISCGT-1 will be held September 5-16, 1998 at Beatenberg above Interlaken, Switzerland. This School will treat in 54 one-hour lectures, from leading crystal growth and epitaxy technology experts, the major technologies for fabrication of large commercial crystals including crystal machining, crystal growth machines, and saws. Emphasis will be on silicon, III - V and II - VI compounds, and sapphire. Posters are welcome.

Contact: Dr. Hans Scheel
Cristallogenes
Ch. de Bellerive 34
CH - 1007 Lausanne Switzerland
Tel. (41) 21 693-4452
Fax. (41) 21 693-4750
Net or Web: Hans.Scheel@epfl.ch

1998 Conference on Lasers & Electro-Optics Europe & The 6th European Quantum Electronics Convention

CLEO EUROPE/EQEC will be held Sep. 13 - Sep. 18, 1998 at the Scottish Exhibition & Conference Center in Glasgow, Scotland.

Contact: Ms. Melissa K. Estrin
IEEE/LEOS
445 Hoes Lane
Piscataway, NJ 08855-1331
TEL [1] 908 562-3896
FAX [1] 908 562-8434
Net or Web: m.estrin@ieee.org
http://www.ieee.org/leos/meet.htm

First Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems

The first IEEE sponsored topical meeting on Silicon Monolithic Integrated Circuits in RF Systems will be held September 17-18, 1998 at The University of Michigan, Ann Arbor, MI. The meeting is devoted entirely to silicon integrated circuits for RF systems and will cover material development, advanced devices, high frequency circuits, passive device development, reliability and yield, and applications.

Contact: George E. Ponchak
NASA Lewis Research Center
21000 Brookpark Rd., MS 54/5
Cleveland, OH 44135
TEL: [1] 216-433-3504
FAX: [1] 216-433-8705
Net or WEB:
george.ponchak@lerc.nasa.gov
http://www.eecs.umich.edu/
RADLAB/SiGe.Conference.

1998 IEEE Bipolar/BiCMOS Circuits and Technology Meeting

BBCTM '98 will be held Sep. 27 - Sep. 29, 1998 in Minneapolis, MN.

This meeting provides a forum for technical communication focused on the needs and interests of bipolar and BiCMOS engineers.

Abstract Submission Deadline: March 16, 1998

Contact: Ms. Janice V. Jopke
CCS Associates
6611 Countryside Dr.
Eden Prairie, MN 55346
TEL [1] 612 934-5082
FAX [1] 612 934-6741
Net or Web: jjopke@aol.com

Eastern Regional Conference on Crystal Growth & Epitaxy

ACCGE/East '98 will be held at September 27-30, 1998 at Bally's Hotel & Casino in Atlantic City, N.J.

Topics to be emphasized include Epitaxial Growth, Laser Materials, Fundamentals of Solidification and Crystal Growth, II-VI and Wide Bandgap Semiconductors, Bulk Crystal Growth, and more.

Contact: Rose Scripa
University of Alabama
Dept of Materials Engineering
1150 10th Avenue S
Birmingham, AL 35294
TEL [1] 205 934 8453
Fax [1] 205 934 8437
Net or Web: rscripa@eng.uab.edu
or http://www.aml.arizona.edu/aacg/conferences.html

2nd Int'l Symposium on Blue Laser and Light Emitting Diodes

The 2nd ISBLLED Conference will be held September 29 - October 2, 1998 at the in Chiba, Japan. The main objective of this symposium is to provide a joint forum for both the GaN community and the ZnSe community to discuss common problems extending from the growth and characterization of materials to device performance and reliability.

University of Tsukuba
Institute of Materials Science
1-1-1 Tennodai
Tsukuba, Ibaraki 305 Japan
TEL [81] 298 53 5287

FAX [81] 298 55 7440
Net or Web: hasegawa@mat.ims.tsukuba.ac.jp or
http://www.etl.go.jp/etl/divisions/material/isblled2/isblled2.html

17th North American MBE Conference

NAMBE-17 will be held Oct. 4-7, 1998 on the Penn State campus in State College, PA. Researchers from all fields who use MBE in their work with all types of materials are invited to attend.

Contact: David L. Miller
The Pennsylvania State University
121 E.E. East Building
University Park PA 16802
TEL [1] 814 865 2730
FAX [1] 814 865 7065
Net or Web: dlm15@psu.eduhttp://www.cde.psu.edu/C&I/MBE/Contact

1998 IEEE/LEOS Semiconductor Laser Conference

The 1998 IEEE/LEOS Semiconductor Laser Conference will be held Oct. 5, 1998 - Oct. 10, 1998 at the Nara Public Hall in Nara, Japan. The scope of the meeting includes semiconductor laser physics; materials and processing; design and modeling; long & short wavelength laser; high power & high speed laser; VCSELs, novel laser structures; and integration and packaging.

Contact: Ms. Elsie L. Vega
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445 Hoes Lane
Piscataway, NJ 08855-1331
TEL [1] 732 562-3897
FAX [1] 732 562-8434
Net or Web: e.vega@ieee.orghttp://www.ieice.or.jp/es/islc98.html

European Microwave Week (Including GAAS '98)

The new "European Microwave Week" event will be held October 5 - 9, 1998 in

New Entries

- The Fifth Wide Bandgap Nitride Semiconductor Workshop, August 4-7, 1998, St. Louis MO USA.
- Eastern Regional Conf. On Crystal Growth & Epitaxy, September 27-29, 1998, Atlantic City, NJ.
- LEOS '98, December 1-4, 1998, Orlando, Florida

Amsterdam, The Netherlands. This event incorporates three previously existing conferences: The European GaAs Applications Symposium (GAAS '98), The European Microwave Conference (EuMC '98), and The MTT-S European Topical Congress on Technologies for Wireless Applications (MTT-S European Wireless '98).

Contact: David Roberts
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TEL [44] 181 855 777 x 5953
FAX [44] 181 316 3174
Net or Web: droberts@unmf.com

25th Int'l Symp. on Compound Semiconductors

ISCS '98 will be held October 12 - 16, 1998 in Nara, Japan. This symposium covers all aspects of compound semiconductors - including growth, processing, devices, ICs, and applications - and deals with III-V compounds such as GaAs, InP, and GaN; II-VI compounds such as ZnSe and ZnS; IV-IV materials such as SiC and SiGe; etc.

Contact: Kimiyoshi Yamasaki
NTT System Electronics Lab.
3-1 Morinosato Wakamiya, Atsugi,
Kanagawa, 243-01 Japan
TEL [81] 462 40 2500
FAX [81] 462 40 2872
Net: kyama@aecl.ntt.co.jp
Web: <http://www.ieice.or.jp/es/iscs98.html>

3rd Int'l Workshop on Novel Index Surfaces

NIS '98 will be held October 6 - 9, 1998, 1998 in La Casona (San Rafael), Spain. The scope of this conference is the growth, characterization and exploitation of epitaxial compound semiconductors on novel index surfaces.

Contact: Mariano Gonz-lez
ETSI TelecomunicaciUn-UPM
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28040-Madrid, Spain
FAX [34] 1 336 73 23
Net or Web: mariano@die.upm.es
<http://www.die.upm.es/research/nis98.htm>

1998 U.S. Workshop on the Physics & Chemistry of II-VI Materials

The 1998 II-VI Workshop will be held October 20-22, 1998 in Charleston, SC. The purpose of this workshop is to bring together the universities and industrial and governmental communities that work with II-VI materials, including HgCdTe and other IR materials, II-VI semiconductor alloys used for X-ray and gamma-ray detectors, ZnSe-based II-VU photonic materials, and II-VI photorefractive materials.

Contact: Jay Morreale
Palisades Institute
201 Varick Street, suite 1006
New York, NY 10014 USA
TEL [1] 212 620 3371
FAX [1] 212 620 3379
Net or Web: jmorreal@newyork.palisades.org

1998 IEEE GaAs IC Symposium

The 1998 IEEE GaAs IC Symposium will be held Nov. 01 - Nov. 04, 1998 at the Westin Peachtree Plaza in Atlanta, GA.

Contact: Dr. William Stanchina
Hughes Research Labs., RL61
Plasma Physics Lab.
3011 Malibu Canyon Rd.
Malibu, CA 90265
TEL [1] 310 317-5089
FAX [1] 310 317-5483

194rd Meeting of the Electrochemical Society

The 194rd ECS Meeting will be held November 1-6, 1998 at the Sheraton Boston Hotel & Tower in Boston, Massachusetts. Symposia include: G1 - Dielectric Science And Technology/Electronics Joint General Session; H1 - Interconnect And Contact Metallization: Materials, Processes And Reliability; I1 - III-V Nitride Materials And Processes; J1 - Fifth International Symposium On Quantum Confinement: Nanostructures; N1 - Compound Semiconductor Power Transistors; N3 - Sixth International Symposium On Long Wavelength Infrared Detectors And Arrays: Physics And Applications; N4 - State-Of-The-Art Program On Compound Semiconductors (SOTAPCOCS XXVIII); P1 - Photovoltaics For The 21st Century
Abstracts Submission Deadline: June 1, 1998

Contact: The Electrochemical Society
10 South Main Street
Pennington, NJ 08534-2896 USA
TEL [1] 609 737 1902
FAX [1] 609 737 2743
NET or WEB: ecs@electrochem.org
or <http://www.electrochem.org>

45th National AVS Symposium

The 1998 AVS National Symposium will be held November 2-6, 1998 at the Baltimore Convention Center in Baltimore, MD. AVS Technical Divisions include: applied surface science; nanometer-scale science and technology; surface science; vacuum metallurgy; electronic materials and processing; plasma science and technology; thin film; and vacuum technology.
Abstract Submission Deadline: May 1, 1998

Contact: Marion Churchill
AVS
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New York, NY 10005 USA
TEL [1] 212 248 0200
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Net: marion@vacuum.org
Web: <http://www.vacuum.org>

6th Int'l Workshop on High Performance Electron Devices for Microwave and Optoelectronic Applications

EDMO '98 will be held November 23-24, 1998 in Manchester, UK. Its purpose is to act as a forum for microwave and optoelectronic device designers, fabricators, modellers and general users to discuss the synergy between system needs and advanced electronic devices and circuits. Contributions concerned with the application of electron devices for microwave and optoelectronics are welcomed.

Abstract Submission Deadline: September 1, 1998

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UMIST, EE& E Dept.
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Manchester M60 1QD UK
TEL [44] 161 200 4797
FAX [44] 161 200 4770
Net or Web: missous@fs4.ee.umist.ac.uk
or <http://www.ee.umist.ac.uk/new/edmo98.html>

1998 Fall MRS Meeting

The 1998 Fall MRS Meeting will be held November 30 - December 4, 1998 in Boston, MA. Symposia include: B) Growth Instabilities and Decomposition During Heteroepitaxy; D) Integration of Dissimilar Materials in Micro- and Optoelectronics; G) GaN and Related Alloys; H) IR Semiconductor Materials and Devices; and I) III-V and SiGe Processing Challenges for Commercial Applications.

Abstract Submission Deadline: June 8, 1998

Contact: Materials Research Society
506 Keystone Drive
Warrendale, PA 15086-7573 USA
TEL [1] 412 779-3003
FAX [1] 412 779-8313
Net or Web: webmaster@mrs.org
or <http://www.mrs.org>

Lasers and Electro-Optics Society Annual Meeting

LEOS '98 will be held December 1-4, 1998 at Walt Disney World, Orlando, Florida. Organizers are expecting more than 700 attendees, 200 invited talks, and 270 contributed papers, on topics including Semiconductor Lasers, Optoelectronic Materials & Processing, Optical Communications, and Electro-Optical Sensors & Systems. There will also be a Special Symposium on Oxidation Technologies of III-V Semiconductors.

Abstract Submission Deadline: June 19, 1998

Contact: IEEE/LEOS
445 Hoes Lane
Piscataway, NJ 08855-1331 USA
TEL [1] 732 562 3989
FAX [1] 732 562 8434
Net or Web: m.estrin@ieee.org
<http://www.ieee.org/leos/meet.htm>

1998 IEEE International Electron Devices Meeting

The 1998 IEDM will be held December 6-9, 1998 in San Francisco, CA.

Contact: Ms. Phyllis Mahoney
Widerkehr & Associates
101 Lakeforest Blvd.
Suite 270
Gaithersburg, MD 20877
TEL [1] 301 527-0900
FAX [1] 301 527-0994
Net or Web: pwmahoney@aol.com

Conf. on Optoelectronic and Microelectronic Materials and Devices

COMMAD '98 will be held December 14-16, 1998 in Perth, Australia.
Abstract Submission Deadline: August 31, 1998

Contact: Lorenzo Faraone
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EEE Department
Nedlands, WA 6907 Australia
TEL [61] 8 9380 3104
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Net or Web: faraone@ee.uwa.edu.au
<http://www.ee.uwa.edu.au/~COMMAD98>

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If you would like your conference to be included in future issues, send the appropriate information by E mail to calendar@compsem.com, or by FAX to [1] 978 750 9740, attention "Calendar"
Contributions must be received by July 10 to appear in our next issue.

Patents related to compound semiconductors issued from March 11, 1998 - April 1.
Headlines contain Patent # / Date Issued / Assignee.

Sources:

"05..." = U.S. Patent Office; "EP..." = European Patent Office;

"WO..." = World Intellectual Property Organization



Electronics

WO9819342 / 1998 05 07 / Daimler-Benz Kaminski, N. & Neubrand, H.

Controllable Semiconductor Structure with Improved Switching Properties. The invention concerns a controllable semiconductor structure comprising a base region, a source region and a drain region, a conductive duct being provided in the base region between the source and drain...the semiconductor material of the base region having an energy gap of more than 1.2 eV.

05747831 / 1998 05 05 / Daimler-Benz Loose, W. et al

SiC Field-Effect Transistor Array with Ring Type Trenches. SiC field-effect transistors with source, gate and drain contacts and in which the source contacts are located on the surface of the semiconductor wafer, the drain contacts on the underside of the wafer and the gate contacts in trench-like structures.

05745857 / 1998 04 28 / ETRI Maeng, S.-J.; Lee, C.-S.; Park, H.-M.

GaAs Power Amplifier for Analog/Digital Dual-Mode Cellular Phones. The present invention relates to...a GaAs power amplifier for analog/digital dual-mode cellular phones which can be operated with a voltage of less than 3.3 volt.

05739559 / 1998 04 14 / Hitachi Kagaya, O & Takazawa, H

Compound Semiconductor Integrated Circuit. A compound semiconductor integrated circuit having a high resistance layer consisting of a compound semiconductor to which oxygen is added as an impurity and an undoped compound semiconductor layer which are formed between a semi-insulating substrate and FETs formed thereon...suited to a superspeed operation because the low frequency oscillation is suppressed.

05753545 / 1998 05 19 / Hughes Electronics Liu, T. & Nguyen, C.

Effective Constant Doping in a Graded Compositional Alloy. Epitaxial growth of a chirped superlattice with constant dopings is achieved with minimal growth interruption time [directed to effective constant doping of the base-collector in a double heterojunction bipolar transistor].

05748056 / 1998 05 05 / ITT Bahl, Inder J.

Compact 900 Monolithic GaAs Coupler. A coupler device is disclosed which has an improved structure...a layer of dielectric material is disposed between the inductors and substrate which improves performance by reducing the dissipation losses and enhancing the frequency response of the coupler.

EP0840942 / 1998 05 13 / Lockheed Gill, D. & Uppal, P.

GaAs Substrate with Compositionally Graded AlGaAsSb Buffer for Fabrication of High-Indium FETS. Abstract not available.

05751030 / 1998 05 12 / Matsushita Electric Fujimoto, K.; Matsuno, T.; Inoue, K.

Field Effect Transistor. On a GaAs substrate are provided a buffer layer comprising an undoped-GaAs layer, a first n-InGaAs layer [In_{0.2}Ga_{0.8}As], a second n-InGaAs layer [In_{0.02}Ga_{0.98}As]...the first n-InGaAs layer and the second n-InGaAs layer form active layers in which an operating current flows. The second n-InGaAs layer having excellent crystallinity is formed on the first n-InGaAs layer. Consequently, a field effect transistor which displays a super low distortion characteristic having IP₂ of 67.2 dBm and IP₃ of 35 dBm can be manufactured with good reproducibility.

05739557 / 1998 04 14 / Motorola O'Neil, Vernon et al

Refractory Gate Heterostructure Field Effect Transistor. A heterostructure field effect transistor and method including at least one passivation layer and at least one etch stop layer. Enhancement, depletion and combined devices with both enhancement mode and depletion mode devices are possible with minor process variations. Refractory gate and non-gold refractory ohmic contact metallization combined with other features allows non-liftoff metal patterning.

EP0841691 / 1998 05 13 / NEC Yamaguchi, Y. & Iwata, N.

Field Effect Transistor. Using a mask opening a gate region, an undoped GaAs layer is selectively etched with respect to an

undoped Al_{0.2}Ga_{0.8}As layer by dry etching...a hetero junction FET having reduced fluctuation of characteristics of an FET, such as a threshold value, lower a rising voltage and higher breakdown characteristics.

WO9820563 / 1998 05 14 / Northrop Grumman Sriram, Saptharishi

Power Field Effect Transistor in SiC or GaN. The invention provides for a FET which includes a substrate and a buffer layer formed upon the substrate and an active layer formed upon the buffer layer...[they] are preferably fabricated of SiC or GaN. Further, the FET preferably includes a p type buffer, n type active layer, and n+ degenerate layers. The FET may also include a surface-effect-suppressive layer which preferably covers portions of the active layer and the degenerate layers.

05751820 / 1998 05 12 / ReSound Corporation Taenzer, J.

Integrated Circuit Design For A Personal Use Wireless Communication System Utilizing Reflection. An integrated circuit chip set design for a wireless hearing aid communication system...The circuits are integrated using a GaAs process and are operated in the multi-GHz range so that the circuits dissipate relatively low power.

EP0841704 / 1998 05 13 / Paul-Drude-Institut Friedland, K.-J. et al

Semiconductor Transistor Device. A method of manufacturing a semiconductor transistor device...is characterized by the step of growing in sequence on said substrate a first superlattice, a quantum well layer and a second superlattice...[and] to form at least one delta doped layer therein, whereby to enhance the conductivity of the electrons in the quantum well layer.

05751027 / 1998 05 12 / Sanyo Electric Sawada, M. & Harada, Y.

Field Effect Semiconductor Device with a Low-Noise Drift Layer and a High-Power Drift Layer. A field effect semiconductor device includes an undoped In_{0.2}Ga_{0.8}As first low-noise drift layer, an undoped InGaAs

Electronics, cont'

second low-noise drift layer and an n-type GaAs high-power drift layer in this order. The high-power drift layer includes a first high-power drift layer doped with n-type carrier at high concentration and a second high-power drift layer doped with n-type carrier at low concentration.

05751029 / 1998 05 12 / Sanyo Electric Matsushita S. et al

Field-Effect Semiconductor Device Having Heterojunction. An undoped $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ layer, an undoped $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ electron-drifting layer, and an undoped GaAs electron-supplying layer are formed in order on a GaAs substrate. An impurity-doped layer delta-doped with Si donor is formed in the GaAs electron-supplying layer. An n- $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ layer and n+ -GaAs cap layers are formed in order on the GaAs electron-supplying layer. A source electrode and a drain electrode are formed on the n+ -GaAs cap layers and a gate electrode is formed on the n- $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ layer.

05747842 / 1998 05 05 / TI Plumton, Donald L.

Epitaxial Overgrowth Method And Devices. A vertical field effect transistor and fabrication method with buried gates; having spaced apart gate fingers and connecting structure and overgrown with source and channel epilayer followed by a doping connection of the gate fingers and connecting structure.

05736417 / 1998 04 07 / TRW Oki, Aaron K et al

Method of Fabricating Double Photoresist Layer Self-Aligned Heterojunction Bipolar Transistor. A method for fabricating an HBT with self-aligned base metal contacts using a double photoresist, which requires fewer process steps than known methods, while minimizing damage to the active emitter contact region. In particular, a photoresist is used to form the emitter mesa.

05747838 / 1998 05 05 / Univ. Calif. Mishra, U. & DenBaars, S.

Ultra-Low Phase Noise GaAs MOSFETs. A GaAs-based field effect transistor has a passivation layer of aluminum oxide below a GaAs channel and aluminum oxide gate oxide layer formed over the channel. The aluminum oxide layers are treated to reduce the density of surface state impurities, particularly arsenic released in the oxide layer as a result of forming the oxide layer. The low surface state GaAs channel has very low phase noise and is suitable for use as a local oscillator in a heterodyne receiver.

Materials

WO9814645 / 19980409 / ABB Research

A Method For Producing A Region Doped With Boron In A SiC Layer. A method for producing a crystalline layer of SiC having at least a region thereof doped with boron atoms comprises a step a) of ion implantation of boron into a layer (1) of crystalline SiC and a step b) of heating the SiC layer for annealing it for making the boron implanted therein electrically active. The method further comprises a step c) of implanting carbon atoms in said layer (1) for forming carbon interstitials in excess with respect to carbon vacancies present in the SiC layer before carrying out step b).

EP0833395 / 19980401 / Canon

Method Of Fabricating A Device. A method of fabricating a compound semiconductor layer structure including a layer containing nitrogen is provided. In a method of fabricating a device including a compound semiconductor layer structure, a portion of crystal of compound semiconductor, which is to be at least a portion of a function layer of the device, is irradiated with material including at least nitrogen, and element of V group of the irradiated portion is substituted by the nitrogen. In a fabrication method, a thickness of the N-substituted layer does not exceed its critical layer thickness. In a fabrication method, a depth of the N-substituted portion is controlled by using material for oppressing the substitution by nitrogen.

05751028 / 1998 05 12 / Fujitsu Kikkawa, T.

Semiconductor Device Formed On A Substrate Having An Off-Angle Surface. A compound semiconductor device includes a compound semiconductor layer having an upper major surface formed with a multi-step structure, wherein said multi-step structure includes a plurality of steps each having a step height of at least 5 atomic layers and a step width of 300 nm or more.

05738722 / 1998 04 14 / Fujitsu Tomioka, Takeshi et al

III-V System Compound Semiconductor Device. The invention relates to a method for manufacturing a III-V system compound semiconductor device, provides such a new C dopant as alkyl halide (CH_2I_2 for example) containing carbon (C), iodine (I), and hydrogen (H) for giving a highly p-type conductivity to a GaAs crystal layer, an InGaAs crystal layer or the like as an object of it, and includes a process of forming a p-type III-V system compound semiconductor layer as using a compound containing carbon (C) as a dopant material for giving a p-type conductivity and further containing iodine (I) and hydrogen (H) as impurity.

05742089 / 1998 04 21 / Hughes Electronics Rajavel, D. & de Lyon, T

Growth Of Low Dislocation Density HgCdTe Detector Structures. An epitaxial structure and method of manufacture for a infrared detector device with low dislocation density, especially for high performance large area focal plane arrays. Preferably, the epitaxial structure includes a buffer layer comprising a Hg-based II-VI material and an overlayer comprising a detector comprising a Hg-based II-VI material. The buffer layer is transparent at the operating frequencies of the detector.

05741360 / 1998 04 21 / OTCR (Japan) Goto, S. et al

Method Of Growing A Crystal Of A Compound Semiconductor At A Low Temperature. In a method of selectively growing a crystal of a compound semiconductor layer which is composed of gallium and arsenic, a selective growth is selectively carried out on a substrate by using a combination of metallic gallium and a reactive gas, such as trisdimethylaminoarsine, which includes a metallic compound of arsenic specified by at least one amine.

WO9813879 / 19980402 / Picolight Inc. Jewell, J & Temkin, H

Extended Wavelength Strained Layer Lasers. Several methods are used in novel ways with newly identified and viable parameters to decrease the peak transition energies of the pseudomorphic InGaAs/GaAs heterostructures. These techniques, taken separately or in combination, suffice to permit operation of light emitting devices at wavelengths of 1.3 micron or greater of light emitting electro optic devices. These methods or techniques, by example, include: (a) utilizing new superlattice structures having high In concentrations in the active region, (b) utilizing strain compensation to increase the usable layer thickness for quantum wells with appropriately high In concentrations, (c) utilizing appropriately small amounts of nitrogen (N) in the pseudomorphic InGaAsN/GaAs laser structure, and (d) use of nominal (111) oriented substrates to increase the usable layer thickness for quantum wells with appropriately high In concentrations.

05753039 / 1998 05 19 / Sanyo Electric Hishida, Y. & Yoshie, T.

Manufacturing Method of P-Type Semiconductor Crystal. The present invention relates to...a method of manufacturing a p-type semiconductor crystal formed of a II-VI Group compound semiconductor containing Zn and Se by vapor phase epitaxy method.

Laser Diodes

05751753 / 1998 05 12 / Fujitsu Uchida, T.

Semiconductor Laser with Lattice Mismatch. A semiconductor laser of 1 micron band is provided whose substrate and clad layer are lattice mismatched and whose clad layer uses group III-V semiconductor having a wide forbidden band and containing Al as the group III element.

EP0834971 / 19980408 / Furukawa Ohkubo, M; Ijichi, T; Ikegami, Y.

Semiconductor Laser. In a semiconductor laser device...[including] a non-absorbing layer of InGaP formed on the facets of the semiconductor laser main body and having a band gap greater than the band gap of the active layer, diffusion blocking layer of, for example, Si, SiN or Ge is formed on the surface of the non-absorbing layer, and a dielectric protective layer of, for example, AlOx, SiOx, SiNx or MgOx for regulating reflectance at the facets and protecting the non-absorbing layer is formed on the diffusion blocking layer.

05742629 / 1998 04 21 / Matsushita Electric Nishikawa, T.; Uemura, N.; Kamiyama, S.

Semiconductor Laser and Production Method Thereof. A semiconductor laser includes: an active layer formed of a II-VI group compound semiconductor material...a light confinement layer provided on the second cladding layer, having an opening for current flow and formed of ZnMgSSe...the second and third cladding layers are formed of ZnMgSSe; and a Mg content and a S content of the light confinement layer are larger than a Mg content and a S content of the second and third cladding layers.

05751754 / 1998 05 12 / Mitsubishi Denki Takagi, K.

Semiconductor Laser Including Tunnel Diode for Reducing Contact Resistance. A semiconductor laser...[which] includes the tunnel diode structure disposed in the reverse bias direction with respect to the current flow direction, [and therefore] the contact resistivity of the ohmic contact of the p side electrode is lowered as compared to the case where the p side electrode is disposed on a p type semiconductor layer.

05737350 / 1998 04 07 / Mitsubishi Denki Motoda, T & Kato, M

Semiconductor Laser Having Multi-Quantum Barrier Including Complex Barrier Structure. A multi-quantum barrier layer includes alternately laminated barrier layers of a III-V compound semiconductor material and well layers of a III-V compound semiconductor material including the same Group V element as in the barrier layers. During the formation of the multi-quantum barrier layer it is not necessary to switch the

Group V element source gas at the interface between a barrier layer and a well layer so that this interface is abrupt, improving the electron reflection efficiency of the multi-quantum barrier layer.

05737351 / 1998 04 07 / Mitsubishi Denki Ono, Kenichi

Semiconductor Laser Including Ridge Structure Extending Between Window Regions. A method of fabricating a semiconductor laser...[whereby] unwanted penetration of the etch stopping layer is avoided.

05737353 / 1998 04 07 / NEC

Sasaki, Yoshihiro

Multiquantum-Well Semiconductor Laser. A multiquantum-well semiconductor laser having a long wavelength, for use in optical communication systems, comprises an active region including a plurality of quantum-well layers each made of InGaAs or InGaAsP, and a plurality of barrier laminates each made of InGaAsP having a bandgap wider than that of the quantum-well layers. Each barrier laminate includes three barrier layers of different compositions of InGaAsP having different bandgaps. Each barrier laminate has a thickness such that the wave functions of carriers in adjacent quantum-well layers do not overlap each other, while carriers supplied to the active region can be effectively injected into the quantum-well layers, thereby obtaining a low threshold current and a high slope efficiency.

EP0834969 / 19980408 / Oki Electric Tsubota, Takashi

Semiconductor Laser And Light Source. A semiconductor laser emits light through a front end and a rear end, the front end being coupled to an application system. The front end has a higher reflectivity than the rear end, to reduce problems caused by returning light. More light is therefore emitted through the rear end than through the front end. In a light source, the light emitted through the rear end is monitored by an optical detector coupled to a control circuit, which controls the voltage applied to the semiconductor laser.

WO9813912 / 19980402 / Philips Electronics

Pomp, Hendrik et al

Method Of Manufacturing An Optoelectronic Semiconductor Device Comprising A Mesa. An optoelectronic device, such as a laser of the ridge waveguide type, can be provided with the necessary mesa by means of wet or dry etching with a mask.

EP0839400 / 1998 05 06 / Siemens Bogner, G.

Semiconductor Laser Chip And Infrared Emitter Component. Abstract Not Available.

05737352 / 1998 04 07 / U.S. Philips Tiemeijer, L; Binsma, J; Thijs, P.

Semiconductor Diode Laser, In Particular A Laser Amplifier, And Method Of Manufacturing This Laser. The present invention has for its object inter alia to provide a laser which has substantially no amplification ripple. The invention also has for its object to provide a method by which such a laser may be readily manufactured.

VCSELs

05747366 / 1998 05 05 / Alcatel Alsthom Brillouet, F. et al.

Method of Fabricating a Surface Emitting Semiconductor Laser. In a method of fabricating a surface emitting semiconductor layer, to achieve good electrical confinement and good flatness of the mirrors delimiting the resonant cavity of the laser, an electrical confinement layer is made by growing a localized aluminum alloy layer on the active layer, except for an opening area on top of which the mirror is to be formed. After epitaxial regrowth, the alloy layer is oxidized laterally. Applications include the fabrication of semiconductor lasers on III-V substrates such as InP and GaAs.

05742630 / 1998 04 21 / Motorola Jiang, W.; Shieh, C-L; Lebby, M.

VCSEL with Integrated PIN Diode. A VCSEL having first and second stacks of DBRs and an active region sandwiched there between is formed. A PIN photo-detector is integrated onto the VCSEL by positioning it on the second stack in the light path. The PIN photo detector includes a first doped region, a second undoped (intrinsic) region, and a third doped region. A first conductive layer is provided in contact with the second stack and the first region and a second conductive layer is provided in contact with the third region.

05753941 / 1998 05 19 / Samsung Electronics Shin, H. & Lee, Y.

Vertical Cavity Surface Emitting Laser. The present invention relates to...a VCSEL having an electrode layer which enhances the optical characteristics of the emitted light...The electrode layer has a metal layer having a high electrical conductivity and a conductive auxiliary reflector layer formed between the metal layer and the second reflective layer. The auxiliary reflector layer has a reflectivity which is lower than the reflectivities of either of the first or second reflector layers.

05753939 / 1998 05 19 / None
Sassa, M. et al

Light-Emitting Semiconductor Device Using A Group III Nitride Compound. A light-emitting semiconductor device having an improved metal electrode and semiconductor structure that lowers the driving voltage of the device. The device has a hetero p-n junction structure...The contact layer is doped with an acceptor impurity more heavily than is the p-layer. The acceptor impurity may be magnesium (Mg). The contact layer may be doped within the range of $1 \times 10^{20} \text{ cm}^{-3}$ to $1 \times 10^{21} \text{ cm}^{-3}$ and may comprise a first and a second contact layer.

05751021 / 1998 05 12 / None
Teraguchi; Nobuaki
Abstract

Semiconductor Light-Emitting Device. The present invention relates to a semiconductor light-emitting device made of a nitride type alloy semiconductor. More specifically, the present invention relates to a semiconductor light-emitting device capable of emitting light by band-to-band radiative recombination in a wavelength region of ultraviolet to blue or green with reduction of growth temperature difference. A semiconductor light-emitting device of the present invention includes a nitride type alloy semiconductor layer. The nitride type alloy semiconductor layer is made of AlGaInN including at least one selected from the group consisting of Sc, Ti, V, Cr, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu.

WO9819964 / 1998 05 14 / Case Western Reserve Univ
Angus, J.; Argoitia, A., Cliff, C.

Method For The Synthesis Of Group III Nitride Crystals. Using the method of the present invention, the crystalline Group III nitride can be grown at pressures of one atmosphere and below. Polycrystalline films grown by this method are of sufficient quality to show luminescence at room temperature.

05739554 / 1998 04 14 / Cree Research
Edmond, J & Kong, H

Double Heterojunction Light Emitting Diode With Gallium Nitride Active Layer. A double heterostructure for a light emitting diode comprises a layer of AlGaIn having a first conductivity type; a layer of AlGaIn having the opposite conductivity type; and an active layer of GaN between the AlGaIn layers, in which the GaN layer is co-doped with both a Group II acceptor and a Group IV donor, with one of the dopants being present in an amount sufficient to give the GaN layer a net conductivity type, so that the active layer forms a p-n junction with the adjacent layer of AlGaIn having the opposite conductivity type.

EP0838866 / 1998 04 29 / General Electric Co
Doughty, D.; Liu, Y.; Duggal, A.

A Light-Emitting Diode White Light Source. A system of at least three multi-coloured LED's has an optimized colour rendering index by proper selection of wavelengths of each LED, such system being useful for general illumination purposes. In a preferred embodiment, a blue LED has a wavelength in the range 455 to 490 nm, a green LED has a wavelength in the range 530 to 570 nm, and a red LED has a wavelength in the range 605 to 630 nm.

WO9819375 / 1998 05 07 / Hitachi
Niwa, A. et al

Optical Information Processor And Semiconductor Light Emitting Device Suitable For The Same. An information processor of a high reliability and a high recording density...[and a] blue semiconductor light emitting device of a low threshold value current density suitably used for the same are provided...A barrier layer in a quantum well active layer of a semiconductor light emitting device is doped with n-type impurities at a high concentration. Alternatively, the face orientation of the quantum well active layer is a plane inclined with respect to the (0001) plane. Thus, the threshold current value of the semiconductor light emitting device can be decreased. A GaN compound semiconductor layer device is a typical example of this semiconductor light emitting device.

05741724 / 1998 04 21 / Motorola
Ramdani, J.; Lebby, M. & Holm; Paige M.

Method Of Growing Gallium Nitride On A Spinel Substrate. A method of growing gallium nitride on a spinel substrate by providing a supporting substrate having a surface, and disposing a plurality of buffer layers on the surface of the supporting substrate. The plurality of buffer layers including a first buffer layer of aluminum oxynitride having a low percentage of mismatch to the spinel substrate. The second buffer layer is disposed on the first buffer layer and includes a plurality of layers of a graded aluminum oxynitride having a low dislocation density. A third buffer layer of aluminum nitride is disposed on the second buffer layer. A fourth buffer layer of gallium nitride is disposed on the third buffer layer. Subsequently, a photonic device structure, such as a laser, LED or detector, an electronic device structure, such as a field effect transistor or modulation doped field effect transistor, or an optical waveguide is fabricated on the fourth buffer layer.

05742628 / 1998 04 21 / NEC
Fujii, Hiroaki

Short Wavelength Laser Emitting Diode With An Improved GaN System Double

Heterostructure. A GaN system compound semiconductor double heterostructure in a light emission device comprises an active layer sandwiched between first and second cladding layers. The first, second and third GaN system compound semiconductor materials have first, second and third hexagonal crystal structures of basal planes tilted from a (0001) plane by an angle in the range of 0 degree to a few degrees, and the basal planes are substantially parallel to interfaces of the active layer to the first and second cladding layers.

05747832 / 1998 05 05 / Nichia Chemical
Nakamura, S.; Mukai, T.; Iwasa, N.

Light-Emitting GaN-Based Compound Semiconductor Device. A light-emitting GaN-based compound semiconductor device of a double-heterostructure. The double-heterostructure includes a light-emitting layer formed of a low-resistivity InGaIn compound semiconductor doped with p-type and/or n-type impurity. A first clad layer is joined to one surface of the light-emitting layer and formed of an n-type GaN-based compound semiconductor having a composition different from the light-emitting layer. A second clad layer is joined to another surface of the light-emitting layer and formed of a low-resistivity, p-type GaN-based compound semiconductor having a composition different from the light-emitting layer.

05751752 / 1998 05 12 / Rohm Co.
Shakuda, Yukio

Semiconductor Light Emitting Device And Manufacturing Method Therefor. The invention relates to a semiconductor laser having a double heterodyne structure...[and] which uses a semiconductor of gallium nitride type compound suitable for emission of blue light, which is capable of reducing operating voltage without reducing the light emitting efficiency. A semiconductor light emitting device of double hetero junction includes an active layer and clad layers. The clad layers include an n-type layer and p-type layer. The clad layers sandwich the active layer. A band gap energy of the clad layers is larger than that of the active layer. The band gap energy of the n-type clad layer is smaller than of the p-type clad layer.

EP0834929 / 19980408 / Toyoda Gosei
Uemura, T.; Shibata, N

Ohmic Contact to n-GaN Related Compound Semiconductor. A base layer of electrode made of at least a metal selected from V, Nb, Zr, and Cr or an alloy containing such metal on an n-type GaN compound semiconductor layer. Further, a main electrode layer made of other metal is formed on the base layer. Then, an n electrode is formed by subjecting the semiconductor layer, the base layer, and the main electrode layer to a heat treatment.

Other Optoelectronic

05739552 / 1998 04 14 / Mitsubishi Denki Kimura, T & Kawazu, Z

Semiconductor Light Emitting Diode Producing Visible Light. A method of fabricating a light emitting diode (LED) device producing visible light includes growing layers of an LED emitting blue light to form a blue LED; growing layers of an LED emitting green light to form a green LED; growing layers of an LED emitting red light to form a red LED; and uniting the three LEDs directly to each other by annealing. Therefore, an LED device that can emit light of all three colors from the same region of the LED device with variable light intensity is obtained.

EP0838861 / 1998 04 29 / Oki Electric Ogihara, M. et al

Light-Emitting-Diode Array And Light-Emitting-Diode Element. A light-emitting-diode array comprises a non-doped compound semiconductor layer between a substrate and a first compound semiconductor layer, a plurality of isolation regions extending from the first compound semiconductor layer to the surface of the non-doped compound semiconductor layer, and providing separation into isolated block regions each containing an equal number of diffusion regions, and a plurality of shared electrode lines connected to the diffusion regions in a plurality of the block regions, in such a relationship that the diffusion regions selected one each from the respective block regions are connected to a common shared electrode line, wherein at least a surface portion of the substrate is formed of silicon. The density of the diffusion regions can be increased without increasing the number of the electrode pads. Moreover, the substrate is free from breakage or cracks.

EP0836235 / 19980415 / Oki Electric Ogihara, Mitsuhiro et al

Light-Emitting Diode. A compound semiconductor layer of a first conductivity type is formed on a substrate, and a diffusion region of a second conductivity type is formed on the compound semiconductor layer. The light-emitting diode has a high emitted light power, using a large-diameter wafer.

05745630 / 1998 04 28 / Sandia Vawter, G. & Smith, R.

Cutoff-Mesa Isolated Rib Optical Waveguide For III-V Heterostructure Photonic Integrated Circuits. A cutoff mesa rib waveguide provides single-mode performance regardless of any deep etches that might be used for electrical isolation between integrated electrooptic devices.

05739553 / 1998 04 14 / Shin-Etsu Noto, N; Adomi, K; Takenaka, T

AlGaInP Light-Emitting Device. The present invention provides an AlGaInP light-emitting device with a longer life and higher reliability.

05744829 / 1998 04 28 / Showa Denko Murasato, S. & Sakaguchi, Y.

AlGaInP Light Emitting Diode. An AlGaInP light-emitting diode includes a double hetero-junction light-emitting structure of AlGaInP on a GaAs substrate. A multi-film reflection layer is provided between the GaAs substrate and the double hetero-junction light-emitting structure. The layers forming the double hetero-junction are lattice matched with the GaAs substrate at an epitaxial growth temperature. A GaP current diffusion layer is disposed on the upper surface of the double hetero-junction light-emitting structure, and ohmic electrodes are provided on the underside of the GaAs substrate and on the upper surface of the current diffusion layer.

WO9813864 / 19980402 / Siemens AG Lell, Alfred

Optoelectronic Semiconductor Device And Method For Producing The Same. The invention concerns an optoelectronic semiconductor device in which at least one functional semiconductor structure is disposed on a III-V semiconductor substrate. According to the invention there is a provided an electrically conductive III-V semiconductor substrate which, at room temperature, has a charge-carrier concentration of more than $1 \times 10^{15} \text{ cm}^{-3}$. At least one electrically insulating oxide layer is provided between the functional semiconductor structure and the III-V semiconductor substrate.

EP0841707 / 1998 05 13 / Sony Ishibashi, Akira et al

Semiconductor Light Emitting Device. A semiconductor light emitting device... [includes] a p-type contact layer being made of II-VI compound semiconductors containing at least one of group II elements selected from the group consisting of Zn, Cd, Mg, Hg and Be and at least one of group VI elements selected from the group consisting of S, Se, Te and O, characterized in that at least the active layer has undulations and at least the p-type layer is flat. A method for manufacturing a semiconductor light emitting device... characterized in that the n-type cladding layer, the active layer and said p-type cladding layer are grown by varying, for the respective layers, the ratio of the molecular beam intensity of the group VI element relative to the molecular beam intensity of the group II element.

05753940 / 1998 05 19 / Toshiba Komotos S.

Light-Emitting Diode Having Narrow Luminescence Spectrum. The preset invention relates to a semiconductor LED having excellent monochromaticity, the LED is made of a lamination of compound semiconductor layers including a light emitting layer formed on a compound semiconductor substrate.

Calendar

cont. from page 48

Photonics West

The 1999 Photonics West Conference and Exhibition will be held January 23-29, 1999 in San Jose, CA. The technical meeting will international symposia on High-Power Lasers and Applications, Integrated Optoelectronic Devices and Applications, and Electronic Imaging: Science and Technology
Abstract Submission Deadline: June 29, 1998

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1999 Int'l Solid-State Circuits Conference

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Abstract Submission Deadline: September 11, 1998
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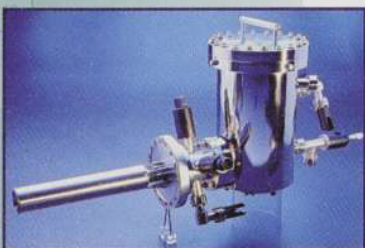
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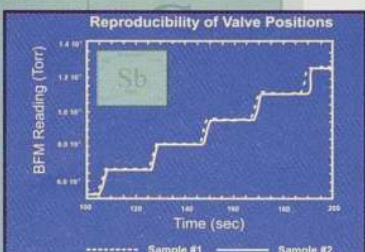
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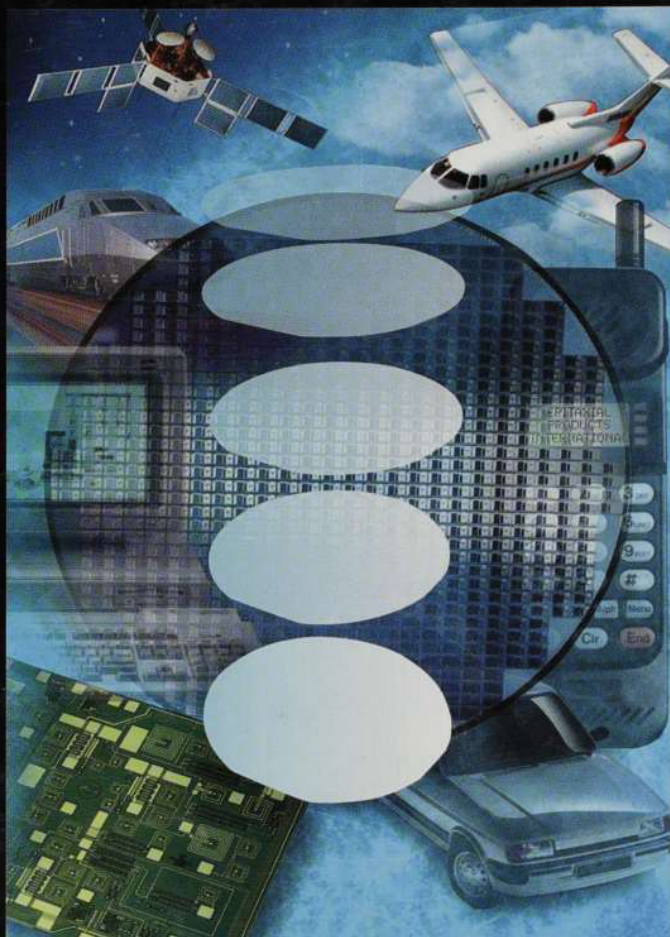
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