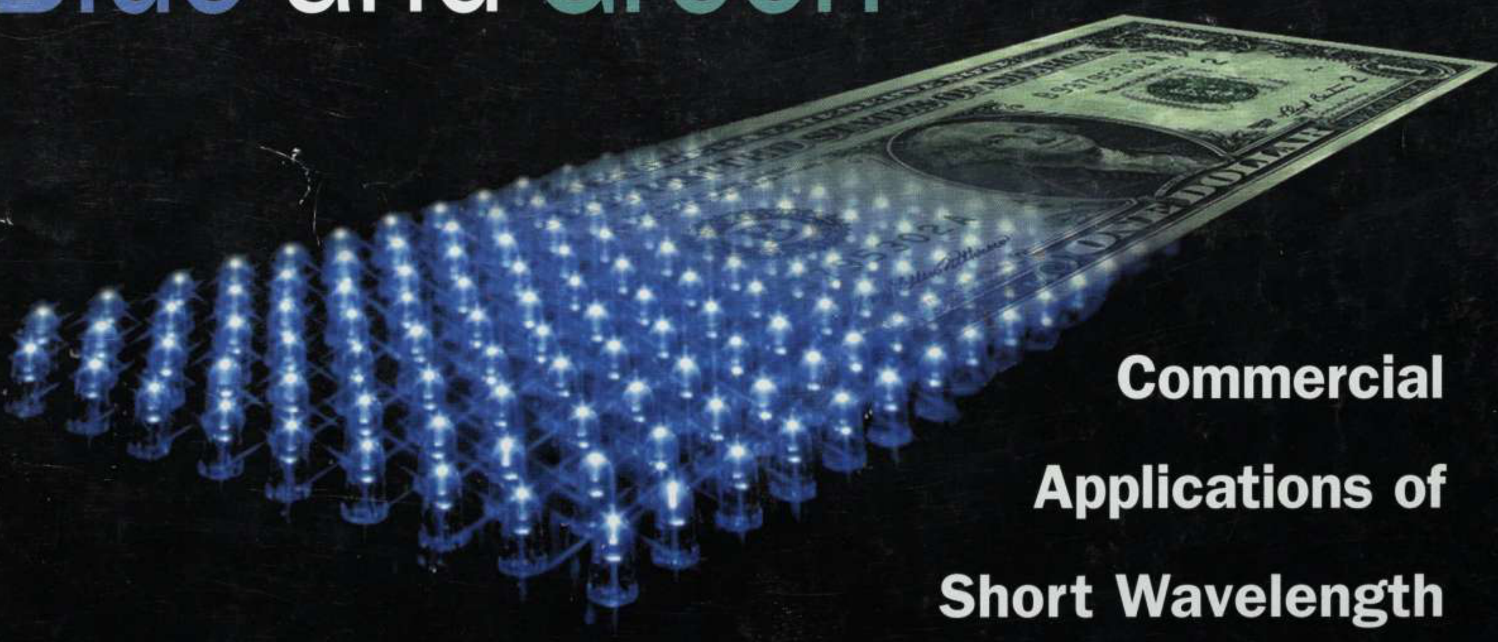
COMPOUND SEMICONDUCTOR

July/August 1995 Volume 1 Number 1

PREMIER ISSUE

Blue and Green



Commercial Applications of Short Wavelength Light Emitting Devices

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ST. ANDREWS ROAD
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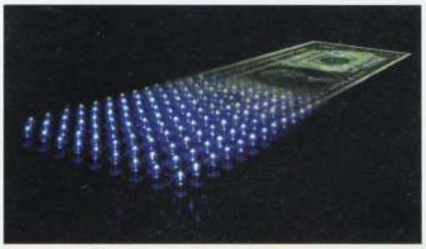
COMPOUND SEMICONDUCTOR

COVER STORY



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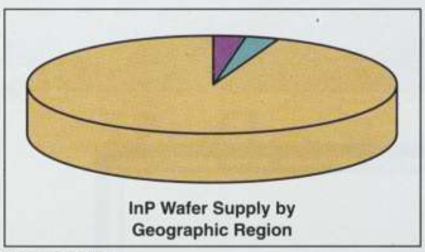

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COMPOUND SEMICONDUCTOR

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Dear Reader:

Welcome to the premier issue of Compound Semiconductor! In future issues this space we will use to print letters to - not from - the editor. If you read something in our magazine that you want to praise, criticize, or comment on, please take a few minutes to send us your thoughts.

Filling the first "Letters to the Editor Page" is just one of the tasks that has to be addressed when putting together a new publication. In fact, it is probably the easiest. More critical, of course, are the decisions about content. We have defined our mission as "providing a focal point for the compound semiconductor industry". This immediately raises the question "is there such an industry?" Or are there just some segments of the semiconductor industry that use "other-than-silicon" wafers, but yet do not share a larger communality of interest with each other? I have met one or two people who think this way - laser experts who say they don't care about microwaves, or vice versa. However, this probably is, or at least should be, a minority opinion. There are many opportunities for exchange between the two sides: for example, epitaxy is essentially the same whether it is done for an HBT or an LED. Even areas which have dissimilar processes - say, implanted MESFETs compared to VCSELs - share certain basic fundamentals. On the systems level there are many applications for opto and electronic devices working hand-in-hand, and, of course, OEICs will bring us into the realm of true integration of these two halves of the industry.

Obviously, we do believe that there is an entity that deserves to be called "the compound semiconductor industry". Our job, then, is to provide thorough coverage of both optoelectronics and electronics - and we will also strive to strike the right balance between research- and production-oriented topics, and to provide appropriate levels of coverage of the various materials systems. Of course, it isn't possible to address every topic in each issue, so we encourage you to subscribe and watch the progress throughout the year.

Some of you are probably wondering : "who are these guys?" *Compound Semiconductor* is largely the work of two people. The first is Robert A. Metzger - Bob to his friends - who has spent many years working in III-V epi at the Hughes Research Labs. Bob received his Ph. D. in EE from UCLA, but his first love is writing, and he tells me that he is quite happy to have turned in his MBE system for a word processor. The second person is myself. My introduction to the compound semiconductor industry was six years "in the trenches", manufacturing and selling MBE equipment, giving me a very good view of the industry, albeit from the ground up. It also makes me very sympathetic toward our advertisers, who are, of course, critical to the success of a free-circulation publication. (If you like our magazine, thank the advertisers!) We also benefit from the contributions of Bob Johnstone, our Tokyo correspondent. Bob is a free-lance writer specializing in the semiconductor industry.

We hope that you enjoy our premier issue, and I hope to hear from you soon!

Marie Meyer
Editor
Compound Semiconductor Magazine

PS: Are you an e-mail enthusiast? If so, here is a BTW: we've set up a special address for letters to the editor: "letters@compsem.com". If you don't want to run the risk of appearing in print, send your message to me personally: "mmeyer@compsem.com".

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Preview of our next issue

See our September/October issue for the following articles:

* The Future of GaAs for Wireless - How Much Competition from Silicon?
* A Look at Current Work in Gallium Arsenide for Microprocessors
* A Retrospective on the US MIMIC Program
* Antimonides for Long-Wavelength IR Lasers

In addition, we'll be introducing our new "Device Feature", and we'll also provide a tutorial on cell phones and standards. Looking further ahead, in our November/December issue we'll present a report on SiGe technology.

You won't want to miss a single issue of *Compound Semiconductor.* If you are not already a subscriber, please take a moment to fill out the form provided on page 17. If your copy has a "sample" sticker on the front cover, *this is the last issue you will receive unless your subscribe*. Don't miss out! Subscriptions are free to qualified engineers, managers, and scientists, so please act today to ensure that your receive our next issue.

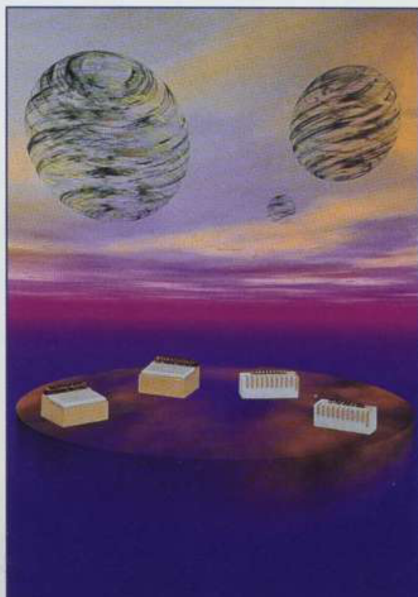
Toshiba Introduces New GaAs FETs

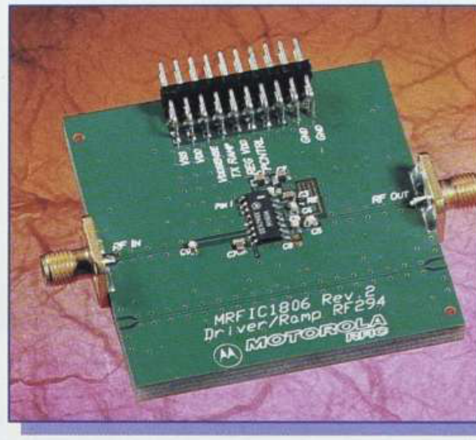
Toshiba America Electronic Components, Inc. has announced the availability of several new GaAs FETs for C-band and Ku-band applications. According to Keith Martin, microwave semiconductor product marketing manager for Toshiba's semiconductor group, these offerings "indicate Toshiba's strong commitment to forge a leadership position in high-power matched GaAs FETs". The new products include a family of C-band GaAs FETs which are targeted for applications such as very small aperature terminals, mobile telecommunications ground stations, satellite uplinks and earth stations, radar and digital radio links. According to Toshiba, these products constitute the broadest C-band line-up in the industry, and they offer lower power consumption resulting in cooler operation and better system reliability. Later this year Toshiba will release a 35 watt C-band GaAs FET which is believed to be the first commercially available product of its type. Also announced was the extension of Toshiba's internally matched Ku-band GaAs FET family, including a 15 watt device also believed to the first of its kind.

New Opto Products from Mitsubishi

The Electronic Device Group of Mitsubishi Electronics America, Inc. has introduced a new package that incorporates a 1300nm InGaAsP laser diode and an InGaAs photodiode in the same module. This bidirectional module replaces fiber optic designs that use separate laser diode and photodiode modules, and can transmit and receive over the same fiber. According to Mike Trapp, Mitsubishi EDG optoelectronics marketing manager, this results in reduced size, more reliable design and lower cost, making the bidirectional module ideal for fiber in the loop (FitL) and lower-speed SONET applications. "As the market for optical components moves closer to the end user, lower cost per subscriber is a major consideration in FitL applications. This bidirectional module helps drive these costs down." US pricing for this units is $375 in quantities of 100.

Also available from Mitsubishi EDG are new discrete laser diode and photodiode arrays. These new products combine 10 laser diodes or 10 photodiodes on the same substrate. According to the company this is a new technology breakthrough which provides higher data rates and high packaging density per discrete, which decreases the board real estate required for optical transmitters and receivers in multi-fiber designs. The laser arrays incorporate multiple quantum well (MQW) active layers, using a facet selective growth buried heterostructure (FSBH), grown by MOCVD. The laser diode array incorporates 10 laser diode chips on 250 μm spacing and operates at a 1300nm wavelength. Each diode has 5mW optical output power and low threshold current. The photodiode array consists of 10 InGaAs photodiodes on 250 μm spacing. Each has a 40 μm active diameter. US pricing for the laser diode arrays is $600 in quantities of 100; the photodiode arrays are $400 in quantities of 100.

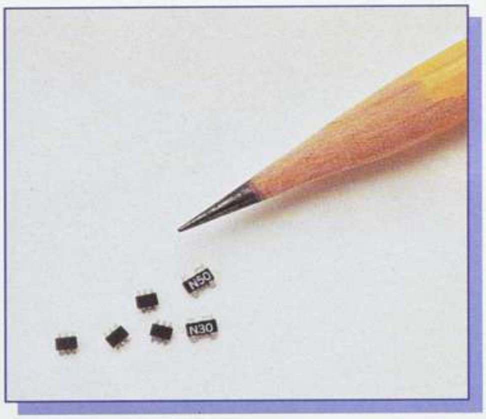




Motorola Offers Complete Transmit/Receive GaAs Chip Set for 1.9 GHz

Motorola Semiconductor Products Sector has announced the expansion of its existing three chip set of GaAs ICs designed for wireless personal communications systems (PCS). The new MRFIC1806 device is a driver/ramp circuit and includes a two-stage driver amplifier and transmit waveform shaping circuitry. The new MRFIC1807 device is a single-stage power amplifier and transmit/receive switch. They are usable in the 1500 to 2200 Mhz range. They complete Motorola's 1.9 GHz PCS chip set, consisting of an antenna switch; an upmixer, exciter and LO amplifier, and a low noice amplifier and downmixer. Together, this family offers the complete transmit and receive functions, less LO and filters, needed for a typical 1.9 GHz cordless telephone. Applications include 1.8 GHz Digital European Cordless Telephone (DECT), Japan Personal Handy System (JPHS) and other wireless Personal Communication Systems.

In addition to the all-GaAs 1.8 PCS chip set, Motorola offers a mixed GaAs/Si chip set for the 900 MHz band (primarily for cellular and ISM applications), and another all-GaAs chip set for the 2.4 GHz band (primarily for wireless LAN applications). According to Mark Williams, a Senior RF Applications Engineer at Motorola SPS, the decision to go with GaAs instead of Si for the 1.9 GHz set was based on both price and performance. Motorola considers its GaAs MAFET process to be cost competitive with the high speed bipolar or BiCMOS processes that would be required to make Si perform at these frequencies. And, according to Williams, any negatives that might attach to GaAs are outweighed by its superior efficiency and gain.

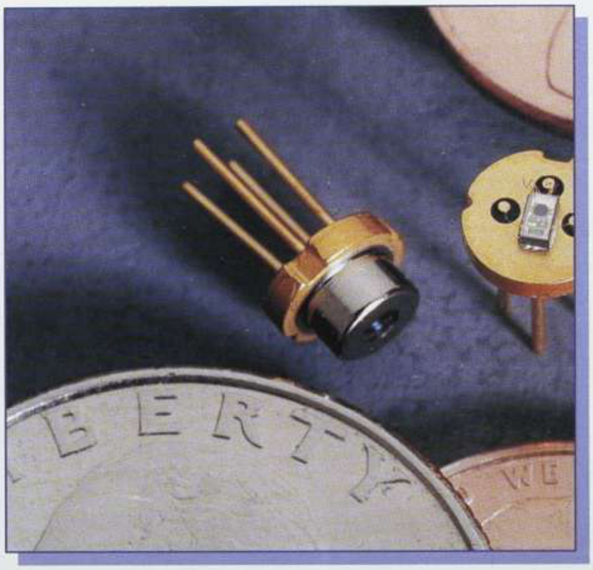


HP Introduces Small Package GaAs RFIC Amplifiers

Hewlett-Packard has introduced a series of six new 3- and 5-volt radio-frequency integrated circuit (RFIC) amplifiers in miniature surface-mount packages. Two of the new devices are GaAs, the others are silicon. Both of the GaAs models use the "ultraminiature" SOT-363 package, which is only 4.2 sq. mm, which makes them suitable for compact designs. The first GaAs product is a 5-V, 14-mA low-noise amplifier that operates from 500 MHz to 6 GHz, and which is targeted for wireless applications and Satcom receiver front ends. The second GaAs product is a 3-V, 4.5-mA low-noise amplifier that operates from 500 MHz to 4 GHz. Operating on 2.7 to 5.5 V, this amplifier is suitable for portable, battery-powered applications.

Vitesse Announces Availability of OEICs & New GaAs Gate Arrays

Vitesse Semiconductor Corporation has announced the availability of two new GaAs products. The first is the VSC7800 series of optoelectronic integrated circuits (OEICs), which consist of a high-gain, low-noise transimpedance amplifier with an integrated metal-semiconductor-metal optical detector that operates at 770-860nm. The company describes them as "the first commercially available high-performance OEICs", because of their bandwidth and sensitivity. Three amplifiers are available in the VSC7800 family; each is designed for a specific Fibre Channel data rate. The original design for these OEICs was formulated at IBM's T.J. Watson Research labs, and the current designs were completed at IBM's AS/400 division. Vitesse manufactures these circuits for sale to the commercial and military marketplace under license from IBM. According to Ray Milano, Director of Foundry Operations at Vitesse, "Combining high-performance optical and electronic functions can be achieved today only in GaAs. These OEICs allow performance levels and system simplicity unachievable with other technologies."



Vitesse has also announced three new members of the FX series of high-performance gate arrays, which have been introduced in direct response to the demand from the telecommunications industry, according to Bob Nunn, Vice-President and General Manager of the Vitesse ASIC Products Division. "GaAs has always been a natural choice for the high-bandwidth applications that require performance beyond the reach of CMOS." Because these new products are available in low-cost, thermally-enhanced plastic packages, and because the arrays are offered in both commercial and extended temperature range (0-110° C) configurations, Mr. Nunn claims that "Vitesse gate arrays are poised to provide the high-performance margins required in the telecommunications industry at prices equal to, or lower than, lower-performance BiCMOS ASICs". These new arrays, which are based on the Vitesse 0.6 µm H-GaAsTM manufacturing process, are priced below 0.3 cents per used gate in volume.

F.W. Bell Introduces GaAs Hall Generators

F.W. Bell, of Orlando, Florida, USA, has introduced the GH Series of Hall effect generators, which are four terminal GaAs devices that produce an output voltage that is proportional to the product of the input current and magnetic flux density. According to Bill Drafts, F.W. Bell Product Manager, the GaAs design provides high sensitivity, operation up to 175° C, and low temperature drift. Surface mount and through hole mounting configurations are available, and models are available in thicknesses as little as 0.028 inches (0.7mm), allowing placement in small air gaps. These devices are intended for a wide range of magnetic sensing applications, including speed, position, displacement and current.

III-V's Pioneer Wins Japan Prize

Nick Holonyak Jr. wins prestigious award for work in optoelectronics

BOB JOHNSTONE

Nick Holonyak, Jr., winner of the 1995 Japan Prize for his work in III-V optoelectronics.

To win the Nobel Prize, you have to make an important discovery. To win the Japan Prize, the Japanese equivalent of the Swedish award, your discovery must also be of practical use.

The criterion of usefulness certainly applies to the work of Nick Holonyak Jr, one of two winners of the 1995 Japan Prize. Many of the billions of light emitting diodes and millions of semiconductor lasers produced each year are direct descendants of the gallium arsenide phosphide alloy devices first made by Holonyak at General Electric's Syracuse, NY, laboratory more than 30 years ago.

Holonyak received the award, which is worth 50 million yen (approx. $575,000), at a ceremony attended by the Japanese Emperor and Empress in Tokyo at the end of April. Previous winners include communications satellite pioneer John Pierce, laser inventor Ted Maiman, and amorphous materials theorist David Turnbull.

Holonyak was not the first to come up with a semiconductor laser. That honor belongs to his friend and former colleague, Bob Hall, whose late 1962 announcement beat out Holonyak and two other groups of researchers working on the same task. But Holonyak was the first to build a visible spectrum laser, using GaAsP. In that same year [1962] he also produced the first practical light emitting diode. While the laser diode would take some 15 years to become a useful device, the LED was of almost immediate commercial significance. This was first recognized by Monsanto, which scaled up Holonyak's process to industrial level, and by Hewlett Packard, which needed miniature displays for its instruments and calculators.

Holonyak has been called a walking history of the semiconductor. He was the first PhD student (and subsequently, the junior colleague) of transistor co-inventor John Bardeen, a mentor whom he reveres to this day, describing him in his Japan Prize commemorative lecture as "the godfather of modern electronics." Later, as a professor of electrical engineering at the University of Illinois (where he has been since 1963), he produced no fewer than 50 PhDs. So many that, on occasion, entire sessions at the Materials Research Conference consist of presentations by his former students. Distinguished alumni of the Holonyak lab include George Craford, head of LED research and development at Hewlett Packard, (and author of this issue's Guest Editorial - see page 48) and MOCVD developer Russell Dupuis of the University of Texas.

Holonyak's first position was at Bell Laboratories where, from 1954 to 1955, he was a key member of the group that developed oxide masking of silicon, the basic process which underlies all integrated circuit production. Military service brought him to Japan, where he met his lifelong friend Makoto Kikuchi, the Japanese transistor pioneer who would later become director of Sony's Central Research Laboratory. Appropriately enough, when Holonyak returned to Japan in April - for the first time in 40 years - it was his old friend who introduced him to the Japan Prize audience. In his introduction, Kikuchi paid tribute to his old friend's uncanny grasp of the physical mechanisms by which semiconductors work. "He understands electronic and photonic processes as if they were practical actions in everyday life," Kikuchi said, "it's really unusual."

A famous instance of this intuition in action was the synthesis in 1977 by liquid phase epitaxy, by Holonyak and one of students, of the first p-n junction quantum well diode lasers. Such lasers, as well as most other types of light emitting devices, have been enthusiastically embraced by Japanese firms such as Sony, Sharp, Matsushita, Sanyo, Stanley, Rohm and Toshiba. Thus, it was appropriate that the Science & Technology Foundation of Japan should choose Holonyak as a recipient of the country's highest award for scientific achievement.

In his commemorative lecture, Holonyak pointed out that red, orange and yellow LEDs such as the AlInGaP devices made at Hewlett-Packard by his former student Fred Kish now out-perform incandescent lamps, and that, with the appearance of GaN bright blue devices, III-V alloys can now cover the entire visible spectrum. "These are remarkable developments," he told the Tokyo audience. "The lighting industry ... has been put under long range threat. It will take some time for the LED to be fully developed in all its possible display uses, and at equal performance across the entire visible spectrum. ... Nevertheless, it will happen, as, indeed, is beginning to occur already."

Also in this issue:

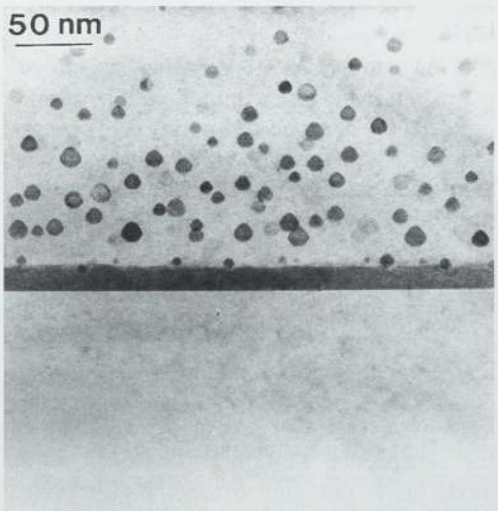
Wanted - A Few Good Defects

New Low Temperature GaAs Research Program at UCSB; \$3.75 Million from AFOSR to Study Non-Stochiometric Materials

Defects are usually things to be be avoided, and many semiconductor engineers spend their entire career battling against them. But in southern California you can find a group of scientists and engineers who are very happy about defects. The University of California at Santa Barbara, and the Hughes Research Laboratories (Malibu, CA), have just received a \$3.75 million, five year award from the Air Force Office of Scientific Research (AFOSR), to not only study a very unusual type of defect, but to also use this defect to enhance the performance of electronic and optoelectronic devices.

Non-Stochiometric Semiconductor Materials, a subset of which includes what is often referred to as Low Temperature (LT) GaAs, exhibit unique properties due to a slight excess of group V elements (As, P, or Sb). These non-stochiometric materials are typically grown by MBE in the temperature range of 200-250˚C (some 400-350˚C lower than normal growth temperatures), where during GaAs growth, a 1-2 atomic % excess of As is incorporated. During post growth annealing (600-700˚C) the excess As forms precipitates with diameters which range from 20-100 Å and at densities on the order of 10^{17} cm^{-3} (See Figure 1). LT GaAs is a markedly different material than conventional GaAs, exhibiting a 4 orders of magnitude increase in trap densities, 1 order of magnitude increase in breakdown fields, 5-6 orders of magnitude (10^{6} ohm-cm) increase in resistivity, and photocarrier lifetimes which have been reduced from 1 ns to as low as 150 fs. Two competing models, one based on the As-precipitates behaving as localized Schottky barriers, and the other utilizing a deep-level compensation mechanism, are both used to explain these changes in material characteristics. This new class of GaAs, because of its unique material properties, has already been used as a buffer layer to reduce sidegating and backgating in GaAs ICs, as a gate insulator in metal-insulator-semiconductor field-effect-transistors (MISFETs), in high speed (< 500 fs) and high voltage (> 1 kV) photoconductive switches, and in ultra-wide bandwidth photodetectors.

Dr. Jerry Witt of AFOSR has been instrumental in the development of non-stochiometric work since the late-80's - both in providing research funds, as well focusing and guiding the non-stochiometric community in both fundamental studies and device applications. Even though a great deal of progress has been made in non-stochiometric work, including many device applications, Witt says that "past experience has amply demonstrated that the failure to answer fundamental materials science questions will result in future stumbling blocks which will impede more widespread commercialization". To address this issue, AFOSR has established a new category of research program - Partnership for Research Excellence and Transition (PRET), the intent of which is to establish university-based research programs of excellence, involving strong industrial ties to accelerate the transition of research results to industry. The new PRET carries the title "Advanced Electronics and Optoelec-tronics Via Non-Stochiometric Semiconductor Materials", and the principal investigator at UCSB is Prof. Umesh Mishra. The industrial



James Ibbetson, UCSB

Cross-sectional TEM electron micrograph of LT GaAs (growth temperature 225°C) above a 20 nm AlAs layer. As precipitates were formed in the LT GaAs layer during a 700°C, 30 s anneal.

component of the PRET is taking place at the Hughes Research Laboratories, and led by Dr. David Grider. Additional active industrial collaborations will take place with Hewlett-Packard (Palo Alto, CA) and Motorola (Tempe, AZ) along with Air Force Laboratory participation occurring through Wright Laboratory (Wright-Patterson AFB, OH) and Rome Laboratory (Hanscom AFB, MA).

Witt says that he wants the PRET to address such issues as: "understanding the kind and concentration of the point and extended defects in both the as-grown and annealed material, as well as investigating the precise role of all growth parameters such as As species, substrate temperature, As/Ga ratio, and growth rate, in the formation of these defects." In addition, he considers other key issues that need to be addressed to include, "the development of a physically realistic model to explain the electronic transport and optoelectronic properties of these materials, as well as to show a convincing demonstration of the material stability and reliability of non-stochiometric semiconductors and their device structures."

UCSB has set up a six professor team, led by Mishra, to address the challenge. "The centerpiece of this program will be physics," says Mishra, "where we want to understand what is going on in non-stochiometric material, and then use that understanding to improve device performance." Dr. Art Gossard will be responsible for materials growth, who in conjunction with Dr. Herbert Kroemer, will work on understanding defect formation and its effect on transport. Dr. Jim Speck will apply TEM expertise to investigate As precipitates and associated defect growth and movement, while Dr. John Bowers will look at optical effects in these materials, and Dr. Evelyn Hu will investigate processing issues of non-stochiometric materials. Mishra will be looking at the use of non-stochiometric materials in electronics devices, and interacting closely with the Hughes Research Laboratories in transferring non-stochiometric techniques into their FET and HBT processes. In addition to these issues, Mishra says that he is very interested in using non-stochiometric materials as "buffers not only in III-V systems, but to also understand what roles LT GaAs may play in the implementation of GaAs growth on silicon."

At the Hughes Research Laboratories, Dave Grider says that he hopes to "further our understanding on non-stochiometric materials for device isolation in a stacked multidevice approach, where LT materials are used to electrically isolate active layers, as well as to use LT buffers to accommodate strain and defects during the growth of non-lattice matched devices." In addition, he says "we are very interested at looking at basic mechanisms of non-stochiometric behavior in As/P compounds."

Non-stochiometric materials have already proved to be much more than simply a defected version of their stochiometric counterparts. It is the intent of this AFOSR sponsored PRET to build upon this existing work and further the understanding of these unique materials, while applying this new knowledge to the improvement of currently existing devices, as well as developing new and unique non-stochiometric materials-based device applications.

Cree Research Awarded $5.8 Million for SiC

APRA will fund improvement in wafer size, defect densities

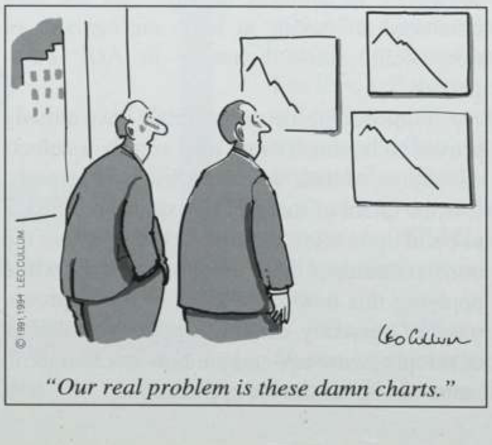
On May 31, Cree Research, Inc. [Durham, NC] announced a $5.8 million contract award from the Advanced Research Projects Agency (ARPA) aimed at enhancing Cree's SiC wafer technology. Cree will team with Motorola, General Electric, and Honeywell on three separate projects under the contract, which has the overall objective of advancing Cree's SiC wafer technology to enable applications that involve electronics in high power and high temperature operating environments. Potential uses for SiC include automotive and aircraft engine electronics, high frequency transistors for radar systems, cellular phone base stations and UHF television broadcast transmitters.

According to Calvin Carter, Director of Technology, Cree's tasks under the contract can be described as "developing all the capabilities needed to get SiC into the fab - including crystal growth, wafering and polishing, and epi". The program calls for dramatic improvements in SiC wafer sizes and quality over its three-year duration. For example, current wafer diameters are 50mm for 6H-SiC (the polytype most commonly used for optoelectronics) and 35mm for 4H-SiC (most commonly used for electronic applications), with micropipe defect densities around 55/cm^2. This new program calls for increasing the diameter of 4H-SiC to 3", and reducing the micropipes to <2/cm^2, or eliminating them entirely. The contract has an optional fourth year wherein diameters would be increased to 4". Carter points out that the wafering and polishing development will also be a challenging area, given that SiC is the 4th hardest known material.

Speaking for Cree's partners in the project, Ben Gingerich, Business Development Manager for Honeywell's High Temperature Electronics, commented "We see the high temperature electronics market growing significantly in the next 5 years and expect SiC to play a major role, particularly in high temperature power electronics." Dr. C.E. Weitzel of Motorola's Phoenix Corporate Research Laboratories said "the larger diameter, lower defect SiC wafers that will result from this program will significantly accelerate the commercialization of SiC power devices." Cree is already working with the third team member, Motorola, under a contract funded by the Office of Naval Research to develop high frequency devices, an effort which Cree believes will benefit from developments under this new contract.

Earlier Award for Blue Lasers

Earlier this spring Cree announced a joint agreement with Philips Laboratories [Briarcliff Manor, NY] to develop blue laser diodes based on nitrides grown on SiC. ARPA is also providing funding for this project, in the amount of $4 million. Diego Olego of Philips Laboratories believes that this joint effort "will push the state of the art of GaN material and device technology to implement GaN injection lasers. The robust properties of GaN thin films combined with Cree's realization of bright GaN blue light emitting diodes on SiC wafers and Philips Laboratories expertise in wide bandgap optoelectronic devices bode well for the successful demonstration of blue and ultraviolet GaN lasers."



"Our real problem is these damn charts."

Wall Street is Bullish on III-V's

SDL and ANADIGICS Raise $50 Million

Two American III-V device manufacturers made their initial public offering (IPO) of stock this spring and together they raised $50 million in funding to expand their activities. Both stocks have subsequently posted healthy gains.

SDL, Inc. (formerly Spectra Diode Labs) of San Jose, CA was first, raising over $35 million in its first public stock offering in March. SDL is a leading manufacturer of optoelectronic integrated circuits and high power semiconductor lasers, with over 200 standard and custom products, as well as systems. According to the prospectus, SDL has developed single mode lasers that emit 6 times higher optical power levels than any other commercial single mode laser. The OEIC product line includes a device containing 1,000 lasers, and two-dimensional arrays of multimode OEICs which deliver 5,000 watts of peak power and 1,400 watts of average power from a 4cm x 4cm array. SDL produces its laser structures using MOCVD, with more than 10,000 wafers grown and processed per year - the equivalent of 15 million single mode lasers.

SDL was formed in June, 1983 as a joint venture between Xerox and Spectra-Physics, and it has been consistently profitable since 1985. In July, 1992 the company repurchased a majority of its outstanding stock from its corporate owners. The proceeds from this stock sale will be used to retire notes issued at that time, to repay other debts, and for capital expenditures to expand manufacturing facilities, and for general corporate purposes, including working capital.

A significant portion of SDL's revenue is derived from large volume sales to OEMs. Examples of applications for SDL products include:

* Semiconductor lasers for optical amplifiers used in fiber telephone transmission systems, and in transmission systems used by cable television (CATV) providers.
* Custom OEICs used by Eastman Kodak for digital color proofing systems, which are used to generate high resolution color proofs for the printing industry.
* Transmitter and beacon OEICs and lasers used by the European Space Agency for its first optical communication satellites (planned launches beginning in 1996).
* Kilowatt-level high power semiconductor laser arrays used for drilling, cutting and welding applications.
* Infrared lasers used to record information onto Kodak's PhotoCDsR, which are used to store high resolution color photography, and red single mode lasers used to read and write data on Kodak's 14" dia. optical Mass Storage System.

On June 2 the stock [NASDAQ symbol "SDLI"] closed at \$25.50, with highs and lows for the quarter of \$29.25 and \$23.25

ANADIGICS

The second company, ANADIGICS, Inc., a leading manufacturer of GaAs ICs, sold just over 2 million shares at \$12 in its initial public offering in April. It plans to use \$12 million of the proceeds to expand its fab line from 3" to 4". Other expansion plans reported in the prospectus include instituting a 3rd shift at its Warren, NJ plant. The company has shipped >20,000,000 GaAs ICs in its 10 year history, and is currently shipping >1 million per month.

ANADIGICS' biggest successes to date have come from the cable television (CATV) and direct broadcast satellite (DBS) areas, respectively accounting for 23% and 53% of 1994 net product sates. They hope to add to that mix by teaming with Ericsson to produce wireless communications products. In fact, the company has a great deal staked on that relationship; the prospectus lists Ericsson as their probable largest customer in 1995.

ANADIGICS has for the past two years been named to INC. Magazine's annual list of America's 500 Fastest Growing Private Companies, posting a cumulative sales growth of 1667% from 1989 through 1993. In 1994 they reported \$1.86 million in net income on revenue of \$34.8 million.

On June 2, the stock [NASDAQ symbol "ANAD"] closed at \$18.25, with high and lows for the quarter of \$20.75 and \$13.25.

EMCORE Reports Systems Sales

EMCORE has announced the sale in May of two production-scale MOCVD reactors for the growth of GaN material for the fabrication of blue LEDs. These are the ninth and tenth such reactors sold by EMCORE for this application in the past twelve months. Most of these orders have been for the company's Discovery 180 model, which is capable of 6x2", 3x3" or 1x6" wafers per run.

EMCORE also announced the sale of a production scale Enterprise 200 MOCVD reactor to Hewlett-Packard FCO of Ipswich, England. The system will be used for the production of 1.3 μm lasers from III-V materials for the fiber optic telecommunications market. EMCORE reports that this is their twelfth MOCVD system in Europe.

QED Development Contract

NASA/Jet Propulsion Laboratories has awarded a SBIR Phase II contract to Quantum Epitaxial Designs (QED) of Bethlehem, PA, USA for the development and production of InGaAs/GaAs quantum well infrared photodetectors (QWIPs). QED will develop MBE growth and characterization technology for QWIP materials and will fabricate 2 space qualified 128 x 128 focal plane array modules for an infrared camera.

NASA is interested in QWIPs for 12 to 16 μm detection, for applications such as the Earth Observation Satellite (EOS), which contains the Atmospheric Infrared Sounder (AIRS). NASA and QED believe that by taking advantage of the growth uniformity provided by MBE and the mature processing methods for III-V materials it will be possible to produce focal plane array devices which are comparable to the performance of HgCdTe arrays, but at a fraction of the cost.

QED was also recently awarded a SBIR Phase II contract for the optimization of InGaAs/InAlAs/InP OEIC structures.

AIXTRON MOVPE Systems for Thomson CSF & Blue LEDs

AIXTRON GmbH has announced that Thomson CSF Central Research Laboratory [Orsay, France] has purchased an AIXTRON AIX 200 series MOCVD system, which will be used for the production of III-V 1.3 and 1.55 μm laser diodes and detectors.

In a separate announcement AIXTRON reports the recent receipt of three orders for its AIX 2000 HT System, each of which will be used to fabricate nitride materials for blue LEDs. This system is capable of growth on 7x2" substrates, which the company claims is the largest reactor made for this application. The reactor is equipped for operation above 1200° C, with optional extension to up to 1600° C for the growth of SiC.

Stop!

Red signal lights look like a promising application for III-V LEDs; One California town has already done a complete conversion

The signal light changes from green to red, you press the brake pedal, come to a stop and then wait, occasionally glancing up at the bright red light, but barely seeing it, not thinking about it or the other 10-20 million red signal lights across the world. The light turns green and you are on your way, certainly never having thought about the nearly $1 billion in energy costs that all those red lights annually consume.

But some people have been thinking about it - and that may create a new market for III-V materials.

The incandescent light bulbs used in traffic signal lights are typically 150 W bulbs which cost on the order of $1-4. With the availability of superbright red LEDs, replacement of some of these 150 W incandescent bulbs with LED arrays is starting to take place. In North America, four different manufacturers are currently producing red LED traffic lights - Ecolux, Inc (Montreal, Quebec, Canada), Econolite, (Anaheim, CA), Electro Tech (Anaheim, CA) and Ledtronics, (Torrance, CA). These LED red signal lights generally consist of some 500-750 discrete AlGaAs-based LEDs (mostly manufactured by Hewlett-Packard or Toshiba) laid out in an array of LED strings, where each string consists of 70-75 LEDs connected in series.

A typical red LED signal light costs $200 - one hundred times more than an incandescent bulb. Yet they are still an attractive option, because of that $1 billion in annual energy costs. Each LED-based stop light consumes only 20 W as compared to the incandescent's 150 W. With US electricity costs averaging 10 cents/kW-hr, this translates into an energy savings of $60/year for each signal. LEDs also offer longer lifetimes, (> 10 years), and when these reduced maintenance costs are included (estimated to be $250 per intersection per year), these red LED traffic lights can be shown to pay for themselves in about three years.

The city of Corona, CA (population 100,000) has converted all of their 750 red traffic lights to LED based lights manufactured by Electrotech. According to city traffic Engineer Steve Libring, "the replacement of red signal lights has reduced traffic intersection electricity costs from $120,000 to $70,000 per year". In the five county area surrounding and including Fresno, a total of 2300 red LED traffic lights have been installed, resulting in an annual savings in energy costs of $142,000 according to the Energy Users News (Vol 20(3), March 1995). Large cities are also beginning to join the trend, with Philadelphia, PA having already converted approximately 10% of their intersections.

Raj Ghaman of the Traffic Management Systems section of the US Department of Transportation estimates that there are some 4,000,000 red traffic signal lights in the US and some 12,000,000 world wide. If all the red incandescent traffic lights in the US were switched to red LEDs, this would represent a market of some 800 million dollars (or 80 million dollars per year averaged out over the LED's ten year lifetime), with annual energy savings of $240 million. The future will also likely see green traffic lights being replaced by LEDs (see page 26). Incandescent lights, however, will likely keep the yellow signal light market - they are on for such short periods of time that the energy savings do not equal the cost of the LED array.

Think about AlGaAs on your drive home tonight.

Cray Computer Crashes

Cray uses GaAs to build world's fastest computer, but then runs out of cash.

Cray Computer Corporation [Colorado Springs, CO] wanted to manufacture the world's fastest supercomputers using GaAs technology. Unfortunately for all concerned, the company was forced to file for bankruptcy protection on March 24.

Cray was nearing completion of its new "Cray-4" supercomputer, a system which was designed to utilize 4 to 32 GaAs-intensive processors, containing over 100 *different* GaAs circuits. This system's clock speed was 1 GHz - over 3 times faster than the nearest Si-based processor.

What went wrong? According to Bryant Welch, former Cray Vice President in charge of Circuit Production, "the Cray-3 computer [predecessor of the Cray-4], of which several were successfully built and run, were very late to the marketplace and none were actually sold, although NCAR [National Center for Atmospheric Research, Boulder, CO] had been successfully running a Cray-3 as a beta-site over the past 18 months. The Cray-4 project was nearing completion at the time of the bankruptcy and it was generating a lot of interest. However, due to the financial condition of the company (Cray needed in excess of $20 million to complete the project), the uncertainty of the commercial supercomputer market, and the unaggressiveness of the DOD to find and seek these types of advanced computer developments as they had done in the past, Cray was unable to secure the neccessary funds to continue operation."

A major asset Cray leaves is a 4" GaAs fab line. Purchased from GigaBit Logic in 1989 for $27 million in Cray stock, its value lies not so much in the equipment it contains but in the processes and circuits it is capable of implementing. At the time of the bankruptcy, both a depletion-mode (D-mode) and an enchantment/depletion-mode (E/D mode) MESFET process were being run, with the fab line starting 100 wafers/week and yielding 85%. The main emphasis of the line was not on the number of wafer starts, but on reducing fabrication cycle times. Cray's 10 mask level D-mode process was taking an average of only 12 days to run, using 2 shifts plus a partial 3rd shift. The quickest cycle time was a mere 4 days. A more complex 16 mask level E/D-mode processwas also being run, which utilized 3 levels of metal, and a 0.5 micron self-aligned gate FET process configured in DCFL [direct coupled field effect transistor logic] was also being run, producing devices with f_t of 40 GHz, and circuits as large as 5,000 gates. This E/D process took an average of 18 days to complete, with the quickest cycle time being 6 days.

Fast throughput was required in order to supply the large variety of GaAs ICs required for the production of the Cray-3 and Cray-4 computers, in which *all* logic was built in GaAs, with Si SRAMS memory. The Cray-3, with a clock rate of 480 MHz, used approximately 500 different GaAs ICs. The GaAs IC count in the Cray-4 was reduced to approximately 120 GaAs IC's due to a larger degree of circuit integration, resulting in greater functionality per circuit. Despite the large number of GaAs-based circuits and the inherent complexity they represent, Bryant Welch says the bankruptcy "had little to do with the GaAs IC line. From all indications, the GaAs ICs were functioning very will in the Cray-4".

Regarding the future of the fab line, Welch says "in all probability the GaAs fab line will continue to exist either within a restructured Cray Computer Company, or potentially as a part of another company who can utilize this asset. We do not believe that the GaAs IC fab line will be auctioned off piece-by-piece, because of the interest in preserving the fab and technology either for continuing the computer project or other GaAs applications".

The Cray-3 Supercomputer.

Two New Semiconductor Laser Companies at CLEO '95

High Power Devices and Semiconductor Laser International offer high power III-V laser diode products

Exhibitors at this year's CLEO Conference, held May 21-26 in Baltimore, MD, USA included two new companies offering semiconductor laser diodes. High Power Devices, Inc. (New Brunswick, NJ) offers high-power CW laser diodes emitting up to 4 watts at 808nm and pulsed laser diodes emitting up to 25 watts at 905nm. Both products are available in optional wavelengths from 785 through 940nm. According to Thomas Moritz, one of three company founders, these structures are grown by MOCVD using a single quantum well structure which yields high conversion efficiency and excellent temperature dependence.

HPD reports that their personnel have over 30 years of laser diode manufacturing experience. They plan to complement their internal processes with a small group of experienced service contractors in order to create an efficient and cost effective manufacturing process, and to speed the development of new products. Commercial prototyping services are also available.

Also attending was Semiconductor Laser International (Vestal, NY). SLI offers GaAs, AlGaAs and InGaAs epi, bars, chips, linear and multi-bar arrays for high power semiconductor lasers from 760nm to 1100nm. According to Geoffrey Burnham, President & CEO of SLI, the company has a cooperative research and development agreement (CRADA) with Wright Patterson Air Force Base to develop high power semiconductor lasers and transfer the technology. SLI also recently entered into a two year CRADA with the USAF Rome Laboratory, with the objective of developing high power, 980nm semiconductor laser diodes for use in pumping fiber lasers.

AIXTRON Opens Service Center in China

AIXTRON GmbH has announced the opening of a service center in China at the Chinese Academy of Sciences. The company reports that the center will by run by Chinese experts in MOCVD, and that it will be used to support three AIXTRON MOCVD systems which were recently installed at Wuhan Telecommunication Devices Co., and at the Chinese Academy of Sciences.

High Temperature HBT Reported

Astralux, Boulder, CO, USA, has announced the first heterojunction bipolar transistor (HBT) to operate above 500° C with a current gain in excess of 100. The device, which was fabricated from GaN and SiC, exhibited room temperature current gain of 10 million. The device was operated at a current density of 1000 Amp/cm^2 and a power density of 20 KW/cm^2. According to Dr. Jacques Pankove, Astralux's Vice President for Research and Technology, high temperature transistors are needed to monitor and control the performance of systems which operate at high temperatures, such as automotive, avion-

AMP and M/A-COM Agree to Merge; Shareholder Approval Expected in Early July

On June 30 M/A-COM shareholders are expected to approve the merger of their company with AMP Incorporated, the world's largest supplier of interconnection products and services. The proposed merger will be conducted as an exchange of stock, with the M/A-COM shareholders receiving 0.280 AMP common shares for each M/A-COM share, giving the M/A-COM shareholders a small premium on their stock's current value. AMP will also assume $75 million in M/A-COM debt, making the total value of the transaction >$300 million.

According to AMP CEO William J. Hudson, "M/A-COM's Microelectronic Division presents an exciting opportunity for AMP to immediately obtain a broad range of proven wireless products, as well as world-class manufacturing and engineering capabilities". M/A-COM's CEO Thomas A. Vanderslice was also enthusiastic: "This linkage with AMP's global infrastructure will dramatically accelerate M/A-COM's ability to service the component needs of leading wireless OEMs worldwide, all of whom are already AMP customers. AMP's strong technical and financial resource base will also enable us to maintain a leading-edge presence in the design and development of advanced wireless components for emerging applications far into the next century."

M/A-COM will be set up as a wholly-owned AMP subsidiary in a new AMP business group dedicated to the wireless industry.

Westinghouse Expands GaAs Facility

Westinghouse Electric Corp. recently expanded their GaAs facility at the Gene Strull Technology Center in Baltimore, MD, doubling fabrication space was doubled to 10,000 square feet. As a class 100 clean room, the facility will produce chip sets for phased-array radar applications, with special emphasis on power devices. In addition to existing defense programs, the facility will support new programs such as Microwave Analog Front-end Technology (MAFET) and commercial foundry services. Technologies available in the new facility will include MESFETs, HBTs, and PHEMTs.

ic, and diesel engines. Other potential applications include controlling the power delivered to motors in electric cars and replacing hydraulic systems by electric motors. High temperature transistors are also attractive for space applications, because they will eliminate the need for weighty electronic cooling systems that add to payload costs. Astralux is working on this high temperature transistor project under a Small Business Innovative Research (SBIR) contract from the US Ballistic Missile Defense Organization/Defense Nuclear Agency.

EMCORE Reports Blue LED Fabricated from Production Scale Reactor

EMCORE Corporation has announced that blue LEDs have been successfully fabricated from GaN grown at EMCORE's Research Laboratories using a "Discovery" Series MOCVD system which is capable of processing 6x2" or 3x3" wafers per run. The announcement is significant, according to EMCORE President Norman Schumaker, because "this is the first reported [blue LED] device produced in a manufacturing scale, multi-wafer MOCVD tool by any technique".

According to a company spokesperson, sapphire substrates were used, and both p-type and n-type layers were grown. The former showed carrier concentrations up to $5x10^{18} cm^{-3}$ with hole mobilities of 20 cm^2/V-sec, and both of these figures are higher than previous reports from other groups working with the MOCVD technique. The room temperature light emission is described as "close to 400nm". EMCORE reports that the work was funded internally through an R&D program to develop production processes for its MOCVD tools. In October, 1993 the company received a $1,000,000 SBIR Phase II contract to investigate Group III nitrides.

According to Bill Kroll, V.P. of Business Development, EMCORE is pursuing this work to aid the sales and support of MOCVD reactors, and the company does not plan to move into the GaN materials or device manufacturing businesses in the foreseeable future.

Plasma Immersion Ion Implantation System in Development

Lawrence Berkeley Laboratory and Spectrum Sciences, Inc. (SSI) have embarked on a joint Cooperative Research and Development agreement (CRADA) to develop a novel plasma immersion ion implantation system. According to SSI spokesperson Don Weeks, this new instrument promises to be well suited to the hydrogen and oxygen implant processes required for GaAs. The system concept involves the generation of a plasma of an implant species in close proximity to the substrate, which is pulse biased to accelerate ions out of the plasma. According to SSI such as system should be able to provide uniform doses with higher throughput than conventional ion beam implanters, especially where high doses are required.

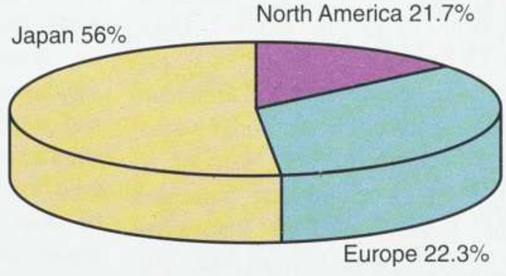
InP Market Study

USAF releases report on worldwide production & consumption of InP wafers in 1993-1994

A detailed picture of the status of the InP wafer market in 1993-1994 is provided by a report recently released by the US Air Force Wright Laboratories [WPAFB,OH]. Based on a survey conducted by Strategies Unlimited [Mountain View, CA] in late 1994, the report presents complete 1993 and estimated 1994 information on the production and consumption of InP wafers in North America, Japan and Europe.

The InP market is still small, but it is growing. As shown in Table 1, the total consumption in 1994 was 67,200 wafers, up a healthy 15% from the previous year. At the time of the survey most respondents were using 2" wafers; recent talks with suppliers indicate that the situation has not changed significantly. For 1994 the total InP market was valued at around $20 million; in comparison, the 1994 GaAs wafer market was $130 million, and the GaP wafer market was $124 million [see box, next page]. The report reveals that the market is also rather spread out, with more than 113 different organizations world-wide using InP in 1994.

Japan is the leading consumer of InP, accounting for over half of the worldwide totals in 1993 and 1994, as shown in Figure 1. Europe was a surprising second, but these figures are somewhat misleading. The consumption of InP wafers in Europe is dominated by a small number of companies, and the largest InP consumer in Europe - possibly the largest in the world outside of Japan - is Epitaxial Products International [E.P.I., Cardiff, Wales], which re-exports most of the InP wafers it "consumes" in the form of epi layers bound for North America or Japan. According to E.P.I.'s Drew Nelson, "relative device production using InP wafers is consequently likely to be less for Europe compared with the US and Japan than the raw data would at first indicate". The report also states that for 1993 just over 60% of the InP substrates consumed were used for production, with the remainder for R&D.



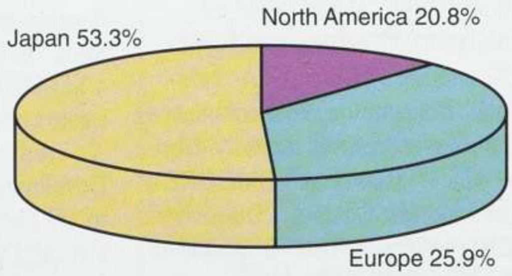


Figure 1. Worldwide InP Wafer Consumption

SI Surprises

The report also provides a breakdown of InP consumption by dopant type. In 1993, the only year when figures are available, 21.5% of the wafers consumed were iron doped to produce semi-insulating substrates. See Table 2. Survey respondents report that optoelectronics devices accounted for 80.1% of consumption, followed by 19.5% for electronics, and a small amount (0.4%) for photovoltaic applications. The electronics figure tracks well with the percentage of semi-insulating material produced. For anyone accustomed to thinking of InP as an exclusively optoelectronic material, these figures suggest a surprisingly large usage of InP for electronics applications.

The US Air Force, however, is not surprised. They are showing a keen interest in InP for high speed, high power electronics. Wright Lab's Laura Rea explains that she commissioned this study because of InP's growing status as a "strategic material", which subsequently raises concerns about domestic availability. Survey results interest in expanding the US supplier base; as shown in Figure 2, Japanese materials suppliers account for over 85% of the world's production.

TABLE 1
1993 AND 1994 WORLDWIDE InP WAFER CONSUMPTION BY GEOGRAPHIC REGION

Region	1993			1994 (Est)			1993-1994 Percent Growth
	Number of Wafers	Wafer Area		Number of wafers	Wafer Area*		
		Sq. In.	Percent		Sq. In.	Percent	
North America	13,300	39,800	21.7	14,600	43,700	20.8	9.9
Japan	31,700	102,600	56.0	34,600	112,100	53.3	9.3
Europe	13,500	40,800	22.3	18,000	54,500	25.9	33.5
Total	58,400	183,200	100	67,200	210,300	100	15.0

*Estimated assuming the 1993 consumption pattern by wafer size.

TABLE 2
1993 WORLDWIDE InP WAFER CONSUMPTION BY DOPANT

Dopant	Wafer Area	
	Sq.In	Percent
Iron (Fe)	39,400	21.5
Sulfur (S)	86,500	47.3
Tin (Sn)	40,000	21.8
Zinc (Zn)	15,400	8.4
Undoped	1,920	1.1
Total	183,200	100

As promising as InP appears for high frequency devices, it is not yet a technology for use in high-volume production – SI InP is being consumed in development programs and research projects. Another fact from the report may be disconcerting to those interested in developing InP-based electronics: the price of 3" wafers was found to be approximately 20-30% higher than 2" wafers on a price per square inch basis, with an overall average selling price of \$96/sq. in. Obviously, typical expectations are that the price per sq. in. goes down as diameter increases. InP substrate vendors attribute the current anomaly to low demand for 3", and the difficulties in growing and polishing InP (generally more challenging than GaAs). Not surprisingly, the quality of today's 3" InP wafers is also an issue for consumers. According to Dwight Streit of TRW's Electronic Systems and Technology Division [Redondo Beach, CA], "InP device design for HEMTs and HBTs has reached a fairly sophisticated level, so that now the major obstacles to further progress are substrate size, with 3" being a minimum acceptable diameter for production, and variations in 3" quality on a wafer-to-wafer and boule-to-boule basis".

Who will provide the motivation to improve supplies? Optoelectronics manufacturers can yield hundreds of lasers out of a single wafer, and are seemingly content to remain at 2" for the time being. The emergence of OEICs could, however, increase demand for larger wafers. More immediate demand is likely to come from the microwave device manufacturers, who already require more wafer area for each of their devices, and who are not likely to consider 2" processing as a viable option.

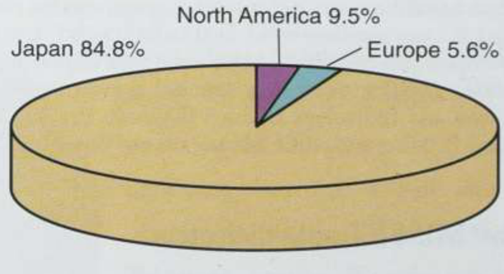


Figure 2. 1993 InP Wafer Supply by Geographic Region

GaAs and GaP Wafer Market Study

The GaAs and GaP wafer market business is forecast to reach \$360 million in 1999, growing from \$254 million in 1994, according to a recently published report by Strategies Unlimited. The growth in wireless communications is creating demand for semi-insulating GaAs wafers at a fast pace, while the production optoelectronic devices is driving semiconducting GaAs and GaP wafer usage. Figure 1 presents the revenue forecast for GaP and semi-insulating and semiconducting GaAs.

The semi-insulating GaAs wafer market experienced good growth from 1993 to 1994, as device unit volume increased 26%, fueled by the increasing use of GaAs FETs and ICs in cellular phones and satellite TV. For 1995, device unit volume is forecast to grow 17%, as demand continues for personal portable phones using GaAs. Semi-insulating GaAs wafer consumption is forecast to grow 14% in 1995 with revenue growth of 11% to \$85 million. According to George Bechtel of Strategies Unlimited, growth in this area will be moderated in the future by competition from improving silicon devices in applications below 2.5 GHz. Given the severe price competition in commercial and consumer electronic components markets, GaAs device manufacturers will have to improve yields and reduce costs in order to be cost competitive with silicon.

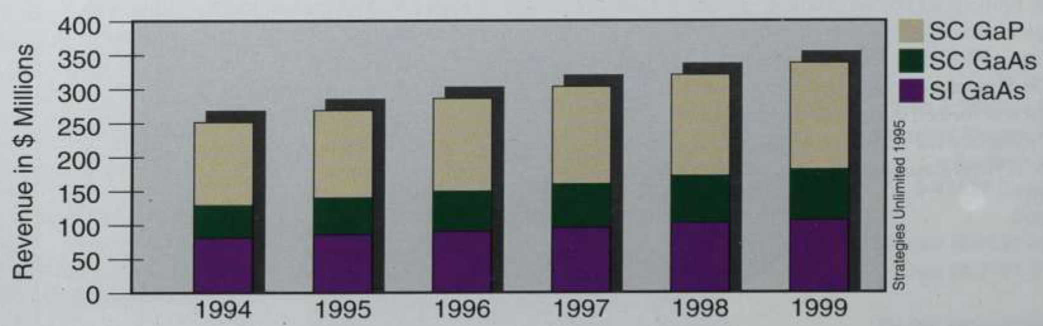


Figure 1. Worldwide GaAs and GaP Wafer Production Forecast

LED lamps and displays are forecast to grow at a 10% rate in 1995, slowed by consumer spending and increasing use of liquid crystal displays. However, the use of LEDs in large outdoor displays is growing, especially in the Far East (see page 26). GaAs and GaP semiconducting wafer consumption is forecast to grow by only 9% as yields continue to improve. Semiconducting GaAs wafer revenue is forecast to grow from 453 million in 1994 to \$75 million in 1999. The study reports that most GaP production is captive, with an estimated value of \$124 million in 1994, growing to \$177 million in 1999.

Strategies Unlimited [Mountain View, CA] is a market research and consulting firm, specializing in the assessment of emerging technologies, particularly high performance materials, wireless communications, and optoelectronic and photovoltaic components and systems. Among their recent projects was the InP market survey described at left.

Research Review

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

Electronic Materials and Devices

140 GHz monolithic low noise amplifier

Millimeter-wave low noise amplifiers (LNAs) are used for radar and radiometric imaging, with higher frequency operation benefiting from higher resolution and smaller size antenna apertures. A two stage 140 GHz LNA using 0.1 µm pseudomorphic InAlAs/InGaAs/InP low noise HEMTs is described. The LNA exhibits a small signal gain of 9 dB at 142 GHz and 5 dB of gain over 138-145 GHz. This is the highest frequency monolithic amplifier using three terminal devices reported to date. Work performed at TRW, Electronic Systems and Technology Division [Redondo Beach, CA]. See "A 140 GHz Monolithic Low Noise Amplifier," H. Wang et al, IEEE Microwave and Guided Wave Lett., 5 (5), 150 [May 1995].

SiO_2 for InP MISFET gate dielectric

Because of its low barrier heights, Schottky barriers made from InP and its related materials are often found to be inadequate as gate control elements. This limitation has led to the investigation of InP-based metal insulator semiconductor FET (MISFET) structures as gate control elements. In this study, photo-enhanced chemical vapor deposition is used to deposit SiO_2 as the MISFET gate dielectric, resulting in an interface density of states in the range of $1.2x10^{11}/cm^2$-eV and 2 µm gate length devices which exhibit transconductances of 63 mS/mm and channel mobilities of 1140 cm^2/Vs. Work performed at National Cheng Kung University [Tainan, Taiwan]. See "SiO_2/InP Structure Prepared by Direct Photo-Chemical Vapor Deposition Using Deuterium Lamp and Its Applications to Metal-Oxide-Semiconductor Field-Effect Transistor," S.C. Shei et al, Japan. J. of Appl. Phys., 34 (2A), 476 [February 1995].

Arsenic implanted GaAs compared to LT GaAs

GaAs which is grown by MBE at temperatures on the order of 200°C incorporates excess arsenic (As), which upon annealing forms precipitates, with the resultant material exhibiting high resistivity (> 10^6 ohm-cm). This work details an alternate technique for the incorporation of excess As into GaAs through high dose As ($10^{16}/cm^2$) ion implantation. Upon annealing of the As-implanted GaAs, this material forms As precipitates and exhibits resistivities which range from 10^3 - 10^9 ohm-cm. Applications for such a high resistivity material would be to eliminate side gating in MESFETS. Work performed at University of California [Berkeley, CA]. See "Conduction Mechanism in Arsenic Implanted GaAs" H. Fujioka et al, App. Phys. Lett 66 (16), 2116 [17 April 1995].

Identification of carbon incorporation in CBE

The use of trimethylgallium (TMGa) during Chemical Beam Epitaxy (CBE) and Metalorganic Molecular Beam Epitaxy (MOMBE) for the growth of GaAs can result in high levels of carbon incorporation with acceptor concentrations ranging from 10^{19} to $10^{21}cm^{-3}$. Using high resolution electron energy loss spectroscopy (HREELS), the mechanism for this carbon incorporation is investigated. It is believed that the source of incorporated carbon comes from CH_2, which is formed through the dehydrogenation of CH_3, which in turn was formed during the decomposition of TMGa. Work performed at Imperial College [London, UK]. See "Evidence for a Surface Methylene Species in the Decomposition of Trimethylgallium on GaAs(100)-(4x1): A High Resolution Electron Energy Loss Spectroscopy Study," A.A. Aquino et al, Surf. Sci. 327, 74 [1995].

Monolithic HEMT-HBT Integration by Selective MBE

The integration of different types of devices into the same integrated circuit is attractive for both microwave and optoelectronic devices. Optoelectronic circuits can benefit from incorporating PIN-diode detectors with high electron mobility transistor (HEMT) or heterojunction bipolar transistor (HBT) amplifiers. Microwave cicuits can benefit significantly from the intrinsically different characteristics of HEMT's and HBT's if the devices are monolithically integrated on the same chip. For instance, the low-noise properties of HEMT's could be combined with the high-linearity properties of HBT's, yielding a nearly ideal single-chip transmit-receive module incorporating a HEMT front-end with an HBT power amplifier and HBT base-collector PIN diode switches.

Researchers at TRW have achieved the first successful monolithic integration of operational HEMT's and HBT's in the same microwave circuit. Selective MBE and a novel merged processing technology was used to fabricate monolithic microwave integrated circuits (MMICs) that incorporate both 0.2 µm gate-length pseudomorphic InGaAs-GaAs HEMT's and 0.2 µm emitter-width GaAs-AlGaAs HBT's. The HEMT and HBT devices produced in this work exhibited performance equivalent to devices fabricated using normal MBE and TRW's baseline single-technology processes. The selective MBE process yielded 0.2 µm gate length HEMT devices with g_m = 600 mS/mm and f_t of 70 GHz, while 2x10 mm^2 HBT devices achieved $\beta > 50$ with f_t of 21.4 GHz. The performance of both a 5-10 GHz HEMT low noise ampliphier (LNA) with active on-chip HBT regulation and a 20 GHz Darlington HBT amplifier were shown to be equivalent whether fabricated using normal or selective MBE.

See "Monolithic HEMT-HBT Integration by Selective MBE," D.C. Streit et al, IEEE Trans. Elect. Dev., 42 (4), 618 [April 1995]. Work performed at TRW Electronic Systems and Technology Division [Redondo Beach, CA].

Optoelectronic Materials and Devices

Long Wavelength Room Temperature Laser

An important application for near infrared lasers is trace-gas sensing using laser-absorption spectroscopy. While near-infrared lasers can probe the overtone absorption bands of many molecules, it is desirable to extend lasing wavelengths to probe the stronger molecular absorption bands, thereby increasing system sensitivity. For example, the atmospheric pollutant, CO_2 absorbs 1000 times more strongly at 2.77 μm than it does at 1.6 μm.

There has been much significant progress recently in 2 to 4 μm lasers using the III-V antimonides. Room temperature devices between 2 to 2.4 μm have been fabricated using InGaAsSb/GaAsSb MQW devices. At longer wavelengths, lasers operating at 3 μm at 255 K pulsed and at 170 K cw have been fabricated from InGaAsSb/AlGaAsSb double-heterojunction (DH) structures; and lasers operating at 4 μm at 155 K and 80 K cw have been fabricated from InAsSb/AlAsSb DH structures.

Researchers at David Sarnoff Research Center recently reported a room-temperature 2.78 μm AlGaAsSb/InGaAsSb multi-quantum well (MQW) laser. This is the longest wavelength reported to date for room temperature operated III-V lasers. Pulsed laser operation was observed at 15°C with a threshold current of 1.1 A (10 kA/cm²), and a maximum power output of 30 mW, and a maximum differential quantum efficiency of 9%. Lasers operated pulsed up to 60° with a characteristic temperature of 58K over the range of 0-40°C. Work performed at David Sarnoff Research Center [Princeton, NJ]. See "Room Temperature 2.78 μm AlGaAsSb/InGaAs Sb Quantum-Well Lasers," H. Lee et al, Appl. Phys. Lett. 66 (15), 1942 [10 April 1995].

In our next issue:

See our September/October issue for a report on antimonides for long wavelength IR lasers.

Low-threshold vertical cavity surface emitting laser

Light sources with low power consumption and mass production capability are needed for future optical interconnection schemes. Vertical cavity surface emitting lasers (VCSEL's) are attractive devices for these applications. A VCSEL with a record low-threshold - 70 μA -.was achieved in a structure with three InGaAs strained quantum wells between reflector stacks of AlAs/GaAs, grown by low-pressure MOCVD. After defining a 20 μm diameter mesa, the AlAs layers of the reflectors were oxidized to reduce the active region diameter to 5 μm. The resulting electrical and optical confinement produced the ultra-low threshold. Work performed at Tokyo Institute of Technology [Tokyo, Japan]. See "Record low-threshold index-guided InGaAs/GaAlAs vertical-cavity surface emitting laser with a native oxide confinement structure", Y. Hayashi, et al, Electron. Lett. 31(7), 560 [30 March 1995].

4.2 μm diode laser approaching room temperature operation

Mid-IR lasers in the 4 μm wavelength region are useful in gas analysis applications. In the past, diode lasers at these longer wavelengths have suffered from high non-radiative recombination, necessitating the operation of these devices at cryogenic temperatures. Recently the operation of a 4.2 μm wavelength laser was reported at a temperature of 9°C. The laser was constructed in PbSe / PbSrSe materials grown by MBE. Work performed at the Fraunhofer Institute of Physical Measurement Techniques [Freiburg, Germany]. See "Midinfrared lead salt multi-quantum-well diode lasers with 282 K operation", Z. Shi, et al, Appl. Phys. Lett. 66(19), 2537 [8 May 1995].

Ultrafast-lifetime and sharp exciton spectra in quantum wells

In the past, either ultra-fast lifetimes or sharp exciton spectra, but not both, could be observed in quantum wells. Generally defect-free quantum wells were required for sharp exciton spectra; high defect densities were required to produce ultra-fast lifetimes. The simultaneous presence of both of these characteristics would be ideal for ultrafast saturable absorber and electrooptic sampling applications. This was recently achieved in GaAs quantum wells by adjusting the MBE growth parameters to create the correct amount of defects. The use of moderately low growth temperatures, nominally 310°C, As_4 fluxes instead of As_2 fluxes and thin AlAs barriers between wells were the keys to achieving the results. Work performed at Purdue University [West Lafayette, IN]. See "Ultrafast-lifetime quantum well with sharp exciton spectra", I. Lahiri, et al, Appl. Phys. Lett. 66(19), 2519 [8 May 1995].

Microgun-pumped blue and blue-green semiconductor lasers

Ohmic contacts and p-type doping are two problems which have concerned researchers in blue diode lasers. Some success has been achieved in these areas. An interesting alternate approach that is independent of doping and contact issues was recently reported. In this work, electron beams were used to pump blue and blue-green semiconductor lasers. The electron beams were generated using low voltage, field emission microtip arrays. Threshold powers were in the range of 10 kW/cm², lower than typical values by an order of magnitude. The semiconductor lasers were based on CdZnSe / ZnSe materials grown by MBE. Work performed at LETI (CEA-Technologies Advancees) [Grenoble, France]. See "Microgun-pumped blue and blue-green lasers", D. Herve, et al, Electron. Lett. 31(8), 459 [16 March 1995].

High efficiency red vertical cavity surface emitting laser

Vertical cavity surface emitting lasers (VCSEL's) in the red region of the spectrum are of interest for plastic fiber applications, laser printing and optical data storage. VCSEL technology has been very successful in the longer wavelength (800-900 nm) materials and edge emitting red lasers are well developed commercial products, but red VCSEL's have not been so successful. Recently, however, significant improvements in the performance of red VCSEL's has been reported. The devices lase in the range of 660 - 680 nm, with output powers of nearly 3 mW and 10% peak wallplug efficiencies. These red VCSEL's were grown by MOCVD on <311> oriented GaAs substrates. Work performed at Sandia National Laboratories [Albuquerque, NM]. See "High efficiency AlGaInP-based 660-680nm vertical-cavity surface emitting lasers", M. Hagerott, et al, Electron. Lett., 31(3), 196 [2 February 1995].

Low-threshold edge emitting laser

An edge emitting quantum well laser with threshold currents of 165 µA at room temperature and 21 µA at cryogenic temperature has recently been reported. The room temperature threshold is the lowest reported value for an edge emitting diode laser; the cryogenic threshold is the lowest reported value for any type of laser. These results were obtained in a buried heterostructure, single quantum well InGaAs/AlGaAs structure grown in a two step MBE/LPE hybrid growth process. Short cavity lengths (125 µm) and mirror coatings with high reflectivities (99%) were used to obtain these low thresholds. Work performed at California Institute of Technology [Pasadena, CA]. See "Parametric study of cavity length and mirror reflectivity in ultralow threshold quantum well InGaAs/AlGaAs lasers", T.R. Chen et al, Electron. Lett. 31(4), 285 [16 February 1995].

Integration of multiple wavelength vertical cavity surface emitting lasers

Integration of multiple wavelength vertical cavity surface emitting lasers (VCSEL's) was recently reported by using masking techniques in the MBE growth of GaAs/AlGaAs structures. In this work, selective growth could be obtained by positioning a mask within 100 µm of the growth surface. The mask could be moved during an MBE growth run, enabling switching between selective and non-selective growth. In this particular work, VCSEL's spaced 500 µm apart had operating wavelengths differing by 10 nm. work performed at NEC Corporation, Opto-electronics Research Laboratories [Tsukuba, Ibaraki, Japan]. See "onolithic integration of multiple wavelength vertical-cavity surface-emitting lasers by mask molecular beam epitaxy", H. Saito, et al, Appl. Phys. Lett. 66(19), 2466 [8 May 1995].

High power diode laser at 1.94 µm

Diode lasers operating at wavelengths near 2 um have potential applications for eye safe and medical applications, remote sensing and optical pumping of Ho-doped solid state lasers. High power operation, 27 watts in quasi-cw operation, has recently been reported a structure that employed strained InGaAs quantum wells and lattice matched InGaAsP/InP. This high power level is the highest yet reported for lasers operating in the 2 µm wavelength range. Work performed at SDL [San Jose, CA]. See "Operation of strained-layer diode laser bars at 1.94 µm to 27W QCW", S. O'Brien, et al, Electron. Lett. 31(2), 105 [19 January 1995].

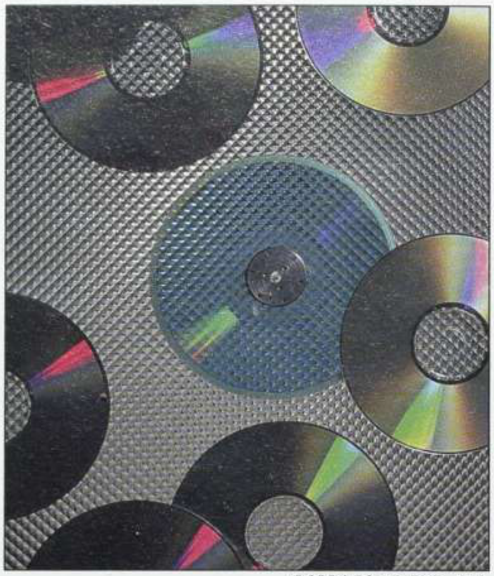
ZnSe/GaAs interface study

ZnSe-based materials are typically grown on GaAs substrates, where due to lattice mismatch and poor growth nucleation, stacking faults are generated which subsequently degrade ZnSe-based devices. Small angle reflectance difference spectroscopy (RDS) is used to study this ZnSe/GaAs heterointerface, where it is found that even when the ZnSe layer is grown beyond the critical thickness, that the interface remains largely intact even after strain relaxation. See "Observation of ZnSe/GaAs Interface States by Reflectance Difference Spectroscopy," Z. Yang, G.K. Wong, I.K. Sou and Y.H. Yeung, Department of Physics, Hong Kong University of Science and Technology, Clearwater Bay, Sai Kung, Hong Kong, Appl. Phys. Lett., 66 (17), 2235 [24 April 1995].

Turning Blue to Green

A look at the commercial applications that are creating demand for shortwavelength light emitting devices.

ROBERT A. METZGER



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Optical Storage

Optical data storage is cited as the key application for blue semiconductor lasers. Experts believe that the devices and systems will be ready by the turn of the century, and that they will provide a 20 times increase in storage capacity as compared to current optical technology.

MAJOR APPLICATIO

Green, in the United States, means money. In the English language "green" can also be associated with jealousy, just as "blue" can mean unhappy or sad. But the compound semiconductor industry now associates these colors with much more positive emotional states - such as enthusiasm and excitement. During the 1990's incredible breakthroughs have occurred in the area of blue/green light emitters - the realization of ZnSe-based blue/green lasers, and the development and commercialization of nitride-based blue LEDs. Several excellent review articles surveying the development the of materials and devices used in this technology are available in refereed journals. What we present here is a look at the "the business end" of the story - an overview of the most important applications that are fueling the interest in shortwavelength light emitting devices.

Data Storage

Of all the applications envisioned for blue lasers, optical data storage is touted as *the* application - it is what drives industry giants such as IBM, Philips, Xerox, Sony and 3M to be involved in blue laser development. According to James Porter of Disk/Trend (Mountain View, CA), sales of optical data storage devices for 1995 are projected to be \$3.7 billion, and to reach \$5.1 billion by 1997. An even greater prize can be won by taking market share away from the huge magnetic data storage market - projected to reach \$35 billion by 1997.

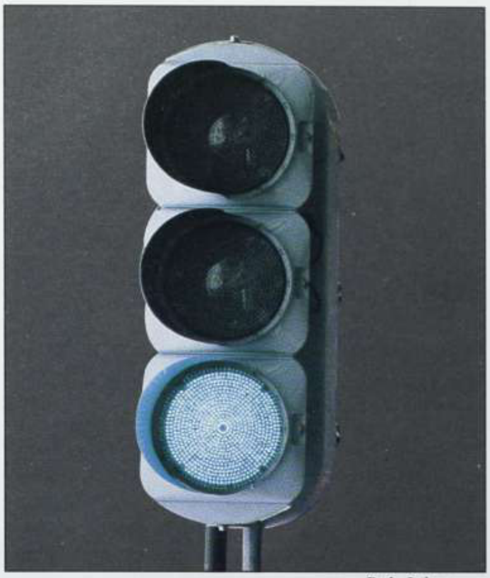
The figure of merit for both optical and magnetic based technologies is the areal density - the density of data which can be stored, expressed in bits/in^2. The optical and magnetic systems which are currently available both operate in the same range of 500 Mbit/in^2.

Magnetic storage, however, is improving rapidly. Magnetic areal densities are currently increasing at a growth rate of between 40-60% per year, due to advances in magneto-resistive heads and more sensitive magnetic materials for recording. Moreover, this field does not require any fundamental breakthroughs in order to maintain this pace until the end of the century. Disk/Trend projects that magnetic areal densities of 10 Gbit/in^2 will be achieved by the year 2000.

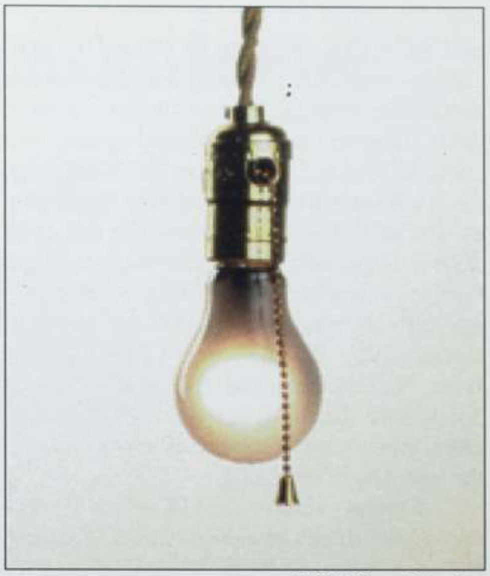
Blue laser technology is the critical component that will allow optical storage to keep up with magnetic media. Optical storage areal densities scale as $1/\lambda^2$ where λ is the wavelength used to read and write data. Current industry standards are based on infrared emitting laser diodes (operating at a λ of 780nm), but a push is already on to scale down to red emitting laser diodes (680nm). The real hope, however is to keep pace with magnetic storage by scaling to blue emitting laser diodes (450nm) when they are commercially available. According to Bill Lenth, manager of optical storage technology at the IBM Almaden Research Center, "by using blue light and blue optimized magneto-optic media, optical storage densities of 10 Gbit/in^2 will be achieved by the turn of the century - values very similar to those projected for magnetic storage."

IBM and Coherent Inc. (Santa Clara CA) have demonstrated a prototype system using a laser in which blue light (428nm) was obtained

Nichia America



Bob Johnstone



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Displays

Full color outdoor displays - like this example from Tokyo, built with Nichia LEDs - are made possible by high brightness blue and green LEDs. Uncommon in the US and Europe, such displays are becoming a familiar sight in many Asian cities. Each requires hundreds of thousands or millions of LEDs.

Signal/Automotive

Japan's bluish-green "go" signals are well suited to GaN's capabilities, but the deep green color used elsewhere presents a more difficult challenge. Auto makers would like to see blue and green LEDs used inside the car as well, to replace more fragile incandescent lights.

White Light (?)

White light can be made by combining red, green and blue - is it therefore possible that compound semiconductor LEDs could someday replace the 100W incandescent light bulb? Perhaps this application is out of reach, but specialized lighting applications may be more easily attained.

FOR BLUE LIGHT EMITTERS

from a frequency doubled 856nm GaAlAs laser. This system was able to operate at areal storage densities of 2.5 Gbit/in^2 - some five times greater than current magnetic or optical areal densities. While demonstrating technological feasibility, this is not an economically viable system, due to both the size and cost ($20,000) of the frequency doubled laser. Semiconductor lasers, on the other hand, cost on the order of a few dollars, and come in much tidier packages.

The advantage of optical storage - even if it cannot surpass magnetic's areal density - is that optical storage allows use of removable media. The distance between the optical read/recording head and the disk is on the order of 1 mm, whereas the distance between a magneto-resistive head and its disk is on the order of 100nm. (It is projected that as magnetic areal densities reach the 10 Gbit/in^2 level that the magneto-optic head and the magnetic disk will need to be in "quasi-contact".)

This means that by the turn of the century, for applications where data requirements are much greater than 5-10 Gbyte, either multiple optical disks, or multiple magnetic hard drives will be required. Multiple optical disks are much more cost effective than multiple magnetic hard drives - and it is this difference, couple with the fact that pre-recorded information can be mass produced in compact disk form for extremely low cost (currently <$1/disk), that will drive the optical storage market, which will in turn create the need for blue semiconductor lasers.

As promising as this application seems, there are two causes for concern. The first is the immaturity of the materials and device technology - see page 34. The second is the fact that optical storage is a prime example of an application where compound semiconductors play the role of "enabling technology" - meaning that most of the system's value will lie elsewhere. For example, consider the existing $3.7 billion optical storage market. Laser Focus World (Jan 1995, pg. 64) estimates the value of laser diodes used in that industry at $67 million (75 million diodes) in 1994 - a respectable sum, but yet a small percentage. It is these kinds of numbers that explain why the primary effort in the blue laser area so far has come not from discrete laser manufacturers, but those companies which will manufacture data storage systems.

LEDs and Displays

3.05 million LEDs.

This is not the number of LEDs produced annually by some manufacturer, or the number of LEDs consumed by some sector of the economy. 3.05 million LEDs are what are used in the worlds largest LED based display - the Sky Screen in Tianjin, China. Built by Hewlett Packard, the sky screen measures 14 meters in height, 40 meters in length and uses 680,000 red LEDs, 680,000 blue LEDs and 1.7 million green LEDs. As large as these numbers are, it represents only a small fraction of the estimated 20-30 billion LEDs produced annually - the majority of which are used for display applications.

Full color displays require red, blue and green light - where these three primary colors can then be used in various combinations to produce any other color of light, including white light when all three primary colors are combined. Until just a few years ago, these primary colors were typically obtained by AlGaAs LEDs operating at 680-650nm for red, GaP LEDs operating at 555nm for green, and SiC LEDs operating at 470nm for blue. AlGaAs red LEDs, suitable for both outside and inside displays are very bright - some 8 times brighter than GaP-based green, and some 100 times brighter than SiC-based blue. As is apparent from these relative brightnesses, the weak links in the chain for full color display (especially for outside displays) have been green and blue LEDs. This situation dramatically changed in 1993 with the advent of commercially available blue LEDs (450nm) from Nichia Chemical Industries, Ltd of Tokushima, Japan. These GaN-based devices offer brightnesses (1000mcd) comparable to the superbright red LEDs.

Current world-wide LED sales, according to Neal Hunter of Cree Research, (Durham NC) are some $1.5-2.5 billion. Photonics Spectra (Jan 1995, pg. 28) estimates $2 billion in LED sales for display applications by the year 2000, with 20% of that ($400 million) for blue. Until the advent of the Nichia GaN based LED, the primary source of blue LED light was the Cree SiC-based LED (with lesser production by Sharp, Siemens AG, Sanyo and Sunkei) producing 10-20mcd, making it best suitable for indoor applications. According to Shuji Nakamura of Nichia, "current production of Nichia packaged blue LEDs operating at 1000mcd is 1,000,000 per month". With the cost in large quantities at $2.30 each (having dropped from $40 each in initial preproduction runs) - this represents sales of some $30 million per year - a very small percentage of the billion dollar LED market.

With such large potential sales, other manufacturers are beginning to enter into the GaN blue-light market, with Cree now offering their new GaN based blue LED (435nm) grown on SiC. Sold in chip form, this LED is some 30 times brighter (400mcd) than their old SiC device and sells in quantity for $0.75 each. According to Neal Hunter, "initial production is expected to be 1,000,000 per month in the summer of 1995, with production reaching the 8-10 million/month level within a year, along with projected light outputs increased to 1500mcd". Unlike the Nichia device which is fabricated on an insulating substrate (sapphire), the Cree device is grown on conducting SiC, thereby allowing backside contacting - this device configuration similar to that of the AlGaAs red LED, which makes it suitable as a direct drop-in for the manufacturing of displays which are accustomed to backside contacting of red LEDs.

Nichia LEDs are currently rated at 60,000 hrs lifetime, with Cree LEDs rated at 100,000 hrs. This means that displays using these blue light sources can be expected to continuously operate in excess of 10 years - reflecting the fact that the technology is well enough in hand to make a reliable part. All that remains according to Neal Hunter, "in order for these devices to be used and exploited to the same degree as red LEDs, is that the cost must drop to the order of 10 cents each". He feels that this is a reachable goal once large scale production is in place.

Even though GaN LEDs are dominating the blue LED arena, there is another approach being considered. Eagle-Picher (Miami, OK) is using conducting ZnSe substrates to grow II-VI ZnSe-based LEDs. They are currently expected to go into pre-production of green LEDs (512nm) in the summer of 1995 with devices producing 1.3 mW, and later in the year with blue LEDs (489nm) which currently produce 327 mW. At the moment, the biggest challenge facing the marketability of all II-VI based light emitters is their reduced lifetime due to defect multiplication during device operation. According to Bill Harsch of Eagle-Picher, "these preproduction devices will be rated at lifetimes of some 1000-4000 hrs, which will make them more suitable at this point for display prototyping, rather than for actual display production". These lifetimes will have to greatly increase in order for these devices to be competitive with GaN-based LEDs.

Unlike the optical storage market, where lasers are an enabling technology, driving sales of much more expensive storage equipment, the blue LED market (estimated to approach $500 million by the end of the decade), will see a large percentage of display sales going directly to the LED manufacturer.

Other Applications

LEDs are now becoming bright enough to be considered suitable as replacements for incandescent traffic lights (see page x). Nichia is actively marketing a 500nm GaN LED for use in "go" lights in Japan. However, if they wish to penetrate the world-wide green signal light market, Nichia and other GaN-based manufacturers will have to increase the In content in the LED in order to increase its operational wavelength into the true green region. This represents quite a technical challenge, since the increase indium content results in strain which can degrade device performance. With an estimated world wide market of some 10-20 million green traffic signal lights, and each signal light requiring some 500-750 individual LEDs, the potential number of LEDs for this application approach 10 billion.

Another potentially large market is the automotive industry, which is currently starting to replace some brake lights and running lights with red LEDs. Green and blue LEDs are being considered for use in car interiors and dashboards. Northe Osbrink of Hewlett Packard says "that the auto industry has expressed interest in placing reliable, long lifetime LEDs behind dashboards - it is very expensive and inconvenient to have to remove an entire dashboard to get at a 10 cent broken incandescent". Blue light also has application for spectrographic detection, ranging from medical applications to analyze blood or monitor for oxygen levels, to using blue light sensors to sniff out biological and toxic agents both on and off the battlefield.

And, finally, one of the most tantalizing possibilities is that of making white light by combining red, green and blue LEDs. Many applications for a solid-state source of light can be imagined - those for harsh working environments where fragile incandescent light bulbs may break - safety flashlights, bright white light sources for emergency workers and vehicles, military vehicle interior lighting, mining operations, underwater work, etc. But the largest imaginable market of all - the market which has the potential to dwarf all others - might be that of the humble household 100 W light bulb. It has been shown that switching from incandescents to LEDs in signal lights reduces energy consumption by >85%. If this same value held for a LED-based white light, the energy savings in US households would approach $35 billion/year. This is an application that would require trillions of units, a market which can be descrided using another American metaphor: "blue skies," which can mean limitless possibility, but can also mean "totally divorced from reality." Time will tell if either is an apt description.

Hewlett Packard

The Sky Screen in Tianjin, China - built with 3.05 million Hewlett Packard LEDs. It is the world's largest LED-based display - for now.

Uncle Sam Wants Blue

Defense applications create perceived need for a domestic manufacturing base.

The US government wants blue - and has wanted it for quite some time. According to Max Yoder from the Office of Naval Research, Washington DC, the US Navy's work on wide bandgap materials dates back to the 1970's. He now finds himself involved in 50 different contracts or monitoring situations with respect to large bandgap materials and devices.

Consortia are very much in vogue in US federally funded research, and this area is no exception. In 1991, after 3M and Philips announced their breakthrough blue laser, ARPA responded by forming several consortia to advance this effort. The most visible consortia was on the university level, created by combining the efforts of Brown University, Purdue University, MIT and NCSU. On the industrial front 3M and Phillips were joined, and later IBM was added.

With the advent of Nichia's blue LED in 1993, new consortia were formed by Anis Husain at ARPA, with the programs being monitored by Yoon Soon Park of the Office of Naval Research. Three teams were formed which consisted of 1) Phillips, Cree and NCSU, 2) APA Optics, Kodak and AT&T, and 3) Hewlett Packard, SDL, Xerox, University of Boston and University of Texas at Austin. These three consortia were well represented by the industrial manufacturers and consumers of LEDs and lasers, with ARPA's intent to bring their manufacturing know how to bear on the blue LED/laser problem to help ensure that the DOD would have a future domestic source of blue emitters.

And why exactly is the Federal government setting up all these consortia? Why is it so interested in insuring a domestic manufacturing base for blue LEDs and lasers? Anis Husain summed up the military's needs with what he considers 6 key areas:

1. High Density Memory - "We need 10 Gbyte first", he says. "We would like to be able to download information into an optical based read write system allowing a pilot to possess the information on where the Scuds were last seen, and to then turn off their radar and enter into the battle arena in a complete stealth mode, relying only on their stored information."

2. Display Applications - full color bright LED displays for cockpit applications and bright backlighting. Low power consuming LEDs are required in order to extend battery lifetime, as well as to reduce battery weight.

3. Battlefield Lasers -both non-lethal lasers, and application for light weight counter-measures. Current argon-ion based systems require soldiers to pack 40-50 lbs onto the battlefield which is not acceptable.

4. Chemical/Biological Battlefield Reagent Detection - Absorption lines of some important chemical/biological agents appear in the ultraviolet portion of the spectrum. Light weight, energy efficient detectors that could be carried by individual soldiers are needed.

5. Communications - blue light can be used for covert applications.

6. Solar blind Detector Area - Missiles coming from the direction of the sun are hard to see due to the background sun. Ultraviolet based detectors would not be blinded by the large infrared and visible component of the sun, and would also be able to detect missile launches in the boost phase by detection of missile plumes.

In conclusion, Anis Husain says, that it is ARPA's role "to look at technologies that are starting to go, determine if they have military applications, and to then bring the necessary resources to form critical mass." He views these resources to include those of money, but even more importantly, those of human resources - to bring together the right people and organizations so that they can make intelligent use of the money that ARPA and the other segments of the military bring to bear on blue light work.

The End of the Beginning

Some fundamental problems still must be solved to make blue lasers a reality

And now for the sobering reality: the lifetimes for even the best blue semiconductor lasers are still measured in minutes. Basic materials work is still required to understand what the capabilities of both II-VI and nitride based devices.

By the end of the 1980's the II-VI's and nitrides both suffered from the same problem - the inability to dope p-type. Then in 1990 Robert Park of the University of Florida, Gainesville, and Kazuhiro Ohkawa at the Matsushita Central Research Laboratory in Japan developed a technique of using nitrogen radicals to produce p-type doping levels of up to $1x10^{18}$ cm^{-3} in ZnSe. That breakthrough directly led to operational ZnSe based lasers grown on GaAs substrates a year later at both 3M and Brown/Purdue Universities. Those initial lasers could only operate at 77K for fractions of a second before they burned out, but they did lase. In 1989 Isamu Akasaki at Meijo University discovered that Mg doping of GaN would produce p-type layers if the films were exposed to low energy electron beam irradiation (see page x). With a p-type doping capability, Akasaki and Amano demonstrated blue emitting LEDs, quickly followed by Shuji Nakamura from Nichia Chemical Industries developing Zn p-type doping for InGaN allowing candela-class blue emission in GaN/InGaN LEDs.

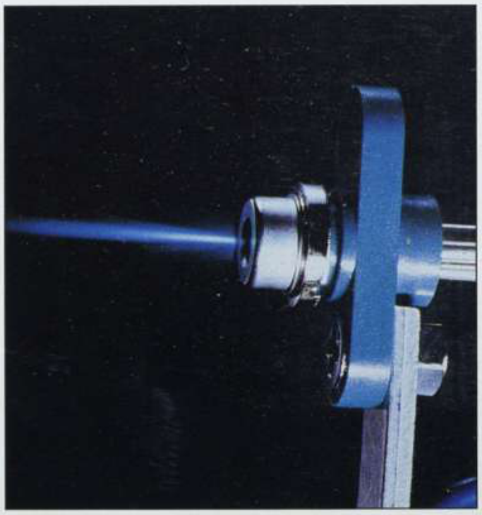
However, acquiring p-type doping was not the "beginning of the end" rather, it was the "end of the beginning," marking the onset of a new phase wherein researchers might begin to investigate how these two material systems behave as blue light emitters, and what they might do to try and improve those materials.

Underneath it All

For ZnSe materials, "all the breakthroughs are in MBE," says Mike Haase of 3M, co-inventor of the first blue semiconductor laser, because the improvements are being driven by material growth. These sentiments are echoed closely by Hadis Morkoc of the University of Illinois when asked what he views as the problems that need to be overcome with respect to nitride-based blue-emitters - "the major problem is that the growth is not well understood".

Whether the growth is by MBE or MOCVD, the first order of business is that of the substrate - and that is exactly where major problems and major work are occurring for both the II-VI and nitride efforts. Ideally, one would like to grow materials on like substrates, i.e. to grow ZnSe based materials on ZnSe and to grown GaN based materials on GaN - thereby assuring lattice matching. However, in the early 90's when this work began, and even to this day, the availability of such suitable substrates are very limited - Eagle-Picher Industries [Miami, OK] is producing n-type ZnSe substrates, but they are held captive to their own efforts. Sumitomo Electric has only recently begun to ship some ZnSe out of an R&D program, but they are available in "development quantities only at this time", according to Thomas Miehe of Sumitomo Electric USA. Experimental work on GaN substrates has just begun.

For most II-VI workers, then, the logical substrate choice is GaAs, with a lattice mismatch to ZnSe of only 0.25%. By using ZnMgSSe cladding layers which can be perfectly lattice matched to GaAs, the only



Sony

A ZnSe-based laser operating at 49lnm, fabricated at Sony.

remaining strain in the lasers comes from the slightly mismatched ZnCdSe QW active layers. Even though nearly lattice matched, and certainly lattice matched at the ZnMgSSe-GaAs interface, these devices typically exhibit stacking fault densities of 10^5 - 10^6 cm^{-2} which are generated at the ZnMgSSe-GaAs interface. As observed by Otsuka of Purdue University by TEM examination, it is found that "dislocation networks are nucleated at threading dislocations which originate from pairs of V-shaped stacking faults". These dislocations multiply during laser operation and result in device failure. This behavior illustrates that even perfectly lattice matched conditions are not sufficient to insure perfect growth. Elaborating on this point, Robert Gunshor of Purdue University says "similar densities of stacking faults are observed even when these structures are grown on ZnSe substrates - we do not yet understand how to properly prepare the ZnSe surface for growth." But progress on this front is being made. Mike Haase of 3M reports "that by working very hard on the growth at the ZnMgSSe-GaAs interface, stacking fault densities much lower than the typical 10^5 - 10^6 have been obtained, directly resulting in CW room temperature laser lifetime improvements which we have seen increase from only a few seconds to 73 minutes." Jan Schetzina of North Carolina State University, in collaboration with Eagle Picher, has grown green LEDs on ZnSe substrates which exhibit lifetimes in the 1000-4000 hour range and which he believes have stacking fault densities on the order of 10^3 cm^{-2}. But, it should be remembered, that even if the ZnMgSSe or other ZnSe based alloys are grown perfectly lattice matched to GaAs, and exhibit very low defects, when the samples are cooled after growth, the layers will experience a tensile strain due to differences in the thermal expansion coefficients between the GaAs substrate and ZnSe based layers - stress which may be relieved by the formation of dislocations. Yoon Soon Park of ONR, and contract monitor for many of the ARPA based consortia, comments on this behavior by saying that "the direction for II-VI work is that of ZnSe substrates".

Sapphire or SiC

Nitride workers were not as fortunate as II-VI researchers in being able to find such a closely lattice matched substrate. The substrate most typically used is that of sapphire ($\propto Al_2O_3$), exhibiting the same hexagonal symmetry as both wurtzite GaN and AlN, but possessing a lattice constant which is 14% larger and a thermal expansion coefficient almost twice as large. In order to grow on such an ill-suited substrate, it was found necessary to first grow low temperature buffers of GaN or AlN, often making these buffers several μms thick. Hewlett Packard and Xerox have analyzed Nichia blue GaN LEDs and discovered that they exhibit dislocation densities in excess of $2x10^{10}$ cm^{-2}. This is an amazingly large number, especially when making comparisons to III-V based LEDs, where if dislocation densities exceed 10^5 cm^{-2}, the devices begin to exhibit severe degradation in LED efficiency, while at dislocation densities of 10^{10} cm^{-2} they simply would not work - the dislocations acting as sites for non-radiative recombination. Theodore Moustakas of Boston University explains "that unlike most other III-V materials, GaN shows no surface state behavior, as evidenced by the Fermi level not being pinned. Dislocations can be thought of as internal surface states, so in the same way that those states appear to have no effect on GaN surface properties, they have no effect on bulk GaN crystalline properties". Even though the dislocations do not appear to be degrading LED behavior, many researchers feel that the dislocation density will have to be reduced in order to achieve laser operation in the nitrides. Similar behavior has been observed in III-V work, where laser operation requires lower dislocation densities than LED operation, and as also been observed in II-VI work where lasers are currently only operating on the order of 1 hr, while LEDs made of the same materials operate on the order of 1000 hr. Max Yoder of ONR, who acts as a central repository on all manner of facts about the nitrides, reports that "at the moment the GaN material grown by Robert Davis at North Carolina State University shows the lowest dislocation densities at 10^7 cm^{-2}". As in the case of stacking fault reduction in the II-VI materials, dislocation density reduction in GaN-based materials have come about by paying careful attention to the initial growth conditions and surface preparation at the sapphire-GaN interface.

Eagle - Picher

Beautiful, and rare - ZnSe substrates, grown by Eagle - Picher Industries.

Because of the inherent problems of sapphire substrates, researchers are actively looking at other substrates for GaN growth. One candidate, is that of SiC. Exhibiting a closer lattice match to GaN, as well as a much higher thermal conductivity (an advantage during high power operation - an example of which would be during the write mode on a magneto-optical disk, which would require high powers of 30 mW), SiC substrates are being used by Cree in the production of their new 400mcd blue LEDs, in which the GaN diodes are grown directly on SiC. Neal Hunter of Cree reports that dislocation densities in this material "are on the order to 10^8 ¢m^{-2}". A more exotic substrate alternative is that of ZnO, with an even closer lattice match to GaN than that of SiC. Eagle-Picher is currently attempting to develop such substrates. And beyond even the ZnO substrate, some researchers, many of whom are being actively encouraged and supported by Max Yoder of ONR, are looking at growth on compliant substrates - special substrates which accommodate the strain produced by the GaN layers, so that dislocations are generated in the substrate before being generated in the growing layers.

Current Status

The II-VI researchers continue to make rapid progress on improving the substrate-film interface quality. Vertical cavity II-VI lasers have been announced by Nurmikko of the Purdue/Brown team. Both Sony and 3M/Philips have reported laser lifetimes in excess of 1 hr, while work continues to focus on increasing p-type nitrogen doping levels in order to improve p-type contact resistances to II-VI lasers.

Nitride workers continue to see improvement in blue light generation from LED sources and are moving ever closer toward laser operation. Amano and Akasaki of Meijo University have reported violet stimulated emission from AlGaN/GaInN structures, as have Asif Khan of APA Optics from InGaN/GaN structures. J.J. Song of Oklahoma State University has recently reported near ultraviolet lasing from an optically pumped GaN film. All of these show the promise of achieving current injection lasing in GaN-based material, but if the past is any way to judge the future, much fundamental work may still have to be done in order to understand the fundamental materials issues before a nitride based laser is achieved.

George Craford of Hewlett Packard says, "it will take a long time to wring this out - decades". And that is probably just as it should be. The quest for blue light emitters is often inaccurately characterized as a horse race between GaN and ZnSe. But in fact the situation is much more complex, and it certainly will require much more than one quick jaunt around the track. In fact, there is no clear finish line in this race. The goals will be continually changing, the markets coming and going, new players entering, old players leaving. All one can say with some degree of certainty is that it is, nonetheless, well worth running.

Current Injection Operation of a Blue VCSEL

Scheduled for presentation at this year's Device Research Conference (June 19-21, Charlottesville, VA) is a report on a blue Vertical-Cavity Surface Emitting Laser Diode (VCSEL) operating by current injection, from S. Yoshii, T. Yokogawa, A. Tsuijimura, Y. Sasai (Matsushita Electric Ind. Co. Ltd., Osaka, Japan) and J.L. Merz (University of Notre Dame, Notre Dame, IN). Although blue VCSEL operation using optical pumping [Ref 1-2] has been previously reported, this is the first time that a ZnSe-based VCSEL has operated under current injection. Optical pumping is often used to evaluate material properties and VCSEL structures when current injection operation has not yet been developed, but is impractical as a pumping source in a commercially viable laser. For this current injection-based VCSEL, Jim Merz says, "laser emission occurs at 490nm under threshold conditions of 3 mA and 17 V for pulsed operation at 77 K". The laser is grown on GaAs using ZnSe cladding layers and a 100 Å $Cd_{0\cdot8}Zn_{0\cdot8}Se$ active region. Dielectric ex-situ distributed Bragg reflectors (DBR) consisting of SiO_2/TiO_2 superlattice stacks are deposited to the top of the laser, as well as to the bottom, once the GaAs substrate has been selectively etched away to expose the ZnSe buffer layer. Critical to the operation of this VCSEL is the method through which current injection is established. This is achieved by a 14 µm diameter AuPd annular ring which surrounds the top 10 υm diameter DBR. The bottom electrical contact is made through the GaAs substrate surrounding the perimeter of the lower DBR stack. 490nm emission occurs through the lower DBR stack of the VCSEL. The vertical cavity configuration has a distinct advantage over edge emitters, producing a single circular longitudinal mode, making it ideally suited for two-dimensional array structures, as well as for possible high density optical storage applications.

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PROFILE

Bright Lights

Nichia's Shuji Nakamura with some help from Isamyu Akasaki surprised the world

BOB JOHNSTONE

On November 29, 1993, when Nichia Chemical Industries announced to the world that it had developed a bright blue, GaN based light emitting diode and was proceeding with plans to put the device in mass production, the most common response from the optoelectronics and compound semiconductor industries was: "Who?". Few people, even in Japan, had ever heard of Nichia. Certainly, the company had no previous track record in the optoelectronics industry.

About the only ones prepared to swallow this outrageous idea were the few who had read the technical papers published during the previous five years by Shuji Nakamura, the smart young researcher at Nichia who made the blue diodes. But not many people were paying attention. In the quarter century since Paul Maruska and Jim Tietjen produced the first single-crystal GaN material at RCA's David Sarnoff Research Center in Princeton, NJ, many people had attempted to do something useful with it, but all were stymied by the lack of p-type doping and suitable substrates. The difficulties were such that one might wonder why would anyone want to waste their time working on this material.

The idea that he might be wasting his time seems not to have occurred to Isamu Akasaki, a Japanese scientist who has dedicated the past 20 years of his life to persuading GaN to behave like a direct-bandgap compound semiconductor should. Of many improvements that Akasaki made to the material, two he made at Nagoya University during the 1980's were of particular importance. The first was the incorporation in 1986 of a mirror-smooth AlN buffer layer between the sapphire and the active layer. This somewhat mitigated the highly mismatched substrate problem. More significantly, in 1989, he serendipitously produced the world's first p-type GaN.

But by that time most people had long since quit the nitride field, and Akasaki's announcement attracted little attention. Then, in 1991, 3M announced its zinc selenide based laser, and seemingly everyone dove into II-VI work. With the result that when, two years later, Nichia made its dramatic announcement, as one Toshiba II-VI researcher put it, "everybody got caught with their pants down." Once they recovered, what people most wanted to know was, who was this guy Nakamura anyway? And what sort of outfit was Nichia?

Avoiding Crowds

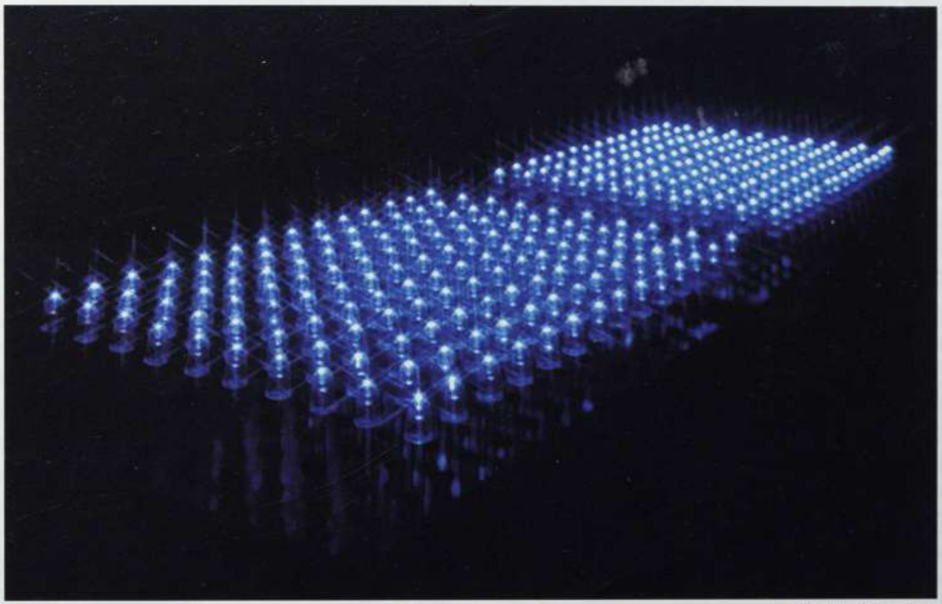
Shuji Nakamura is a native of the island of Shikoku where Nichia is based. The smallest of Japan's four main islands, Shikoku is also the most sparsely populated. Located in the southwest of the country, the region is best known for produce such as sweet potatoes and seaweed, and for a midsummer folk dance that the locals do in the streets of Tokushima, the island's principle city. While doing a masters degree at Tokushima University Nakamura had married a local girl and neither was keen to move to crowded Tokyo or Osaka. But Nakamura had to find a job, and outside of Otsuka Pharmaceutical - maker of a popular athletic drink called "Pocari Sweat" - there's not a lot of industry on Shikoku.

About the only other option was Nichia, this little family-owned chemical company out in Anan, a city of some 60,000 people located out in the middle of nowhere, about half an hour south of Tokushima. And though he was not particularly thrilled with the prospect of joining Nichia - the smell emanating from company factory was bad enough to put most people off - Nakamura felt that he didn't have much choice in the matter. He had no way of knowing that his new boss - Nobuo Ogawa, the firm's founder and guiding light - was one of Japan's least known but most remarkable entrepreneurs.

Born in 1912, Ogawa is a pharmacist by training. His first laboratory was a back room in his pharmacist's store in Anan. There in 1951 he developed a superior chemical precursor for streptomycin, an antibiotic used to treat TB. Muscled out of this market by much bigger rivals, Ogawa came up with another product: calcium phosphate, which is used to produce phosphors for fluorescent lamps. Ogawa founded Nichia Chemical in 1956 to manufacture and market this phosphor. He also came up with a motto - "ever researching for a brighter world" - that the firm has stuck to ever since.

In 1971 Nichia began making phosphors for color TV picture tubes, and they are now the world's largest independent supplier (most phosphor firms are subsidiaries of large picture tube makers). But like many small Japanese outfits, Nichia until recently has had trouble squeezing financial backing out of Japan's ultra-conservative banks. During the 1974 recession, a cash crisis brought the company's factories to a standstill. Characteristically, Ogawa turned the situation to his advantage, urging his employees to enjoy a long holiday that year - and the practice of taking a 20-day midsummer break has become company policy. Ogawa himself spends the summer break climbing mountains, usually the nearby Japan Alps. He claims that high altitudes are conducive to his strategic thinking. These days, aged 82, he confines himself to peaks of less than 10,000 feet

When Shuji Nakamura joined Nichia immediately after his graduation in 1975, Ogawa had diversification on his mind. The first job Nakamura was assigned to was the refining of high purity gallium metal. He took that as far as production, then moved on to growing single crystals of gallium arsenide and indium phosphide. But though development went smoothly, when Nichia got product out the door, they found they couldn't compete with giants like Sumitomo Electric. The next thing Nakamura tried was epitaxial wafers for LEDs. Here too, Nichia ran into serious competition from much bigger rivals like Toshiba.



Nichia Chemical

Nichia's famous blue LED's.

Slow Start

All told, Nakamura spent the better part of a decade developing high purity metals, compound semiconductors, and epitaxial wafers, none of which was a commercial success. But though the experience was bitter, at least it had taught him a lot about LEDs, and shown him that there were no good blue diodes, and that the search for a suitable material was the number-one topic at conferences.

Until that point, Nakamura had basically done as he was told. Now, Ogawa gave him the freedom to decide for himself what his next project would be. "And in 1988, I decided to go for the blue. Having heard all sorts of things at conferences, I thought that as the crystal growth method MOCVD would be good, but I had no idea what MOCVD was, how it was done."

As it happened, one of his seniors from Tokushima University, S. Sakai, was an expert on MOCVD. Sakai was then at the University of Florida, but when he came back to Japan that summer, Nakamura invited him down to Nichia and got him to persuade Ogawa that MOCVD was the way to go. Sakai also recommended that Nakamura should go to Florida to learn how to do MOCVD. Nakamura had been told that there were two MOCVD machines at Florida, but on arrival he discovered that the one at his lab was not built yet. Construction took ten months, and by the time the machine was ready, he had only about a month left before he had to come back. "There were about ten students and me, and we all wanted to use the machine, so we were able

Bob Johnstone

Shuji Nakamura and Nichia Chemical Chairman Nobuo Ogawa

to use it about three times before I returned," Nakamura recalls, laughing.

Because the machine was not ready, Nakamura had lots of free time to go to conferences, in particular, the sessions on blue light emitters. "And there were so many people doing zinc selenide, especially in Japan where most companies and universities were doing ZnSe. But I had had the bitter experience that, if you do the same as everybody else, when it comes to making products, you can't sell them. So I decided to choose a different material." Nakamura was well aware of the lattice mismatch problem, but for him the most important thing was that the field was empty. "When I started, it was simply a case of no one else was doing gallium nitrite," he says, "I wasn't confident that I could do it either, but I wanted to use a material that no-one else was using."

Akasaki's Discovery

No-one else, that is, except Isamu Akasaki, who had been working on gallium nitride since 1974. Initially, as a researcher at Matsushita's Tokyo laboratories, Akasaki had grown the material with MBE. But MBE equipment was still relatively primitive, and the resultant crystal contained lots of impurities. Nonetheless in 1981, Akasaki did manage to produce a metal-insulator-semiconductor flip-chip LED with a conversion efficiency of 0.12%. Matsushita announced that they would develop this device as a commercial product, but in fact the material had too many cracks, and a product never emerged.

While still at Matsushita, Akasaki switched to MOCVD, but left to return to Nagoya University before the equipment was built. At Nagoya, he discovered that using MOCVD would not of itself solve the crack problem. Ultimately, he hit on the idea of using AlN - a material he had previously worked on at Matsushita - as a buffer layer, and in 1986 he and his student Hiroshi Amano were able to produce high quality GaN.

And then, in 1989, a "happy accident" occurred in Akasaki's lab. While examining a sample of magnesium-doped GaN under an electron microscope, Akasaki and Amano were astonished to notice that, under bombardment from electrons, the sample was producing brighter and brighter light. When they finished, the microscopy they, measured the resistance, and found that the film had become p-type!

Back at Nichia

Akasaki's serendipitous discovery was a fantastic stroke of luck for Nakamura. On his return from Florida in 1989, Nakamura had built his own MOCVD machine, and began working on buffer layers. Akasaki had used AlN for his layer. Nakamura, determined not merely to copy (and aware of the potential for patent problems if he did), decided to use GaN instead. This turned out very well — "we were able to get a mirror-like surface, and when we measured the electrical characteristics, we found that gallium nitride was much better [than AlN], mobility is very high."

When word came of Akasaki's momentous p-type achievement, Nakamura was quick to reproduce the older man's work. "And we noticed that when the sample was exposed to the electron beam, its temperature went up quite a bit. So I thought, isn't this just a simple problem of temperature? And we did heat-annealing in a nitrogen atmosphere, we found that the resistance dropped. So it wasn't as a result of the electron beam, but simply as a result of the heat." Armed with his simpler process and his proven method of growing good films on sapphire substrates, Nakamura had no doubt that he would win the race with his rival to produce a bright blue diode. "I was confident because, in Japan, when a university professor and a company compete, the company usually wins ... because Japanese universities don't get much money."

And so it proved. Nakamura produced his first blue light emitter on 28 March 1991. That was all very well, but what would its lifetime, be? He left it switched on when he went home that evening. After a sleepless night, he came in to the lab early next morning and found, to his enormous relief and delight, that it was still on. Nakamura ran to tell Ogawa, who pausing only to pick up his camera, came to see it. But the light was not very bright, and Nichia's chairman was unimpressed. Two and a half years and many improvements later, when Nichia went public with its announcement, the diodes were capable of putting out 1000 mcd; and six months later, the company announced a 2000 mcd diode that was so bright you could hardly look at it.

Today, the company is gearing up to ramp production from one million to ten million devices a month while Nakamura works on his next target, a blue GaN laser. These are difficult challenges but, as Nichia's earlier triumphs demonstrate, this maverick company is quite capable of surprising the world.

Bob Johnstone

Isamu Akasaki of Meijo University

The Color of Light

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We're all familiar with the perception of different colors of light. Quantitative description of color may not be so familiar. The quantitative study of the perception of color, colorimetry, has applications in such areas as color CRT's and flat panel displays, and visible light emitting devices.

Monochromatic Light

Monochromatic light is a mixture of only a narrow band of wavelengths. The color of monochromatic light is easy to classify - all that's needed is a single parameter, the wavelength. Although somewhat subjective, the various pure, or monochromatic, colors are usually categorized as shown in Table 1. Laser light is a good example of monochromatic light, the colors of the rainbow is another.

Other than laser light and rainbows, most light consists of mixtures of fairly different wavelengths. If present individually, the wavelengths would be perceived as different colors. However, when mixed together, the individual wavelengths (colors) are not apparent - only a single color sensation is perceived. It is interesting that perceptions of light and sound are so different in this respect. We *can* detect individual wavelengths (or frequencies) of multiwavelength audio sources.

Color	Wavelength (nm.)
Violet	shorter than 450
Blue	450 - 490
Green	490 - 560
Yellow	560 - 590
Orange	590 - 630
Red	longer than 630

Table 1: Categorization of Monochromatic Colors

The Colorimetry of Mixtures of Wavelengths

The description of the color of arbitrary mixtures of wavelengths requires three parameters. The need for three parameters arises from the way the eye is built. The color receptors in the eye, the cones, come in three varieties. The sensitivity curves of the three types of cones are shown Figure 1. The output of each type of cone is the weighted average of the intensities of the various wavelengths, where the weighting function is the cone's sensitivity curve. The eye condenses the complete wavelength dependence of every light source into only three parameters, the outputs of the three types of cones. Any two light sources that produce the same three cone outputs will be perceived to be the same color, *i.e.*, have the same chromaticity. This can occur, in some cases, for quite different mixtures of wavelengths. Many color matching studies have been made in which human subjects view mixtures of different intensities of three colored light sources (primaries). Such experiments show that the chromaticity of most test colors can be matched by mixtures of various amounts of three primaries. The matching of a test color, Q, with certain amounts, x_1, x_2 and x_3, of the three primaries, P_1, P_2 and P_3, is represented as

$$Q = x_1 P_1 + x_2 P_2 + x_3 P_3.$$

Some test colors, however, cannot be matched with any combination of three primaries. In most of these cases, although a match of the test color cannot be obtained, a mix of the test color and one of the primaries can be matched by a mix of the other two primaries:

$$Q + x_1 P_1 = x_2 P_2 + x_3 P_3$$
or
$$Q = - x_1 P_1 + x_2 P_2 + x_3 P_3.$$

This last equation suggests that this situation be described as matching the test color with a *negative* intensity of one of the primaries. This is obviously artificial - negative intensity of light does not exist. For a few colors, negative amounts of two primaries must be used in the color match. The use of negative

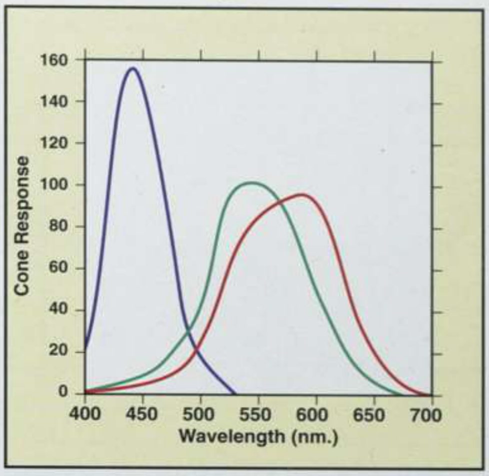

Figure 1. Wavelength dependence of the sensitivities of the three types of cones.

amounts of primaries arises because the cone sensitivity curves overlap, as seen in Figure 1. For example, in trying to match a certain test color, the red primary needed to produce the correct output of the red cone will also excite the green cone. In some cases the red primary's excitation of the green cone is more than is needed, requiring a negative amount of the green primary to bring the green cone excitation down to the required level. The choice of primaries is not unique. To avoid the need for negative amounts of primaries, hypothetical primaries have been invented. These primaries are for computations only; they cannot be actually produced. The standard choice for the hypothetical primaries are the CIE (after the French for *Commission on Illumination*) primaries. The amounts of each of the hypothetical CIE primaries that are be required to match the chromaticity of a monochromatic source are the *tristimulus values*. The tristimulus values, $\bar{x}$, $\bar{y}$, $\bar{z}$, for the wavelengths of the visible spectrum are shown in Figure 2.

Luminosity

Since the choice of primaries is not unique, the designers of colorimetry were able to make one of the standard CIE primaries do double duty. The middle wavelength (greenish) primary was chosen so that its tristimulus curve (Figure 2) is also be the luminosity curve, representing the wavelength dependence of the eye's response. The green line in Figure 2, now interpreted as the luminosity curve, shows that the eye is most sensitive to the wavelength of 555nm. As an example of the use the luminosity curve, consider the visibility of GaInP red laser diodes and LED's. 670nm emitting devices are easier and cheaper to make, generally producing higher efficien-

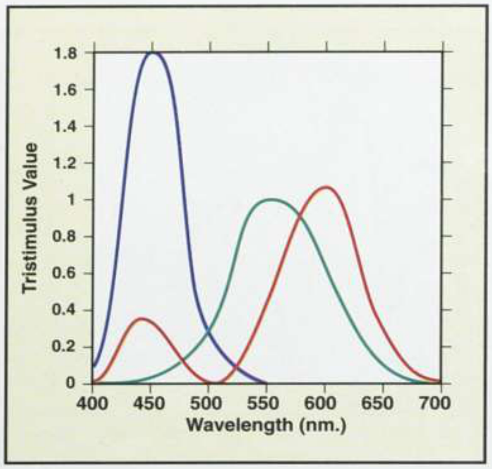

Figure 2. Tristimulus values for the CIE primaries.

cies than similar 633nm emitters. However the luminosity at 633nm is eight times larger than that at 670nm. Thus, for equal visibility to the human eye, the 670nm emitter would require eight times the output power of the 633nm device. Perhaps the extra difficulty required for the 633nm emitter is worth the trouble and expense.

The Chromaticity Diagram

The foundation of colorimetry, the chromaticity diagram, relies on the tristimulus values to designate colors. The chromaticity of a light source is specified by the normalized tristimulus values, or percentages of each CIE primary, that is used for the color match. Since the sum of the three percentages always adds to 100%, only two of the percentages need to be given - the third is fixed once the first two are known. Primary x's percentage, *x*, and primary y's percentage, *y*, are expressed in terms of the tristimulus values as:

$$x = \frac{\bar{x}}{\bar{x}+\bar{y}+\bar{z}} \quad \text{and} \quad y = \frac{\bar{y}}{\bar{x}+\bar{y}+\bar{z}}$$

The chromaticity diagram locates all colors on a set of axes depicting the two normalized tristimulus values, x and y (Figure 3). The pure, monochromatic colors are located on the arc of the chromaticity diagram. The straight line connecting the long wavelength (red) end of the pure color arc with the short wavelength (violet) end is the purple line. All real colors are represented inside the area bounded by the pure color arc and the purple line. White is in the center. A particular sample of light with a known dependence of intensity on wavelength, I(λ), is located on the chromaticity diagram by first determining the tristimulus values. The tristimulus values are the weighed average of I(λ), where the weighting functions are the curves of Figure 2. The tristimulus values are used to compute the chromaticity diagram coordinates, x and y, as indicated in the equations above. Colors near the white point are pale, or in colorimetry language, unsaturated. Colors out near the pure color arc or the purple line are rich, or saturated. Quantitatively, the saturation of a color is computed by dividing the length of a line from white to the color by the length of the line from white through the color to the pure color arc. The point of the intersection of the latter line with the pure color arc determines the dominant wavelength. Two pure colors on the arc that are connected via a straight line through the white point can produce white, when mixed in the proper ratio of intensities, and are termed complementary. For example, 494nm (violet) and 670nm (red) are complementary wavelengths, as are 474nm (blue) and 575nm (yellow). Wavelengths in the range between 492nm and 568nm (greens and some yellows) have no complementary wavelengths, since a line from one of these wavelengths on the pure color arc, through the white point, does not intersect other side of the arc. In order to get white from a green-containing mixture, at least two other wavelengths are needed. This, of course, is commonly done with the red, green and blue dots on a color television screen. The three colored dots on television screens are usually located on the chomaticity diagram just inside the pure color arc near the avelengths, 615, 540 and 470nm. The triangle formed by connecting these three points encloses all the possible colors that can be created by on a TV screen. Since this triangle does not cover the whole area inside the pure color arc and the purple line, a TV cannot create all possible colors. In particular, televisions cannot match any of the pure colors. Rainbows do not do well on TV. In order to maximize the range of colors produced by hree color displays like TV screens and flat panel liquid crystal or LED isplays, moving the green primary to the range around 515 - 520nm would be helpful.

Anomalous Color Vision

Color matching tests performed on most people produce very similar results, giving rise to the three-primary scheme discussed above. This type of vision is called normal trichromatism. A small segment of the population has anomalous color vision. Many people with anomalous color vision require only two primaries to match any given test color. This type of color perception is called dichromatism. Dichromatism is caused by the absence of one of the three types of cone responses. There are three types of dichromatism corresponding to the absences of the response of the red, green or blue cones. The absences of the red or blue response are equally prevalent, each occurring in about one per cent of the male population. The absence of the green response is very rare, occuring in less than a one hundredth of a per cent of the population. The absence of the responses of two cones results in the need for only one color to match any test color, a condition known as monochromatism. Monochromats essentially only match by shades of gray. Dichromatism exists in a few per cent of the male population, but only in one half of one per cent of the female population. It is estimated that monochromatism exists in less than a one hundredth of a per cent of the population. Over 90 per cent of the population has normal color vision; colorimetry is designed for them.

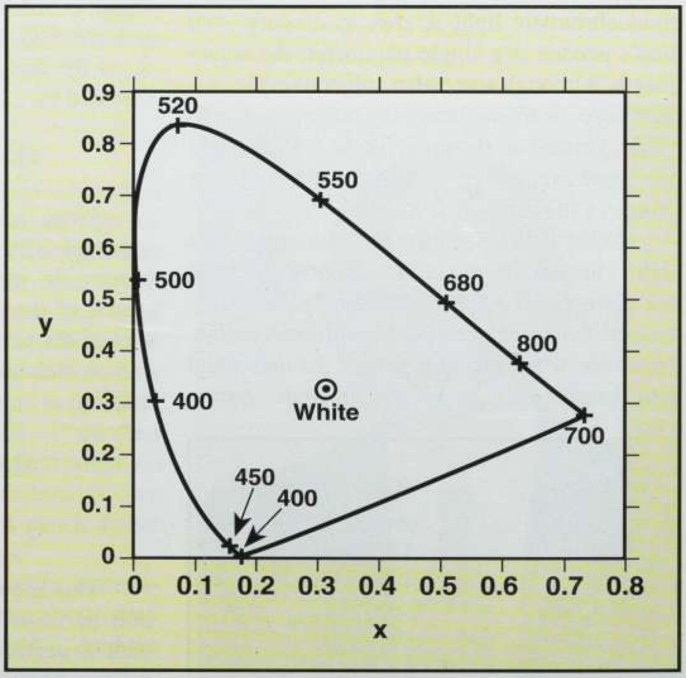

Figure 3. CIE Chromaticity diagram. The wavelengths in nm. of the pure, or monochromatic, colors are indicated on the arc. White light is located near the center of the diagram.

TopoMetrix Announces New Scanning Thermal Microscope

TopoMetrix Corporation [Santa Clara, CA] has announced a scanning thermal microscope (SThM) probe which measures the thermal conductivity and surface temperature of samples with nanoscale spatial resolution. Topographic and thermal images can be obtained simultaneously. TopoMetrix reports that a major application is failure analysis of microelectronics. For example, hot spots on an integrated circuit may due to metal trace defects or voiding due to electromigration or resistive shorts - which can be determined using this instrument. The photo at right shows a SThM image of an energized IC, wherein current flowing through one conductor caused resistive heating, which appears dark in the image. ***Circle 19 on Reader Service Card.***

Variable Temperature UHV STM from Omicron

Omicron Vakuumphysik GmbH [Taunusstein, Germany] recently introduced a novel Variable Temperature UHV Scanning Tunneling Microscope (VT STM) allowing atomically resolved imaging of materials at temperatures between 50 and 1100 K. The VT STM design concept combines minimized heat dissipation and thermal drift with spring suspension vibration isolation resulting in continuous scanning capability, even during temperature variations over the full temperature range. Standard features include in-situ sample exchange, remote controlled tip exchange, and 3-D tip coarse positioning (x/y: 5x5mm^2). Omicron believes that this instrument opens a new area of material research of dynamic processes including structural phase transitions, migration, segregation, growth and many other applications where direct, continuous atomic level observation over a wide temperature range is of interest. ***Circle 124 on Reader Service Card.***

New ECR Source from Wavemat

Wavemat, Inc. [Plymouth, MI] has introduced the MPDR 6101 Electron Cyclotron Resonance (ECR) microwave plasma source. This advanced ECR plasma source generates a stream of ions, atomic neutrals, and activated species for use in MBE or other UHV thin film processes. The new MPDR 6101 employs a computer-designed permanent magnet array that maximizes the electron confinement inside the source's plasma chamber, which both increases the source performance and allows it to operate at lower pressures. The new MPDR 6101 can produce ion current densities in the 0-1.5 mA/cm^2 range on nearly any gas without the use of grids, filaments, or electrodes. The source's ion energy, which has been kept very low to avoid damage to delicate compound semiconductor materials, typically ranges from 10 to 30 eV. Operating range is from 10^{-5} to 10^{-2} Torr. The MPDR 6101 is UHV-compatible, and can be installed into most commercial MBE, gas-source MBE (GSMBE), metal-organic MBE (MOMBE), and many UHV deposition systems. Several of these plasma sources are already in place at key customer sites in North America, Europe, and the Pacific Rim. Applications include growth of Group III/nitride films such as GaN, nitrogen doping of II-VI devices, low-energy plasma cleaning, and plasma-assisted UHV sputtering. ***Circle 56 on Reader Service Card.***

New RF Cracker for Solid Source Materials from Oxford

Oxford Applied Research [Oxford, UK] has announced a new instrument for solid source MBE which produces atomic species from normally polymeric evaporants. In the new model RFK30 an effusion cell section has been combined with the RF cracking zone used in Oxford Applied Research's gas crackers, to allow evaporation of solid source materials such as As, S, Se and P, whose vapor is subsequently cracked to atomic species by the RF plasma. As a result, improved sticking coefficients/solubility can be expected, given the enhanced reactivity of atomic species. The company reports that the results of As doping of II-VI materials using this instrument will be presented at the International II-VI Conference in Edinburgh this August. ***Circle 27 on Reader Service Card.***

Praxair Offers Higher Purity Semiconductor Gases

Praxair, Inc. [Danbury, CT] has announced a new grade of higher purity silane, nitrogen, helium, hydrogen and argon for semiconductor manufacturing. The new grade, called GigaPlus™, raises the highest purity standard available from Praxair to 99.9999%. Previously, the highest grade offered by Praxair was 99.999%. ***Circle 175 on Reader Service Card.***

New Ellipsometry Package, Easier to Retrofit to MBE Systems

The J.A. Woollam Company [Lincoln, NE] has reported an improved method implementing spectroscopic ellipsometry onto existing MBE systems. Ellipsometry is a potentially powerful in-situ growth control technique, but its application to MBE has been hampered by the need for specialized ports. Woollam, working with SVT Associates [Eden Prairie, MN] has developed a patented method of combing RHEED and ellipsometry onto the same ports so that both techniques can be used on systems which are currently equipped only for RHEED. This new "M-44 RHEED" package will be manufactured by SVT Associates and sold and supported by Woollam, which also offers a 44 wavelength length spectroscopic ellipsometry system. ***Circle 91 on Reader Service Card.***

Characterization Software from IPS

Integrated Photonic Systems, Inc. [Clarksburg, NJ] has released two new software products. The first is "Heterostructures for Windows", which is used to calculate quantum energies and wavefunctions in quantum wells and heterostructures. The program uses non-parabolic band models, and calculates intersubband dipoles. Also available is "Multil for Windows", which is used to calculate field distributions in propagation through layered semiconductors. A direct interface is provide between the two packages. ***Circle 38 on Reader Service Card.***

Bio-Rad Release New Software for 2DEG

Bio-Rad Microscience, Ltd. [Hempel Hempstead, Herts., UK] have announced the release of a new multilayer transport analysis software package, MULTAN, which allows selective determination of the carrier density and mobility of each of the layers including the 2D electron or hole gas in HEMT structures. This information is easily derived from the magnetic field dependent resistivity and Hall coefficient over a field range of up to 1 Tesla. Analysis may be performed at multiple temperatures with outstanding resolution. The software runs on a standard PC under Windows™. Bio-Rad also plans to introduce a Variable-Field Hall System, the HL5600, designed to complement MULTAN. ***Circle 100 on Reader Service Card..***

New Process Control Software

EpiSoft [Sambourne, Warks., UK],a company specializing in process control over MBE and other advanced deposition systems, have introduced a new release of their EpiSoft Process Information Center (EPIC) software and modular hardware interface system. The new release emphasizes automation, including: automated source calibration (for example, using the ion gauge flux monitor); automated control over complex loop systems, such as multiple zone cracker/valved sources, with optional feedback control from the pressure/flux sensor; source and system monitoring and alarms; and automated start-up/preparation of sources to maximize operator use time. EPIC's optional direct temperature source control system provides full PID processing from source thermocouples. Features added in the latest software release include improved could junction compensation, linearization for a range of thermocouple types, and enhanced temperature sensitivity and resolution. ***Circle 5 on Reader Service Card.***

Circle 84 on Reader Service Card.

1995 IEEE MTT-S International Microwave Symposium

Orlando, Florida, May 16-12, 1995, May 8-11, 1995

Wireless communications the focus, big money at stake

ROBERT A. METZGER

54 Sessions
+ 2 Open Forums + 20 Workshops
+ 4 Panel
Discussions
Presentations: 400
Attendance: 5000+
Vendors: 490
Theme: "Microwaves on the Move"

Living up to its theme, microwaves certainly were on the move at the 1995 MTT-S International Microwave Symposium - to be exact, moving some 10,350 km above the surface of the earth. The keynote plenary session was given by Roger Rusch of TRW, Deputy Managing Director for the TRW Odyssey Services Organization. He described the proposed Odyssey satellite based cellular communications system which is scheduled to be operational by 1999, which will consist of up to 12 satellites in Medium Earth Orbit, coupled with 8 ground stations - offering total global coverage. Odyssey is projected to provide cellular phone services for 5 million customers at costs ranging from $0.50-1.00 per minute. The system is designed to mesh with existing ground based cell systems, so that satellite communication will automatically take over when a customer leaves an area which is serviced by ground based cell service.

Rusch estimates that there are currently 52 million cellular phones world-wide, with 23 million of those in the US. He further estimates that there will be 150 million cell phones by the year 2000 and 260 million by the year 2005. Of course, he hopes that Odyssey and TRW will capture a significant portion of those many hundreds of millions of customers, but he pointed out that satellite based cellular communications systems will be a highly competitive business, with many companies already competing for this potentially massive market. These companies include Motorola with the Iridium system which will use 66 satellites in a low earth orbit (LEO) of 740 km, Loral and Qualcomm offering GlobalStar which will use 48 satellites in LEO at 1390 km, and Hughes Spaceway system which will require 8 satellites in geosynchronous orbit. More than half a dozen other companies are queuing up at the launch pad hoping to get a piece of this market, including Bill Gates of Microsoft, who has proposed a system which would require an astonishing 840 satellites. What makes even considering these multi-billion dollar satellite systems economically feasible, are the large potential revenues that cellular services represent. John Day, of Strategies Unlimited (Mountain View, CA), presented a market overview at the Power Devices and MMICs for Wireless and Military Applications MTT workshop, in which he estimated that the 1995 service revenues for US cellular phones would be $20 billion, and are growing at an annual rate of 42%. Those large annual revenues have required a ground-based cumulative capital investment of some $30 billion. Numbers of this magnitude make the cost of multi-billion dollar satellite systems seem not all that unreasonable. At this point it is not clear which, if any, of these companies will be the winners in the satellite based cellular communications battle. But regardless of who wins in earth orbit, those satellite systems will be useless without supporting hardware back on earth - i.e. cellular phones - several 100 million of them in the next ten years.

Wireless

Appropriately, many of the MTT presentations focused on wireless communication systems. The basic RF IC components required for cellular phones operating in the 800 to 1900 MHz range can be broken down into four distinct categories: RF switches, Low Noise Amplifiers (LNAs), Mixers and Power Amplifiers. On both the research and production front, the basic drive for improvement in all these ICs focuses on a reduction in power consumption, which translates into longer battery lifetimes and therefore longer intervals between recharging - features that the consumer demands. Reduction in power consumption can also lead to smaller, lighter batteries - where at the moment, batteries are a significant weight and volume component of cellular phones. Of all the various ICs used in the cellular phones, the largest power consumption takes place in the power amplifier.

What device should be used in the power amplifier in order to reduce power consumption, while at the same time maintaining or even improving performance, and of course, offering the lowest possible cost? Should it be a HEMT, HBT, MESFET, Si Bipolar, SiGe

Bipolar, MOSFET, or NMOS? After a week's stay at MTT I can answer that question quite simply.

The answer is yes - all of them.

Attending 10 different presentations, I heard 20 different schemes for obtaining the best power amplifier. It soon became obvious that there was no single solution. Each system, each circuit, each frequency of operation, has different requirements and characteristics, making any of those devices the best for a certain set of circumstances. However, Mike Golio of Motorola (Tempe, AZ), presented some generalizations-observations that are useful when considering what devices might go into a cell phone power amplifier:

1. A single polarity power supply is preferred. This puts both D-mode MESFETs and HEMTs at a disadvantage since they require both positive and negative polarity power supplies. Golio estimates that dual polarity power supplies add a $2/unit cost and increase battery drain. E-Mode MESFETs and HEMTs, along with Si-Bipolars, RF MOSFETs and III-V HBTs require only a single power supply.

2. The f_t and f_{max} of the device are irrelevant. Cell phone operating frequencies do not exceed 2 GHz, which is some one to two orders of magnitude lower than the f_t and f_{max}- values of most of these devices. This means that the intrinsic speed of all these devices is not a rate limiter in performance.

3. High efficiency is essential, where efficiency is benchmarked as the Power Added Efficiency (PAE) - defined as the RF to DC conversion ratio. Golio reports that over the last five years PAEs of 800 MHz devices operating at powers > 3W have improved from 30% to 70%. Golio feels that this high efficiency requirement favors III-V devices over Si-based devices. It is interesting to note that at this conference that M. Versleijen of the Philips Research Laboratories (Eindhoven, The Netherlands), reported a PAE of 60% and power gain of 14 dB for a Si-Bipolar operating at 1.8 GHz with a 3.5 V power supply - these outstanding results illustrating just how difficult it is to even make generalities. Golio notes that III-V HBTs, and E-mode MESFETs and HEMTs all provide high PAEs

4. In any commercial product, cost is a primary driver. This favors Si-based devices above all other III-V competitors.

Even these generalities are not internally consistent, often conflicting with each other, reflective of the fact that there is no single optimum approach or solution in the quest of the ultimate cell phone. What was obvious from attending the MTT was that rapid progress is being made on all fronts in the cell phone arena, from satellite systems to cell phone ICs - all of this progress driven by the huge revenues already being generated in the wireless communications market. The approaches are varied and the solutions even more varied. The theme of this years MTT certainly held true throughout the conference - Microwaves on the Move - where in the case of cell phones, they were moving in a multitude of directions, attempting a multitude of approaches and arriving at a multitude of solutions.

1995 GaAs IC Symposium

The 1995 GaAs Integrated Circuit Symposium will be held October 29 through November 1, 1995 at the Sheraton Harbor Island Resort in San Diego, CA. It is jointly sponsored by the EDS and MTT, and over past 17 years has been the preeminent international forum on the most recent advancements in integrated circuits using GaAs, InP, and other compound semiconductor devices. Coverage embraces all aspects of the technology including materials issues, device fabrication, IC design and testing, volume manufacturing, and systems implementation.

Based on the history of the Symposium, it is anticipated that over 70 technical papers will be selected from world-wide submissions for oral presentation and publication in the Symposium Digest. In addition, there will be several invited papers and panel sessions on a wide range of topics of interest to the GaAs supplier and customer community.

Of special interest is this years Short Course covering the application and design of GaAs MMIC's for use in cellular telephone systems. This short course will cover the application of GaAs MESFET's, PHEMT's, and HBT's to hand held cellular telephones as well as cellular base station switching systems. The short course will be held all day Sunday, October 29th preceding the conference. Organizer: Phil Wallace, Anadigics. Phone : (908) 412-5987, FAX: (908) 412-5985, or email: wallacepw@aol.com.

For those new to the GaAs industry, the Symposium will again offer the popular primer short course, "Basics of GaAs IC's", which is an introductory-level class intended for those with little or no experience in GaAs IC's. The Sunday evening course will cover materials and processes, device operation, and both analog/microwave as well as digital IC's. The course is tailored to provide the specific background needed for participants to understand and appreciate the papers presented in the Symposium Technical Program.

Attendees will have the opportunity to talk and visit with CAD tool, material, process equipment, and device suppliers at the vendor exhibition which is held on Monday and Tuesday in conjunction with the conference. In addition, there will be vendor product forums where the latest GaAs RF and telecommunication IC product offerings will be announced.

San Diego offers a wonderful setting for this years conference. The Sheraton Harbor Island Resort is just minutes from the San Diego International Airport providing attendees easy access to and from the conference. Attendees should plan on spending some extra time to enjoy the many activities San Diego has to offer, such as the world renowned San Diego Zoo, Sea World, or a simple afternoon at the beach.

For further information on the Symposium content please contact Ellisa Sobolewski, Advanced Research Projects Agency. Phone: (703) 696-2254, FAX: (703) 696-2203, or email: lsobolewski@arpa.mil.

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US Conference on GaAs Manufacturing Technology MANTECH 1995

New Orleans, Louisiana May 8-11, 1995

Progress in reducing costs reported; need for future reductions forseen.

ROBERT A. METZGER

Single Continuous Session + Interactive Forum

Presentations: 49
Attendance: 135 Vendors: 15
Theme: GaAs Solutions - Concept to Application At An Affordable Cost

The old joke goes that the three most important considerations when buying real estate are: location, location and location. In a similar vein, the 10th GaAs MANTECH conference left the impression that the three most important considerations for GaAs manufacturing technology are: cost, cost and cost. This theme was set by Jim DiLorenzo of Raytheon (Andover, MA) in his keynote address - "GaAs Solutions - An Affordable Reality". DiLorenzo described Raytheon's flexible manufacturing line, which has the ability to adapt a set, or subset, of the process steps involved in making GaAs MMICs, and then tailoring the process toward a particular product or set of products. Raytheon's single manufacturing line can be used to fabricate PHEMTs, multifunction circuits (digital circuits combined with microwave FETs), along with ion implanted power MMICs and low noise products. He showed that by coupling this flexible manufacturing approach with increasing GaAs substrate diameter the relative cost/mm^2 of fabricated circuits has been reduced by an order of magnitude since 1990, while production has increased by a factor of 30. Increasing substrate size has been critical to this cost reduction. During 1993-1994 Raytheon shifted from 3" to 4", which reduced cost/mm^2 by a factor of two. In a similar manner, Bill Hitchens of Watkins Johnson Company (Palo Alto, CA) described that going from 2" to 3" improved wafer yield from 50 to 75%, so that when the increased area of the 3" wafer was taken into account, the absolute device yield increased by a factor of 4. The US government is becoming a key player in increasing GaAs wafer size, not only because it wants to ensure a domestic source of GaAs, but also because it understands that increasing wafer size increases the total number of yielded devices, which in turn decreases chip costs in DOD systems. John Blevins of Wright Patterson AFB (OH) described the $30 million Title III program "GaAs Wafer Project" which is funding Litton/Airtron, AXT and M/A-COM in establishing not only a production worthy domestic source of 4" GaAs substrates, but also initial production of 6" GaAs.

Testing

As GaAs manufacturing technology matures and processes become more established, the devices and circuits that are being fabricated are becoming more complex, and the transistor count and number of functions per circuit are increasing. As a result, the cost of test and packaging is beginning to exceed fabrication costs. DiLorenzo notes that when 100% RF testing is done on the chip level, the resulting MMIC related performance failures at the module level are less than 3%. Accordingly, 100% RF testing of wafers is now common before insertion into T/R (transmit/receive) modules. Elissa Sobolewski of ARPA (Arlington, VA) gave a review of the Microwave and Millimeter Wave Monolithic Integrated Circuits (MIMIC) program which included a description of a 75-100 GHz on-wafer probe system developed by Cascade Microtech under this program. Equally important is the time required to test the chips. DiLorenzo says that in 1988, using standard commercial test equipment, complete parametric testing of a T/R module at one temperature (many different temperatures are required) took 40 minutes. In 1995, that time has been reduced to 1 minute. In a similar manner, testing of less complex single chips has been reduced from 30 seconds down to 3-5 seconds. Along with reduction in testing costs, remarkable reduction in packaging costs have also been seen. Since 1990, DiLorenzo says that packaging costs for Ku band devices have been reduced from $5-10 to only $0.21.

All these cost reductions and yield enhancements have had direct impact on the cost of phased array radars, a major application for many of these circuits. These nose-cone, jet aircraft, radars, typically consist of 1000-2000 array elements, each of which require a T/R module. According to West Katzenstein of the Naval Air Warfare Center Weapons Division (China Lake, CA), in 1985, X-band hybrid modules cost $10,000 per element, while X-band MMIC modules manufactured in 1993 had seen costs reduced to $2,000 per element. This cost reduction resulted in a 1000 element radar array costing $2 million - a significant reduction, but a price that the DOD wanted to further reduce. Frank Lamb of the Solid State Electronics Directorate of Wright Laboratories, WPAFB (OH) described the government's High Density Microwave Packaging (HDMP) program, which is scheduled to be completed in 1997 and has as its goals to see T/R module costs reduced to $200 per element, while at the same time seeing module volumes reduced by a factor of 5. Three teams consisting of:

1) Texas Instruments/Martin Marietta/GE
2) Westinghouse/TRW/ IBM/MCNC and
3) Hughes Aircraft

are pursing these goals. Tom Midford of Hughes (Torrance, CA) reported that current T/R modules have already dropped to $1000.

Larger wafer sizes, increases in production volume, and 100% RF testing, have all led to reduction in the cost of complex MMIC systems and modules. Based on the presentations given at this conference, there is hope that these cost reductions will continue, thereby opening up more and more cost-sensitive applications for GaAs MMICs, which in turn further expand the market and decrease costs.

5th Int'l Conf. on Chemical Beam Epitaxy and Related Growth Techniques

ICCBE-5 will be held August 14-16, 1995 in La Jolla, CA, USA. This conference covers the entire spectrum of CBE, metal-organic molecular beam epitaxy (MOMBE), gas-source MBE, and other related techniques.
Proceedings: Journal of Crystal Growth
Deadlines: Abstracts - passed Late News - July 31, 1995
Contact: Prof. Cammy Abernathy, ICCBE-5 Program Chair
University of Florida, Dept. of Materials Science
Gainesville, FL 32611 USA
TEL [1] 904 846 1087 FAX [1] 904 846 1182
E mail caber@mse.ufl.edu
Vendor Exhibit? Yes - contact: Lene Hartman
UCSD, Conference Services
La Jolla, CA 92093-0513 USA
TEL [1] 619 534 4220 FAX [1] 619 534 2042
E mail anita_sorgenfrey@housing.ucsd.edu

7th Int'l Conf. on II-VI Compounds & Devices

II-VI '95 will be held Aug 13-18, 1995 in Edinburgh, Scotland. This conference covers II-VI semiconductors, growth, electrical and optical properties, spectroscopy, devices, surfaces and contacts.
Proceedings: Journal of Crystal Growth
Abstract Submission Deadline: passed.
Contact: Dr. K.A. Prior
Herriot-Watt University, Physics Dept.
Edinburgh, Scotland
TEL [44] 131 451 3035 FAX [44] 131 451 3088
E mail phykap@clust.hw.ac.uk
Vendor Exhibit? Yes - contact: Dr. A.K. Kar
Herriot-Watt University, Physics Dept.
Edinburgh, Scotland
TEL [44]131 451 3049 FAX [44] 131 451 3136
E mail phyakk@clust.hw.ac.uk

3rd Int'l Conf. on the Applications of Diamond Films and Related Materials

ADC '95 will be held Aug. 21-24, 1995 at Gaithersburg, MD, USA. The objective of this biennial, international conference is to allow manufacturers and end-users to interact with scientific researchers for the purpose of devising research strategies and identifyıng technical barriers hindering the large-scale commercial applications of diamond and related materials.
Proceedings: Provided at the meeting
Abstract Submission Deadline: passed.
Contact: Albert Feldman, chairman, ADC '95
National Institute of Standards and Technology
Room A329, Bldg. 223,
Gaithersburg, MD 20899-0001 USA
TEL 1 301 975 5740 FAX 1 301 990 8729
E mail feldman@micf.nist.gov
Vendor Exhibit? No

22nd Int'l Symp. on Compound Semiconductors

ISCS-22 will be held Aug 28-Sept. 2, 1995 at Cheju Island, Korea. This conference is a premier forum on all aspects of compound semiconductors, including growth, processing, devices, and ICs. Materials covered include GaAs InP, GaN, ZnSe and SiC etc.
Proceedings: IOP Publishing
Abstract Submission Deadline: passed.
Contact: Prof. Jong-Chun Woo, Chair, Program Committee
ISCS-22, 4th Fl, Jisung Bldg.,
645-20 Yoksam-Dong
Kangnam-Ku, Seoul 135-081 Korea
TEL [82] 2 889 5049 FAX [82] 2 871 7505
Vendor Exhibit? Yes - contact: Prof. Young Se Kwon
ISCS-22, 4th Fl, Jisung Bldg.,
645-20 Yoksam-Dong
Kangnam-Ku, Seoul 135-081 Korea
TEL [82] 42 869 3421 FAX [82] 42 869 8021

Gettering and Defect Engineering in Semiconductor Technology

GADEST '95 will be held September 2-7 at Parkhotel Schlop Wulkow, near Berlin, Germany. The subject matter of this conference is the intensive exchange of opinions between physicists and engineers, regarding fundamental aspects as well as technological problems of semiconductor electronics.
Proceedings: Transtech Publications Zurich
Abstract Submission Deadline: passed.
Contact: Dr. Hans Richter
Institut fur Halbleiter Physik Frankfurt (Oder)
PSF 409, Frankfurt D-15204 Germany
TEL [49] 335 373 128 FAX [49] 335 326 195
Vendor Exhibit? No

15th European Conf. on Surface Science

ECOSS15 will be held Sept. 4-8, 1995 at Lille, France. It will cover all experimental and theoretical fields related to the physics and chemistry of surfaces and interfaces.
Proceedings: Surface Science
Abstract Submission Deadline: Passed
Contacts: Dr. Guy Allan
IEMN-ISEN, BP 69,
F-59652 Villeneuve Diasco Cedex, France
TEL [33] 20 19 78 13 FAX [33] 20 19 78 84
E mail ecoss15@isen.fr
Vendor Exhibit? Yes - contact: Dr. X. Wallart
IEMN-ISEN, BP 69,
F-59652 Villeneuve Diasco Cedex, France
TEL [33] 20 19 78 57 FAX [33] 20 19 78 84
E mail ecoss15@isen.fr

25th European Microwave Conf.

The 25th EuMC will be held Sept. 4-7, 1995 at Bologna, Italy - marking the 100th anniversary of the first radiowave transmission experiments made by Guglielmo Marconi at the Villa Griffone, near Bologna. The conference's goal is to allow participants to investigate and verify new research and development trends in the field of microwaves.
Proceedings: Nexus Media, Ltd.
Abstract Submission Deadline: Passed
Contacts: Gillian Shinar, Conference Co-ordinator
Nexus Information Technology
Nexus House, Swanley, Kent BR8 8HY, UK
TEL [44] 1322 660 070 FAX [44] 1322 661 257
Vendor Exhibit? Yes - contact Beverly Lucas
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Nexus House, Swanley, Kent BR8 8HY, UK
TEL [44] 1322 660 070 FAX [44] 1322 661 257

15th North American Conference on Molecular Beam Epitaxy

The 15th NAMBE Conference will be held Sept. 17-20, 1995 at College Park, Maryland. This conference encourages presentations on all aspects of molecular beam epitaxy.
Proceedings: J. Vac. Sci. Techn. B
Abstract Submission Deadline: Passed
Contact: Prof. Colin E.C. Wood, Conf. Chair
Univ. of Maryland, Lab for Physical Sciences
8050 Greenmead Drive,
College Park, MD 20740 USA
TEL [1] 301 935 6473 FAX [1] 301 935 6723
E mail colin@lps.umd.edu
Vendor Exhibit? Yes - contact: Jennifer Moore,
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Annapolis Hall, College Park,
MD 20742-9122 USA
TEL [1] 301 314 7885 FAX [1] 301 314 6693
E mail jmoore2@umdacc.umd.edu

Int'l Conf. on SiC & Related Materials

ICSCRM-95 will be held Sept. 18-21, 1995 at Kyoto, Japan. The subject mater for this conference is SiC, III-V nitrides, and other materials, in the following areas: 1) Fundamental Physics 2) Bulk Crystal Growth & Epitaxial Growth 3) Amorphous & Polycrystalline Films 4) Control of Material Properties & Characterization 5) Modification of Surfaces & Interfaces 6) Device Processes & Fabrication 7) Devices, Simulation & Modeling.
Proceedings: IOP Publishing
Deadlines: Abstract - passed. Late News: August 10, 1995.
Contact: Prof. Hiroyuki Matsunani, General Chairman,
Kyoto University, EE Dept.,
Sakyo, Kyoto 606-01 Japan
TEL [81] 75 753 5340 FAX [81] 75 751 1576
E mail matsunam@kuee.kuee.kyoto-u.ac.jp
Vendor Exhibit? Yes - contact: Prof. Shigehiro Nishino
Kyoto Inst. of Tech. , EECS Dept, Gosho-Kaidocho
Matsugasaki, Sakyo, Kyoto, Japan
TEL [81] 75 724 7415 FAX [81] 75 724 7400
E mail nishino@ipc.kit.ac.jp

1995 Topical Workshop on III-V Nitrides

TWN '95 will be held Sept. 22-23, 1995 in Nagoya, Japan, immediately following the 6th International Conference on SiC and Related Materials in nearby Kyoto. The objective of the workshop is to provide a forum in which practitioners of nitrides and related compounds and devices can gather for in-depth technical discussions, encompassing every aspect of GaN and its related materials.
Proceedings: Will be published
Abstract Submission Deadline: Passed
Contact: Dr. Sadafumi Yoshida
Electrotechnical Laboratory,
Quantum Material Section
1-1-4 Umezono, Tsukuba, Ibaraki 305, Japan
TEL [81] 298 54 5222 FAX [81] 298 58 5434
E mail syoshida@qm.etl.go.jp
Vendor Exhibit? no.

Asia-Pacific Microwave Conf.

APMC'95 will be held Oct. 10-13, 1995 at Taejon, Korea. This is an academic conference in the area of microwave electronics. Approx. 270 papers will be presented, together with four tutorials, and exhibition
Proceedings: Will be published by the program committee
Abstract Submission Deadline: passed.
Contact: Prof. Noh-Moon Myang
KAIST, Dept. of Electrical Eng.
Taejon, Korea
TEL [82] 42 869 6417 FAX [82] 42 869 8010
Vendor Exhibit? Yes - contact Prof. Myang

Microwaves and RF 1995

Microwaves and RF '95 will be held Oct. 10-12, 1995 in London, England. This is an international conference of invited presentations addressing topical issues of concern to both commercial and military microwave and RF sectors. One of the special topics for this years meeting is a session on "SiGe vs. GaAs".
Proceedings: Nexus Media, Ltd.
Abstract Submission Deadline: NA
Contacts: Gillian Shinar, Conference Coordinator
Nexus Information Technology
Nexus House, Swanley, Kent BR8 8HY, UK
TEL [44] 1322 660 070 FAX [44] 1322 661 257
Vendor Exhibit? Yes - contact Beverly Lucas
Nexus Information Technology
Nexus House, Swanley, Kent BR8 8HY, UK
TEL [44] 1322 660 070 FAX [44] 1322 661 257

3rd Int'l Symposium on Atomically Controlled Surfaces & Interfaces

ACSI-3 will be held Oct. 12-14, 1995 at Raleigh, NC, USA. This conference's goal is to further, on the atomic scale, our understanding and control of the formation of surfaces, interfaces, nanostructures, etc. through a combination of theory and experiment.

Proceedings: Applied Surface Science
Abstract Submission Deadline: passed.
Contact: Prof. D.E. Aspnes
NC State University, Dept. of Physics
Raleigh, NC 27695-8202 USA
TEL [1] 919 515 4261 FAX [1] 919 515 1333
E mail aspnes@unity@ncsu.edu
Vendor Exhibit? No

42nd American Vacuum Society National Symposium

This year's AVS meeting will be held October 16-20, 1995 at Minneapolis, MN, USA. It will feature 100 technical sessions and 10 poster sessions, presenting over 1000 papers. Areas of interest include electronic materials and processing; vacuum technology and metallurgy; thin films; surface science; plasma science and technology; nanometer-scale science and technology; manufacturing science and technology; biomaterials interfaces; and applied surface science.

Proceedings: J. Vac. Sci. Technol.
Abstract Submission Deadline: passed.
Contact: AVS National Symposium
American Vacuum Society
120 Wall Street
New York, NY 10005-3993 USA
TEL [1] 212 248 0200 FAX [1] 212 248 0245
E mail avsnyc@vacuum.org
Vendor Exhibit? Yes - contact the AVS.

Int'l Union of Materials Research Societies 3rd Int'l Conf. in Asia

IUMRS-ICA-95 will be held Oct. 17-20, 1995 at Seoul, Korea. Its subject matter includes functional materials, structural materials, polymers, materials characterization, and advanced materials for semiconductors.

Proceedings: IUMRS-ICA
Abstract Submission Deadline: passed.
Contact: Prof. Hyeong Joon Kim
Seoul Nat'l Univ., Dept. of Inorganic Matls Engr.
Seoul 151-742, Korea
TEL [82] 2 880 7162 FAX [82] 2 884 1413
Vendor Exhibit? Yes - contact Prof. Hyeong Joon Kim

1995 IEEE GaAs IC Symposium

The 1995 GaAs IC Symposium will be held Oct. 29-Nov. 1 in San Diego, CA, USA. For the past 17 years this conference has been the preeminent international forum on the most recent advancements in integrated circuits using GaAs, InP and other compound semiconductor devices. Subject matter includes all aspects of the technology, including materials, device fabrication, IC design and testing, volume manufacturing, and systems implementation.

Proceedings: IEEE Publishing
Abstract Submission Deadline: passed
Contact: Ellisa Sobolewski
Advanced Research Projects Agency
3701 N. Fairfax Ave.,
Arlington, VA 22203-1714 USA
TEL [1] 703 696 2254 FAX [1] 703 696 2203
E mail lsobolewski@arpa.mil
Vendor Exhibit?: Yes - contact Harry Kuemmerle III
VIP Meetings & Conventions
1515 Palisades Drive, Suite 1
Pacific Palisades, CA 90271 USA
TEL [1] 310 459 4691 FAX [1] 310 459 0605

8h IEEE Lasers and Electro-Optics Society Annual Meeting

LEOS 8 will be held Oct. 30 -Nov. 2, 1995 in San Francisco, CA. This is the annual meeting of the LEOS society, covering a broad spectrum of topics of interest to the laser and electro-optic communities.

Proceedings: IEEE Publishing
Abstract Submission Deadline: passed
Contact: Samantha Phillips, Conf. Manager
IEEE/LEOS
445 Hoes Lane, PO Box 1331,
Piscataway, NJ 08855-1331 USA
TEL [1] 908 562 3894 FAX [1] 908 562 8434
E mail s.phillips@ieee.org
Vendor Exhibit? Yes - contact Samantha Phillips

1995 Fall Meeting of the Materials Research Society

The 1995 MRS Fall Meeting will be held November 27-December 1, 1995 in Boston, MA, USA. This conference includes 30 different symposia on topics ranging from beam-solid interactions and fullerenes to laser processing, GaN, and low-cost manufacturing of materials.

Proceedings: MRS Proceedings Series
Abstract Submission Deadline: passed.
Contact: M. Geil, Dir., Meeting Activities
Materials Research Society
9800 McKnight Road, Pittsburgh, PA 15237 USA
TEL [1] 412 367 3004 FAX [1] 412 367 4373
E mail info@mrs.org
Vendor Exhibit? Yes - contact Mary Kaufold, Exhibit Mgr.
Materials Research Society
9800 McKnight Road, Pittsburgh, PA 15237 USA
TEL [1] 412 367 3036 FAX [1] 412 367 4373
E mail kaufold@mrs.org

1995 Defect Recogniition and Image Processing in Semiconductors

DRIP VI will be held Dec. 3-6, 1995 at Estes Park, CO. This is an international conference devoted to furthering understanding of defect inhomogeneitites in semiconductor materials and devices. Topics include, but are not limited to, 1) optical, electrical, and acoustical substrate defect imaging techniques as applied to semiconductor substrates, epilayers, nanostructures and devices for electronic, optoelectronic and optical applications; 2) techniques for processing the quantities of data coming from automated defect testing methods; and 3) correlation of device performance with defect density and distribution.

Abstract Submission Deadline: Sept. 1, 1995
Contact: Prof. Alan R. Mickelson
University of Colorado, ECE Dept.
Campus Box 425, Boulder, CO 80309-0425 USA
TEL [1] 303 492 7359 FAX [1] 303 492 2758
E mail mickel@boulder.colorado.edu

3rd Int'l Conf. on the Physics of X-Ray Multilayer Structures

The 3rd International Conference on the Physics of X-Ray Multilayer Structures will be held March 3-7, 1996 at Breckenridge, CO, USA. This conference focuses on the interaction of x-ray and extreme ultraviolet radiation with multilayer structures, as well as multilayer growth, structures, and properties

Abstract Submission Deadline: Nov. 10, 1995
Contact: Ms. Marty Benson, Admin. Asst.
Univ. of Arizona, Dept. of Physcis
PAS #81, Tucson, AZ USA 85721
TEL [1] 520 621 2878 FAX [1] 520 621 4356
E mail pxrms-info@nanook.div111.att.com
Vendor Exhibit?: Yes, contact Ms. Marty Benson

1996 Spring Meeting of the Materials Research Society

The 1996 Spring MRS Meeting will be held April 7-11, 1996 in San Francisco, CA, USA. This conference includes 30 different symposia on semiconductor materials and processing, polymers, amorphous silicon, microwave processing, ceramics, and other topics.

Proceedings: MRS Proceedings Series
Abstract Submission Deadline:TBA.
Contact: M. Geil, Dir., Meering Activities
Materials Research Society
9800 McKnight Road, Pittsburgh, PA 15237 USA
TEL [1] 412 367 3004 FAX [1] 412 367 4373
E mail info@mrs.org
Vendor Exhibit? Yes - contact Mary Kaufold, Exhibit Mgr.
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9800 McKnight Road, Pittsburgh, PA 15237 USA
TEL [1] 412 367 3036 FAX [1] 412 367 4373
E mail kaufold@mrs.org

8th Int'l Conf. on MOVPE

ICMOVPE 8 will be held on June 9-13, 1996 in Cardiff, Wales. This conference seeks to bring together specialists in growth, characterization and device applications of MOVPE and to present a forum for discussion of recent progress and the latest achievements in the field of both fundamental and applied research. Topic area include: precursors; process design/communication issues; developing applications of MO compounds; growth technologies; advances in devices by MOVPE; and characterization.

Proceedings: Journal of Crystal Growth
Deadlines: Abstracts - December 1, 1995
Late news - On-site, June 9
Contact: Glenda Bland
Global Meeting Planning, GMP 22 Plas Taliesin
Portway Village Marina, Penarth,
South Glamorgan CF64 1TN, Wales
TEL [44] 1222 700 053 FAX [44] 1222 700 685
E mail 100416.1402@compuserve.com
Vendor Exhibit? Yes - contact Prof. Colin Whitehouse
Univ. of Sheffield, EE Dept.
Mappin Street, Sheffield, S1 4DU UK
TEL [44] 1142 825 254 FAX [44] 1142 726 391

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

* Full name of conference, plus acronym or abbreviation
* Dates and location
* Brief description of content, focus, or goals
* Whether the proceedings will be published, and, if so, in what journal
* Abstract submission and late news deadlines
* Primary contact name, address, phone, FAX and E mail
* Whether there will be a vendor exhibit, and, if so, contact name, address, phone, FAX and E mail

Contributions must be received by August 4 to appear in our next issue.

Wide Bandgap LED Overview

M. George Craford, R&D Manager
Hewlett-Packard Optoelectronic Division
San Jose, CA

Research in the area of wide bandgap emitters has been increasing for the past several years. This work was first focused primarily in the area of II-VI emitters, following the first demonstration of a blue-green ZnSe based injection laser diode in June 1991 by a group at the 3M company. In late 1993 Nichia Chemical company introduced a high performance GaN blue LED which caused many researchers and companies to begin efforts in the GaN materials system. Both materials systems continue to be intensively studied, although in the United States and Europe the majority of the work appears to be focused on the nitrides whereas in Japan more work appears to be continuing in the II-VI materials area.

The market potential for wide bandgap LED's is large. Visible LED sales already exceed a billion dollars per year and the market is expected to grow rapidly with the emergence of a variety of applications in areas enabled by high performance devices. AlInGaP red, orange and yellow devices introduced in recent years have luminous efficiencies higher than incandescent lamps and are finding applications such as exterior vehicle lighting and highway signs. Improved blue, blue-green and hopefully green LED's will complete the color spectrum, enabling applications such as traffic signals, large area full color outdoor signs, and more efficient LCD back lighting. By mixing red, green and blue LED's efficient white solid state light sources should become available which could compete for some low power lighting applications.

Reliability may be the key factor in determining which material system dominates for LED applications. LED packaging typically requires the semiconductor chip to be mounted on a lead frame and encapsulated in epoxy. For outdoor applications, the device will be expected to withstand a variety of tests including temperature cycling, and high and low temperature operation aimed at ensuring that in outdoor environments the devices will operate with less than 50% degradation for tens of thousands of hours. The semiconductor chip experiences stress due to the epoxy encapsulation and, at low temperature can even be fractured if the packaging is not optimized. It is generally found that substantially more effort is required to make reliable devices which meet customer expectations than to make devices which are bright enough initially. High speed die attach and wire bonding are additional process steps which can easily damage the semiconductor chip.

The nitride system is harder and more robust than the selenide system. Devices with acceptable brightness in the blue and blue-green spectral regions are already available commercially with adequate reliability for some applications and it appears likely that the reliability will continue to improve so that the more stringent requirements can be met. High performance green and blue II-VI LED's have been demonstrated by a research group at North Carolina State University. However, nothing approaching commercially viable reliability has been demonstrated and it remains to be determined whether it will be achievable given the relative ease with which defects are created and move in these materials. Even if acceptable reliability can be demonstrated on a research scale it could be a formidable challenge to maintain this reliability in a low cost high volume production environment. Thus, it is probable that the nitride system will be the choice for blue and blue-green LED's, but "true" green LED's may be more difficult to obtain because growing GaInN with sufficiently high indium concentration to make green has not been demonstrated.

The materials for choice for lasers may be different than LED's. At this time, injection lasers have not been demonstrated in the nitrides. Furthermore, lasers are not encapsulated in epoxy, and since lasers are less cost sensitive the assembly process can be slower and possibly less damaging to the chip. Furthermore, burn-in can be used to eliminate defective devices. However, lasers generally operate at substantially higher current densities than LED's which markedly accelerates degradation and would be expected to be a much more severe problem in the selenides than the nitrides.

Dr. Craford is the R&D Manager for Hewlett-Packard's Optoelectronics Division, San Jose, CA. He has been a semiconductor materials researcher, focusing primarily on LED technology since receiving his Ph.D. in physics from the University of Illinois in 1967. He has over 50 patents and publications. Prior to joining HP in 1979, he was Technical Director at Monsanto's Electronics Division. He is a fellow of the IEEE and a member of the National Academy of Engineering.

ICMOVPE VIII

Cardiff'96

8th International Conference on Metalorganic Vapour Phase Epitaxy

9-13 June 1996
Cardiff International Arena
Cardiff, Wales, UK

Topic Areas

Growth Mechanisms
Precursors
Selective Area Epitaxy
III-V's
II-VI's
Nitrides
Oxides

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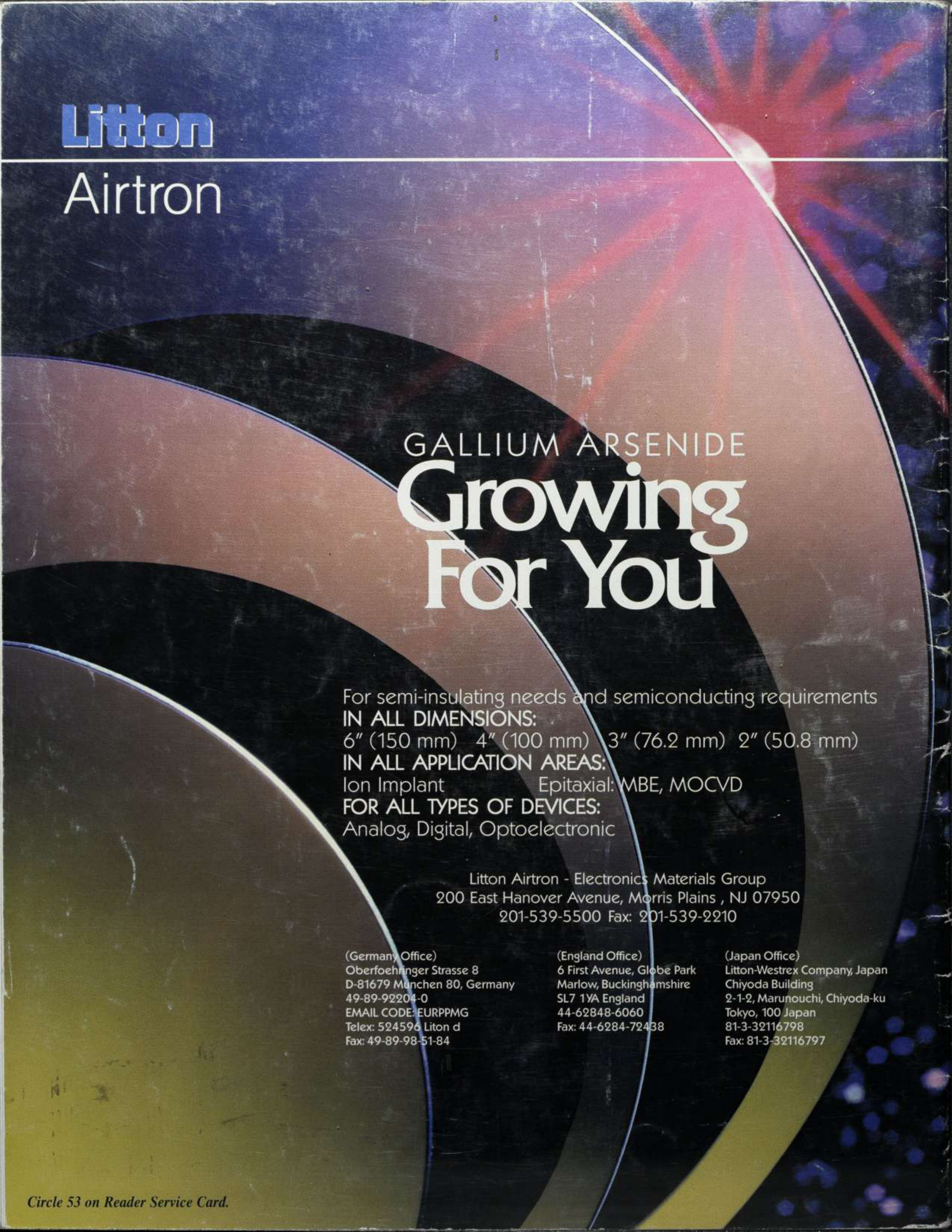
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