



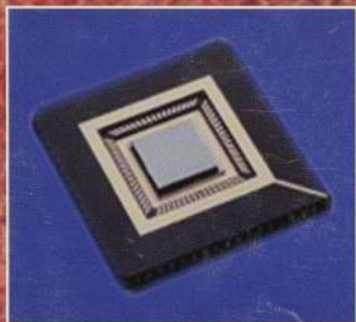
COMPOUND

SEMICONDUCTOR

Spring II - May, 1998

Volume 4 Number 4

Sensors and Detectors



- Focal Plane Arrays
- Magnetic Sensors
- QWIPs

Also in this Issue:

- MESFETs v. HBTs for 3V phones
- Uniphase bolsters its laser diode business
- New HBT foundry opens
- Losses mount at SLI

Includes Directory of Materials Suppliers

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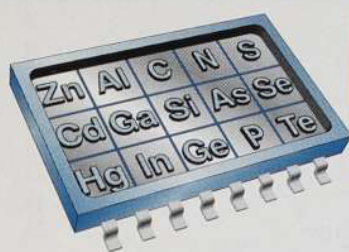
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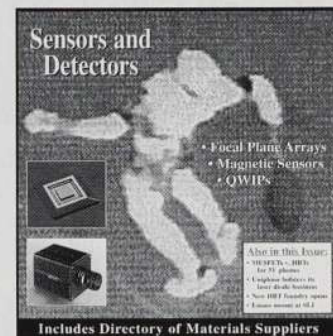
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Infrared imaging has many applications, such as monitoring fatigue in tennis players (background, courtesy Raytheon Systems). Many imaging systems contain focal plane arrays (top left, courtesy Raytheon Systems) which are central components in commercially available cameras (bottom left, courtesy Sensors Unlimited). Coverage begins on page 17.

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Uniphase Bolsters its Laser Diode Business

Opens new facility in Zurich, tenders an offer for Philips Optoelectronics

On March 27 Uniphase Corporation officially opened its new laser diode fab in Zurich, Switzerland. A few weeks later, on April 21, the company announced that it had reached an agreement with Philips Electronics to purchase the latter's Optoelectronics business unit in Eindhoven, The Netherlands. If that deal goes through (it is still subject to regulatory approval), the combined effect of these two events will be to make San Jose, CA-based Uniphase a major supplier of telecomm lasers.

Rolling out the 980nm Pumps

The new facility in Zurich will be home to Uniphase Laser Enterprise (ULE), a business which Uniphase purchased from IBM's prestigious Zurich Research Laboratory in March, 1997 for around \$50 million.

ULE could be considered "the home of the 980nm pump". In the late 1980's researchers at IBM Zurich developed a process (known as "E2") for suppressing facet degradation in AlGaAs lasers. Their work is widely considered to have been the critical breakthrough leading to the commercial acceptance of 980nm-pumped Er-Doped Fiber Amplifiers (EDFAs), which are now used in virtually all terrestrial long-haul fiber installations.

What is less well known is that IBM was not really very interested in this application. They wanted a high-power 850nm AlGaAs diode that could be frequency-doubled to produce a 40 mW blue laser for optical data storage - an area which was much more relevant to IBM's business than a telecommunications component. But IBM's success with high power, long-lived AlGaAs diodes at 850nm attracted the interest of companies developing EDFAs, who requested that the Zurich group make similar lasers operating at 980nm. At the same time, IBM was cutting its research budget.

In response to these factors, the Zurich laser team took the unusual step of forming a business unit within the IBM Research Lab. Their focus was the commercialization of an InGaAs/AlGaAs 980nm laser using the E2 facet formation process. The first commercial E2 pumps were shipped in 1990. To date, more than 100,000 of these lasers have been deployed in telecommunications networks. In addition, at least four other companies - Hewlett-Packard, Pirelli Cable, Lasertron and Nortel - have paid handsomely to license the E2 process from IBM. Nevertheless, Big Blue was never able to reconcile the unit with its overall strategy - hence the sale to Uniphase.

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The new facility has received over \$20 million in investment, much of which is aimed at replacing process tools which had been adapted from the research environment to specialized manufacturing tools designed for high-throughput production. Initial capacity is in excess of 100,000 completed devices per year. A company spokesperson reports that ULE had sales "well in excess of \$20 million" in 1997, capturing ~70% of the 980nm market. ULE forecasts that the market for these lasers will grow to around \$300 million a year by 2001.

Acquiring InP (and More)

Clearly, ULE gives Uniphase a firm footing in GaAs-based laser technology. One of the interesting aspects of the Philips Optoelectronics acquisition is that it would give them access to InP-based laser diode technology as well.

Philips Optoelectronics was, until recently, part of Philips Research. It was split out as separate legal entity just this past February (CS 4(3), p. 7) - possibly as a prelude to this transaction. For the telecommunication market, it offers wavelength-selected lasers for WDM, Fabry-Perot and DFB lasers (some with integrated electro-absorption modulator), as well as 1480 nm pump lasers for use in Yb-Er-doped fiber amplifiers (YEDFAs). For the CATV market, it offers analog lasers, photodiodes, amplifiers, and 1550nm CW lasers for trunk lines.

Uniphase at a Glance

Corporate Headquarters: San Jose, California

1997 Revenues: \$106 million*

Employees: 650*

NASDAQ Symbol: UNPH

**Not including Philips Optoelectronics*

Operations

- **Ultrapointe** (San Jose, California) -- laser-based systems for semiconductor wafer defect examination and analysis.
- **Uniphase Lasers & Fiberoptics** (San Jose, California) -- OEM gas lasers for biotechnology, graphic arts, & semiconductor processing
- **Uniphase Fibreoptics** (Whitney, Oxfordshire, England) -- transmitter products based on LED and laser sources from 635nm to 1550nm and Si & InGaAs receivers
- **UTP Transmission Systems** (Chalfont, Pennsylvania) -- 1500 nm CATV transmitters and amplifiers
- **UTP Electro-Optic Products** (Bloomfield, Connecticut) -- high-speed external modulation transmitters for CATV and long-haul telecommunications
- **Uniphase Fibre Components** (Eveleigh, Australia) -- fibre Bragg gratings for WDM networks
- **Uniphase Laser Enterprise** (Zurich, Switzerland) -- 980nm pump lasers for telecommunications.
- **[Proposed] Philips Optoelectronics** (Eindhoven, The Netherlands) -- 1310nm and 1550nm telecom lasers.

High capacity fiber optic networks require five types of components: semiconductor lasers (1550nm or 1310 nm); modulators (typically lithium niobate for long distances, and integrated electro-absorption modulators for short distances); amplifiers (either EDFAs or semiconductor amplifiers); fiber gratings (to ensure accurate and consistent wavelength spacing); and receivers (typically InGaAs photodiodes). Uniphase is already the market share leader for 980nm pumps and lithium niobate modulators, and the company is establishing production of fiber Bragg gratings. The Philips Optoelectronics product lines will give Uniphase the two missing pieces - source lasers and receivers. In addition, Uniphase will be acquiring a top rank laser research organization consisting of ~50 people, including 20 Ph.Ds.

"With this acquisition, Uniphase takes a major step towards achieving our goal of providing a complete solution to our customers in the telecommunications and CATV industries," said Kevin Kalkhoven, Uniphase Chairman and CEO. "We believe that the business we are acquiring from Philips fits extremely well with Uniphase's existing optoelectronics product lines for the telecommunications and CATV markets. We also believe that Philips Optoelectronics products can provide not only near-term product revenue, but also a number of products under development could represent substantial opportunities for the future. In addition, we are looking forward to a long and mutually rewarding relationship with Philips, which will become a substantial Uniphase stockholder following the closing."

Uniphase says that the unit will continue to operate in Eindhoven. In addition, a new 60,000 square foot semiconductor fabrication facility under construction in Eindhoven would be leased to Uniphase.

The parties hope to close the deal in June, subject to certain regulatory clearances, including worker protection rules in The Netherlands and antitrust laws in the U.S. The terms of the deal were not disclosed.

Vitesse Ships 1st Chips from 6" Fab

Several months ahead of schedule, Vitesse Semiconductor has begun shipping GaAs ICs from its new fab in Colorado Springs, CO. According to President and CEO Lou Tomasetta, around \$1 million in chips were shipped from the new facility in late March, and he is hoping for \$5-6 million in shipments during the current quarter. These are the first commercial products to be produced on 6" GaAs wafers.

Tomasetta predicts that scaling up to 6" will reduce the cost per mm² of their GaAs ICs by up to 40%, once they are in full volume production at the new fab. The company hopes to be running 300 - 400 wafers/week by early summer. Full capacity for the fab in its current configuration is ~750 wafers; it can also be expanded to around 1500 wafers/week.

Vitesse will continue to operate its 4" GaAs fab at its headquarters in Camarillo, CA.

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New GaAs HBT Fab Starts Production

A new company, Excellence In Communications (EiC) Corp., has sprung up with a new foundry in Fremont, CA, exclusively for the production of HBT-based integrated circuits. The facility was set up in just over a year and has begun initial production runs. Samples and data sheets are currently available, with full product announcements expected in the near future. These first products will all be RF ICs targeting the wireless market below 3 GHz.

The facility at Fremont has a total capacity of more than 44,000 square feet, with 4" wafer fabrication and high-volume lithography equipment. EiC is fabricating ICs from MOCVD-grown HBT wafers, supplied by a merchant epiwafer vendor. The choice not to use existing device foundries was a critical decision, according to Larry Wang, Vice President of Engineering. "As we watched the wireless market expand, we determined that existing foundries would not be able to support the growing customer demand, and rather than allow EiC to be squeezed between its customers and suppliers, we went ahead to build a full fabrication capability."

Wang sees a shift in emphasis in the wireless market towards products incorporating better technology. "Customers want a product matching their system requirements, rather than something that will work, but offers nothing more," he says. "However, a wireless phone designer does not care what technology is used, so our products must offer both performance and low cost. We believe our GaAs HBT technology will be cost-competitive with silicon or GaAs MESFET technologies in the

800 MHz to 3 GHz range. We will be offering higher performance, but we won't rely on this to offset a higher price." Wang acknowledges that epitaxial-based technologies are more expensive in terms of the wafer cost. "However, the customer buys an IC from us, not a wafer, so you have to include factors like yield, uniformity, die size and assembly cost."

EiC consider that bipolar technologies, whether GaAs HBT or silicon, are more suitable than FETs for analog products such as modulators or VGAs. HBTs also offer fabrication advantages over pHEMTs, where gate-etching is a very difficult step to control. "We do not believe there is a single technology that offers the best answer to every wireless problem," says Wang. "However, when we looked at technologies capable of offering a solution for all known function blocks, HBT came out on top. In comparison, SiGe only offers a 10-20% increase in speed over silicon bipolar, in an unproven and much less mature technology."

Wang acknowledges EiC will compete with RF Micro Devices and Rockwell for a number of similar slots. He believes EiC's commitment to GaAs HBTs and a strong base of proprietary technology developed in-house will allow the company to compete successfully. "Also, several of our team have worked as wireless system designers, so there is a strong understanding of the environment where the parts will be used."

For more on the MESFET vs. HEMT or HBT debate, see the "Forum" section of the issue, beginning on page 38.



EiC's new GaAs fab in Fremont, CA.



Company Briefs

Coherent (Santa Clara, CA) has joined the Precision Laser Machining (PLM) Consortium, a group of 24 companies working to develop a new generation of laser machine tools. The objective of the project is to extend the power and brightness of diode-pumped solid-state lasers. The consortium is 50% funded by DARPA. Coherent's participation will involve the development of Al-free InGaAsP active-region laser diodes for higher power, long-life uses.

AMP Inc. and the Fibre Optics Division of **Siemens AG** have announced an agreement under which both companies will supply parallel transmitter and receiver modules which are designed to be interchangeable at the printed circuit board level. In both cases the parallel links will use VCSELs as the light sources. The modules are pin-for-pin compatible and have an equivalent mechanical footprint. The agreement includes transmitters and receivers operating from 125 Mb/s to 1.25 Gb/s on each channel with aggregate throughput ranges up to 15 Gb/s.

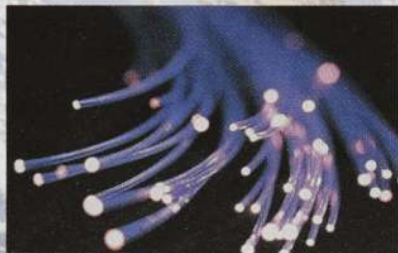
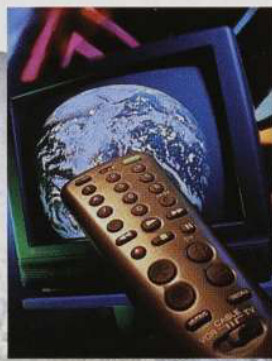
Hughes Space and Communications Co. (Los Angeles, CA) has been awarded a \$2.6 million DARPA contract to investigate the use of commercial-grade diamonds in high-power transistor packages. Under this contract, diamond-enhanced packages will be developed for use with high-power GaAs RF devices for satellite communications and radar systems. HSC is the prime contractor for the two-year project and has awarded Crystalline Materials Corp. (CMC) of San Ramon, CA, a privately held producer of diamond substrates, a \$1 million subcontract to support the effort. HSC hopes the use of man-made CVD diamonds will enable it to increase satellite performance.

ITT Industries has restructured and renamed their former GaAs Technology Center (ITT-GTC) in Roanoke, VA. The unit is now known as **GaAsTEK**. The company says sales of GaAs chips have more than doubled since last year.

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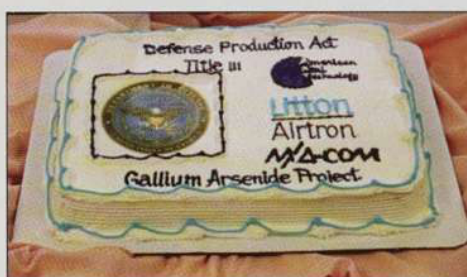
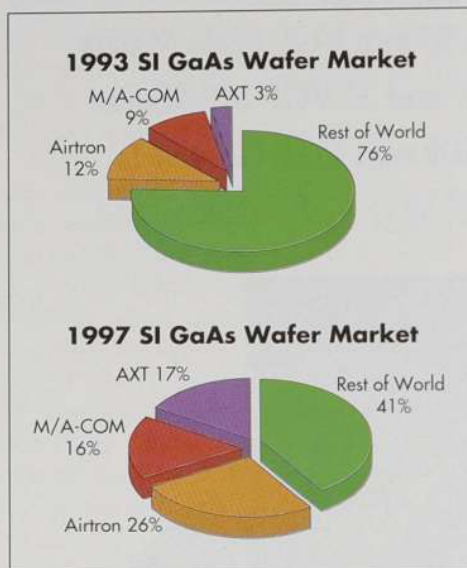
GaAs Title III Program Ends

The GaAs Title III Program came to an official end on April 17, marked by an awards ceremony held at the Pentagon in Washington DC. This \$23 million project, which commenced in 1994, was intended to improve the supply of semi-insulating GaAs wafers manufactured in the U.S. By all measures, it appears to have been a success.

U.S. capacity for the production of SI GaAs wafers has tripled since the program was launched, rising from 1,000 KSI (thousand sq. in.) in 1993 to 3,000 KSI today, according to John Blevins of the U.S. Air Force Research Laboratory at Wright Patterson AFB, who administered the program. In addition, the three participants - American Xtal Technology, Litton-Airtron, and M/A-COM - have significantly improved their positions in the GaAs wafer market. In 1993 these three, the only remaining U.S. suppliers of SI GaAs, had a combined 24% of the world market. In 1997, their combined market share was 59%. This is seen a critical factor in ensuring continued participation in the market now that the program has ended.

The Title III Program was made possible by a law that allows the Department of Defense to assist in the establishment or expansion of domestic production capabilities for military-critical materials. At its heart, the Title III program was intended to ensure that American defense contractors would have a steady supply of high quality GaAs wafers. But the program has also had an obvious positive impact on the supply of GaAs for commercial applications as well.

According to Blevins, "Prior to the Title III Project, U.S. suppliers were thought to be inferior with respect to their foreign counterparts. Resources to improve production processes and material quality were not readily available [because of relatively small total revenues, typically under \$5 million]. External financial resources provided by the Government allowed each contractor



U.S. GaAs takes the cake: top, market share before and after Title III program; bottom, a bit of the festivities at the Pentagon.

to improve their processes and quality, reduce cost and expand capacity to better compete in a global market place." He reports that emphasis was placed on achieving an efficient, high yield growth process at each facility. AXT was able to double their yields; Airtron and M/A-COM improved theirs by 20 - 44%. In addition, each contractor was required to establish and demonstrate a 6" GaAs manufacturing process. All three also received ISO 9000 certification.

Blevins sums up by saying "the alarming deterioration of the North American GaAs substrate manufacturing base has been reversed", and he predicts that the GaAs industry will continue to reap the benefits of this turn-around well into the 21st century.

Wafer Technology Expands, Increases Investment in InP

Increase in demand for substrates for laser diode and LED production have prompted Wafer Technology Ltd. to invest in additional production. A new manufacturing unit, providing an extra 4000 square feet was opened on March 1. The new space will be used to facilitate rapid expansion of the company's capacity for the growth of VGF GaAs.

The company says it has already increased their VGF capacity 5x the past four years, but demand continues to outpace supply. Karen Lamb, Sales and Marketing Director said "our VGF GaAs business has been increasing rapidly in the past few years with Wafer Technology substrates being the material of choice for many major laser diode and LED manufacturers world-wide. We need to make this investment now to ensure we will be ready to keep pace with our customers anticipated growth in demand for this product".

Wafer Technology also recently added two additional high pressure crystal pullers for InP production. Further growth capacity has been obtained as the result of an intensive internal process improvement programme resulting in the development of much longer 2" diameter crystals.

Martin Lamb, Manufacturing Director, explained "the transfer of this process to production has had a huge impact on Wafer Technology's InP manufacturing operation. The new process routinely yields more than 250 wafers per ingot, compared with 60-80 slices per batch from the original process, and material properties are similar in both cases. The cost savings are significant since the fixed consumable costs and manpower requirements are the same for either process".

Wafer Technology is the leading European manufacturer of indium phosphide and a wide range of other III-V materials. The company employs 40 people at its manufacturing plant in Milton Keynes, England.

Aixtron 1997 Revenues Up 63%

Aixtron's 1997 sales totaled DM77.8 million (US\$43.7M), an increase of 63% over the previous year's DM47.6 million (US\$26.7M). Pre-tax profits were DM9.3 million (US\$5.22M), resulting in net profits of DM4.4 million (US\$2.47M) for the year, up 33% on the previous year. Results were affected by a one-time charge of DM4.1 million (US\$2.3M) related to the company's IPO.

The company's most important market in the past year was North America,

accounting for 44% of total revenues, followed by Asia with 37% and Europe with 19%. Among customers who received or accepted equipment for shipment in the fourth quarter of 1997 were Hewlett-Packard, Tecstar and Nortel (North America), Thomson and Siemens (Europe) as well as several Asian research institutes.

Shares in Aixtron, which were priced at DM100 at the time of the company's IPO in November, 1997, have continued to rise. At the end of December 1997, the share price stood at DM210, in March it passed the DM400 mark, and since late April it has been over 600. At their annual meeting, set for May 19, 1998, Aixtron plans to recommend a 2-for-1 stock split. The company will also declare a dividend of DM0.45 (US\$0.25) per share (DM675,000 or US\$379,147 total).

Litton to Offer Silicon Carbide Wafers

Litton Airtron has signed a license agreement with Northrup Grumman Corporation's Electronic Sensors & Systems Division (ESSD) that allows Airtron to produce SiC substrates for the semiconductor industry using processes developed by Northrup Grumman. Terms were not disclosed.

Awards for Bede Directors

Neil Loxley, Managing Director of Bede Scientific Instruments, was recently awarded the 1998 Paterson medal by the U.K. Institute of Physics for "outstanding contributions to the development, invention or discovery of new systems, processes or devices that show the successful commercial exploitation of physics." And Keith Bowen, Strategic Research Director for Bede, was recently made a Fellow of the U.K. Royal Academy of Engineering.

Aixtron Shares, Feb - April 1998



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Nichia Reports High Power, High Temperature Blue Laser with Cleaved Facets

Nichia Chemical has recently achieved a room temperature CW blue laser which delivered an output power in excess of 400 mW per facet. In previous reports, CW blue laser output powers have been ~5 - 10 mW. The high power results were obtained from an InGa_N MQW narrow-stripe laser measuring 3 μ m wide x 450 μ m long. This is not only the best result ever achieved for a blue laser, but it is also equivalent to or higher than the maximum output power one might expect from narrow-stripe laser diodes based on more mature materials, such as AlGaAs.

Nichia continues to employ the GaN-on-sapphire ELOG (epitaxial lateral overgrowth) substrates that were used to fabricate the first 10,000 hour blue lasers last fall (CS 3(4), p. 4). But, as always, Shuji Nakamura, who heads R&D at Nichia, has

added some new twists. As previously noted, he has experimented with removing the sapphire backing from the ELOG substrate by polishing it off (see CS 4(2), p. 11). This leaves the 80 μ m thick epitaxially grown GaN layer to serve as a substrate for MOCVD growth of the laser diode structure. The operating voltage and threshold current density of the lasers in this experiment were 6V and 5 kA/cm², respectively. In contrast, other Nichia diodes have exhibited operating voltages as low as 4 V and threshold current densities down to 1.2 kA/cm². Nakamura conjectures that the growth conditions need to be re-optimized to accommodate the "pure GaN" substrate, which is 5 - 6 times thinner than what is typical for MOCVD growth.

Removal of the sapphire substrate should improve thermal conductivity, and it should make it easier to cleave the mirror facets. In the past, most of Nichia's reports have involved laser diodes with etched facets. But Nakamura has fabricated laser diodes with one etched and one cleaved facet from the material grown on the thin GaN substrate. The immediate results were encouraging: he was able to coax 90 mW of CW power out of the diode at 200 mA.

In more recent work, Nakamura has tried a different tack. Instead of polishing off the sapphire and growing on just the GaN portion, he has grown the laser structure on the complete ELOG substrate and then thinned the sapphire backing down to ~70 μ m. The resulting lasers have lower threshold current densities (3 kA/cm²), but are still compatible with cleaved facet formation. The output power of samples with two cleaved facets was as high as 420 mW at an operating current of 490 mA. These samples were also capable of high temperature operation. One diode was operated for more than 160 hours at 50°C at an output power of 30 mW; Nakamura reports that other diodes have been run all the way up to 100°C.

Which approach will be the winner when it comes time to move into production? It may be too early to be certain, but Nakamura indicates that he is hoping that the "pure GaN" approach - wherein the sapphire backing is completely removed - can be made production-worthy. This would provide the best possible thermal conductivity. He also plans to use cleaved facets in the production models.

At the Spring Meeting of the Japan Society of Applied Physics and Related Societies, Nichia reported the actual lifetime of its 2 mW blue lasers at room temperature has passed the 4,000 hour mark. The company is still on schedule to begin shipping samples of these lasers later this year.

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Emcore Offering Blue LED Process

On March 25 Emcore Corporation announced it has developed a "commercial quality" InGaN based process for blue LEDs. As reported previously, Emcore is already in a technology licensing agreement with Uniroyal Technology Corporation that is intended to allow Uniroyal to enter into the blue and green LED market (CS 4(2), p. 11).

Emcore claims to be the largest supplier of MOCVD reactors for high volume blue LED production, and they are also a merchant supplier of blue LED wafers. Reuben Richards, President and Chief Executive Officer of Emcore, said "In the short term, we will continue to do our best in helping meet projected OEM volume requirements by quickly moving our SpectraBlue multi-wafer machines into the field. In parallel, we are working closely with key customers to help assure them a steady supply of finished wafers or production technology as they project their ramps in 1998 and beyond."

Power output for Emcore's 470 nm blue LEDs was >1 mW, with a forward voltage of approximately 4 V. The company says it is currently expanding its wafer manufacturing facilities in Somerset, NJ, to meet the demand for the new blue LED wafers. Emcore also offers other processes, including InGaAlP-based LEDs.



Testing of blue and yellow LEDs at Emcore.

Cree Shifts to New LED

Cree Research plans to be completely transitioned over to its new "conductive buffer layer" GaN-on-SiC LED by the end of this quarter. This new vertical structure device is meant to be a higher brightness, lower cost product than Cree's previous LEDs, which will be discontinued.

Over the past nine months Cree's LED sales revenue has increased 87%, but LED unit volume has grown 126%. Cree President Neal Hunter recently told investors that Cree can become both the high brightness and the low cost leader. But in the meantime, they are focusing on the low cost side of the equation. According to their quarterly report: "Management continues to believe that market growth for this product [the conductive buffer LED] remains dependent on its ability to substantially lower pricing. The Company has recently introduced the conductive buffer product to Asia and has received positive feedback. This product, which is 50% brighter than the Company's prior product, but which remains less bright than a higher priced competing product, is expected to drive increased volume, however, significant impact may only be achieved through reduced pricing."

The quarterly report also shows that shipments of SiC to faux-gemstone developer C3 now account for at least 10% of Cree's product revenue.

A commitment to progress in MOCVD

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GaAs SI Wafer Market Up 43% in 1997

Four inch GaAs eclipses all, North America accounts for over half all consumption

The rapid rise in the uptake of GaAs MMICs in mobile communications applications is proving to be a major driver not only for the IC manufacturers, but also the wafer vendors supplying them. According to a recent study by Strategy Analytics¹, 4.9 million square inches of SI GaAs wafer material was shipped worldwide in 1997, up 43% over 1996 shipments. The market is valued at \$86 million.

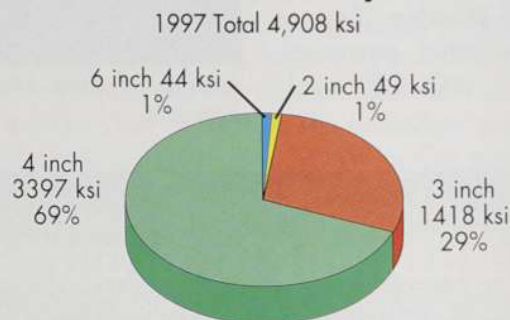
1997 saw the long predicted move to a market dominated by 4" material - 69% of wafer shipments were four-inch wafers. Says Richard Endersby, Service Director "With almost all of the major users now on 4", or at advanced stages of conversion, there is a real danger that those 3" users which are remaining will begin to see a restriction in the supply of smaller wafer diameters". This situation is made worse by the fact that some of the leading wafer suppliers face production capacity shortfalls in the short term and are dedicating equipment to supply their key large volume customers, almost invariably 4" users.

Shipments of 6" GaAs wafers were just barely visible in 1997, accounting for only 1% of total shipments. The key user for 6" in the short term is, of course, Vitesse Semiconductor; however, several other users are now seriously sampling 6" and Strategy Analytics believes that Vitesse is likely to be joined by other users 'shortly'. As for the future? "Demand for 6" will be restricted", according to Endersby. "The main driver for Vitesse's move to accommodate the large die sizes which digital devices require, and still maintain acceptable yield. For MMICs with their smaller die area the drive for larger wafer size isn't there to the same extent, although it isn't eliminated completely." That's partly why many of the 4" MMIC lines which have been installed are upwardly compatible with 6". Despite this potential for 6" usage, Strategy Analytics does not expect 6" wafers to account for more than 10% of the market, even by 2002.

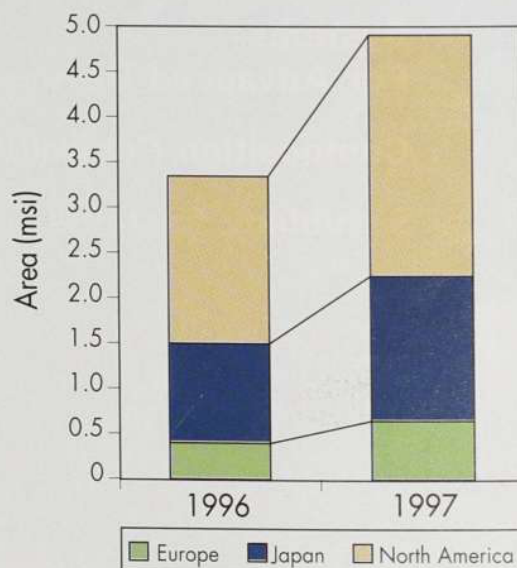
In terms of geographical distribution, in 1997 North America leads demand with 54% of wafers destined for users in this region which is approximately the same as the previous year. North American IC vendors have seen a significant rise in demand for their devices for applications in cellular and cordless handsets. North America is also the home to virtually the entire

worldwide digital IC production which is finding increasing application in long-haul telecommunications applications such as SONT/SDH and ATM switches, data communications and instrumentation. In addition, according to Endersby, the increasing interest in HBT and pHEMT technologies is creating a demand for epi wafers which is also being supplied by commercial epi vendors in North America.

SI GaAs Wafer Market by Diameter



SI GaAs Wafer Market: 1996 - 1997



¹ Contact Richard Endersby, tel +44 1582 405678, fax +44 1582 454828, email rendersby@strategyanalytics.com website : <http://www.strategyanalytics.com>

ICs for Wireless to Approach \$14 Billion by 2003

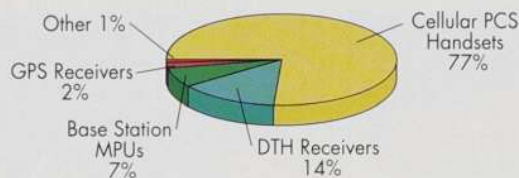
The world market for ICs employed in wireless communications devices is expected to grow from \$5.3 to \$13.7 billion over the next five years, according to a new report from Allied Business Intelligence². Cellular telephones will continue to dominate the market, especially in the short term. The largest growth segments will result from Global Position System (GPS) chipsets and less dominant digital cellular standards such as CDMA. Growth rates from LMDS (Local Multipoint Distribution Systems) and satellite sectors are also expected to be high - but this is due in part to the fact that they are evolving from almost zero dollars.

Sales to Cellular/PCS handset makers account for 77% of the current market for wireless ICs, with a value of just over \$4 billion. ABI predicts that this segment will grow to \$9.6 billion by 2003. GaAs currently accounts for 11% of Cellular/PCS IC sales.

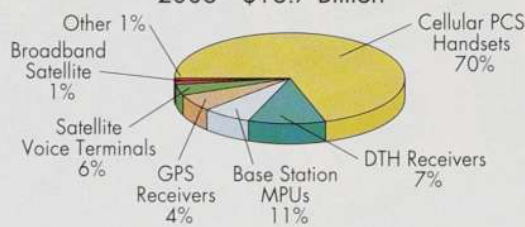
The report foresees increasing interest in off-the-shelf chipset solutions, as new companies set up OEM handset manufacturing. These late entrants are expected to demand easy-to-implement chipset solutions in order to get to market quickly, while established suppliers continue to seek customization service from IC suppliers who can offer a broad product line. Three-chip solutions (RF, IF and baseband) are expected in the short term.

Communications ICs World Wireless Market

1998 - \$5.3 Billion

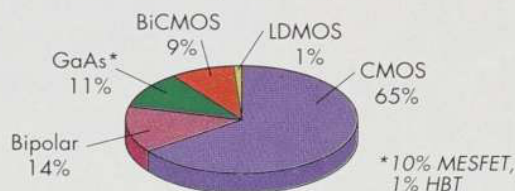


2003 - \$13.7 Billion



ICs for Cellular/PCS Handsets by Process

World Market, 1997 - \$4.18 Billion



Allied Business Intelligence

Allied Business Intelligence

SILICON UPDATE

If You Can't Beat Them, Join Them

ROBERT A. METZGER



A repairman with a single tool in his toolbox finds himself in a very precarious situation. There are undoubtedly certain jobs which are well suited to his tool of choice, other jobs which he can take on with his tool, but might not handle them with a great deal of efficiency or cost effectiveness, and a wide range of jobs which he simply can't do. If the nature of the repair jobs change, or other repairmen with different, or improved tools arrive on the scene, the lone-tool repairman may suddenly find his marketshare evaporate to nothing.

Unfortunately, many circuit fab companies, especially in the III-V community, operate with a single tool in their toolboxes. Such companies as Vitesse Semiconductor, TriQuint Semiconductor and Anadigics, all of which use internal fabs which run GaAs MESFET processes, have been especially successful over the past several years in the areas of RF ICs and communication applications by exploiting the superior device characteristics of the GaAs MESFET. But just like the repairman with the single tool in his toolbox, these companies are now beginning to face a challenge from silicon-based technologies whose improving performance and often lower costs is resulting in penetration into what had been considered the domain of the GaAs MESFET.

No where is this problem more evident than in the RF front end market over the 900-2500 MHz range. In the past, when many GaAs operations generated a sizable fraction of their revenues through military programs, if other technologies improved in performance and began to compete, then there was usually a new higher frequency, higher power application that the military required, which was better suited to GaAs. However, now that commercial applications dominate the marketplace, there are no real commercial RF applications beyond the 2500 MHz frequency level. Commercial silicon RF is taking real market share away at the 900 MHz level, and R&D efforts at 1800-2400 are starting to look very good. What can you do if the GaAs MESFET is your lone technology? Perhaps a lesson can be learned from what RF Micro Devices is doing.

A more recent arrival in the GaAs IC market than TriQuint, Vitesse and Anadigics, RFMD did not start as a fabrication facility which used that technology to enter into the RF market. Historically, they were an RF IC design house, which used outside fabrication facilities to implement their designs. Although at times they are perceived as a GaAs HBT house, the GaAs HBTs have been fabricated at TRW. However, that is not the only tool in their toolbox. They also offer products based on GaAs MESFETs and silicon bipolar technologies. And despite the fact that they are just completing their own GaAs fab, and have already run initial GaAs HBT product

² "Communications Integrated Circuits: Global Wireless Markets, Technologies & Forecasts". Contact Tim Archdeacon, TEL [1] 516 624 3113; FAX [1] 516 624 3115, email info@alliedworld.com

through that line, they plan on not only continuing to offer products based on silicon, but actually expanding that portion of their business. According to Jerry Neal, RFMD's Vice President of Sales and Marketing, "Our current mix of Si to GaAs circuits is about 10% silicon and 90% GaAs, however within the next two years we anticipate that this will change to 40% silicon and 60% GaAs." He goes on to say, "that our increase in silicon product is not coming about as a result of less GaAs production - the GaAs portion of our business continues to show excellent growth, however, the silicon portion of the business is growing even faster." Neal explains that they are finding silicon-based devices encroaching primarily into those applications which had been dominated by GaAs MESFETs in the 800-900 MHz region, while at the higher 1800-2500 MHz regime, GaAs HBTs are still the clear choice, especially in those applications where PAE and linearity are important.

RFMD's commitment to silicon is reflected in the fact that they already offer 40 RFICs in silicon and have 60 new Si RFICs in development. Furthermore, RFMD has just signed a multi-year Master Purchase agreement with IBM to satisfy this increase in silicon RFIC demand. Contrary to what had been reported elsewhere, the IBM technology which RFMD will be utilizing is IBM's advanced Blue Logic BiCMOS process, a 24 GHz f_t all Silicon process, and *not* IBM's SiGe technology. The IBM line runs 8 inch silicon, as a result of which each wafer can produce 4 times more circuits than can be obtained from a 4 inch wafer run on a typical GaAs line - a decided cost advantage.

As mentioned above, one of the primary silicon vs GaAs battlegrounds is that of the 800-900 MHz front end market.

RFMD has recently offered a trio of new products for that application based on IBM's silicon processes, the RF2406, the RF2405 and the RF2404. The RF2406 is a complete LNA/mixer front end which can handle CDMA/FM applications, featuring digital control of the LNA gain and IF output selection, along with buffered LO output, an onboard power-down mode and a "lazy" mode that reduces IP3, noise and current drain (by approximately 10 mA). The RF2406 operates from 500 MHz to 1100 MHz with a 2.7 to 4.0 V power supply. The RF2405 and RF2404 are variations of the RF2406, with the RF2405 offering a lower noise figure, and does not have the LNA gain control, while the RF2404 does not have the VCO output buffer.

Despite these silicon-based front ends offered for 850 MHz RF applications, RFMD also offers the RF2411, a GaAs HBT device, very similar in function to the RF2405, with the most notable difference being that of the cascaded noise figure, with the RF2405 having a NF of 3.8 dB, while that of the RF2411 of 2.4 dB. Jerry Neal comments that "GaAs still has applications at 850 MHz. To determine whether a GaAs or silicon device is best suited depends on the specific application." This is quite apparent in the case of the silicon as compared to the GaAs part at 850 MHz. If the improved NF of 1.4 dB is required for the specific phone, then the GaAs part is the obvious choice, while if NF is not that stringent a requirement, then the silicon device will be used.

And what other tools might RFMD add to their toolbox in the future? Jerry Neal says, "we are always looking at a broad spectrum of technologies, but I believe that we may take a closer look at PHEMT technology."



A Range of Possibilities

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MgO

YBCO

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BST

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Picture This

Focal plane arrays fabricated from compound semiconductor materials are at the heart of many infrared imaging systems and night vision cameras

TIM WHITAKER*

Infrared imaging has evolved from high performance, highly expensive military systems to become an affordable technology in widespread use in a variety of military and civil applications. These include surveillance cameras, night sights, missile warning, fire-fighting, search and rescue, industrial or building maintenance, process control, medical imaging and astronomy. The capability to detect and analyze IR radiation is enabled in modern systems by a focal plane array (FPA), consisting of an array of IR-sensitive detector elements coupled with signal read-out circuitry in the focal plane of an optical, light-gathering system.

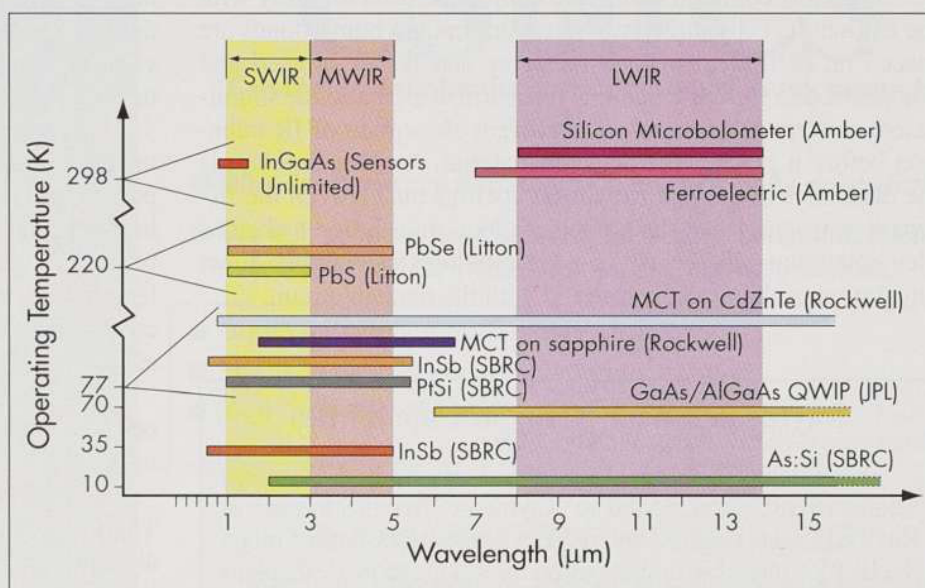
The choice of detector material depends on the targeted wavelength band (see figure), and the desired performance and cost. The most widely used material, mercury cadmium telluride (HgCdTe), provides very high performance imaging across the IR region, and is traditionally grown by LPE, although MBE growth is emerging as a strong alternative. Indium antimonide FPAs are mainly used in the 3-5 μm band, and are fabricated by ion implantation in to bulk single crystal material. InGaAs cameras and GaAs/AlGaAs quantum well IR photodetectors (QWIPs) both rely on complex epitaxial heterostructures.

Infrared Background

At temperatures above absolute zero, all bodies emit infrared (IR) radiation. The useful wavelength bands for detecting this radiation are restricted due to absorption by water or CO_2 in the atmosphere. The long wavelength IR band (LWIR, or far-IR) is found between 8 and 14 μm , and has almost 100% transmission in the 9-12 μm range. A large fraction of the total IR radiation emitted naturally from objects at ambient temperatures falls within the LWIR band (see figure, page 18). At higher temperatures, objects emit more radiation, and the peak emission wavelength decreases. The medium wavelength

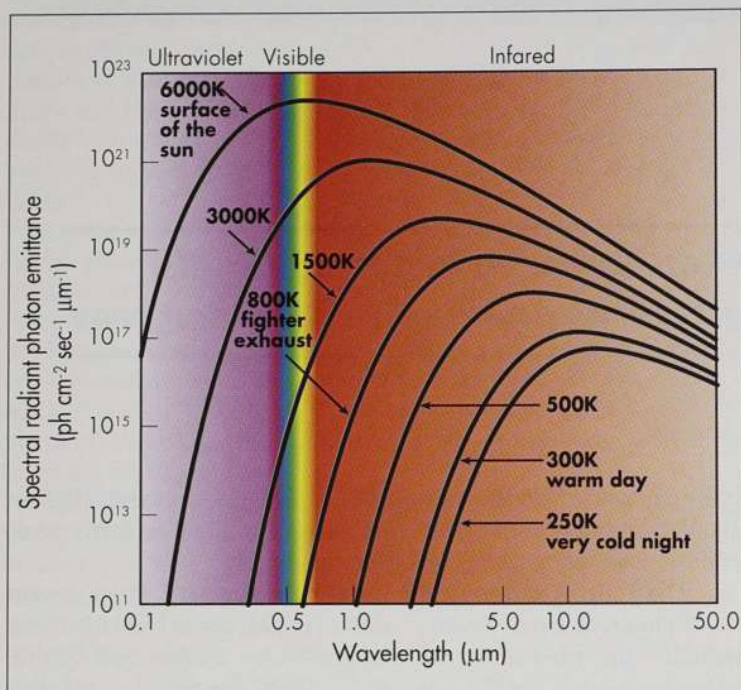
infrared band (MWIR, or mid-IR) at 3-5 μm contains slightly smaller amounts of ambient radiation, but also contains peak emissions from bodies at several hundred $^\circ\text{C}$.

The short wavelength IR (SWIR, or near-IR) band covers wavelengths down to the edge of the visible region (700 nm), and includes the fiber-optic wavelengths. The visible and SWIR bands between 0.3 and 1.8 μm have a high transmission and contain high levels of natural radiation from the sun, thus providing the best resolution imaging. Detectors in the SWIR rely on reflected light, because their targets don't emit at these wavelengths at ambient temperatures. The performance of SWIR image intensifiers and other low light imagers is drastically reduced in the absence of artificial light or moonlight. At the other end of the IR spectrum, the wavelength band extending above 12 μm is designated very long wavelength IR (VLWIR), and is used for astronomy and space-based applications.



Spectral response and nominal operating temperature of various FPAs and imaging cameras, from the data sheets provided by the indicated manufacturer. Also shown are the short-, mid- and long-wavelength IR bands (SWIR, MWIR and LWIR respectively).

* Additional material supplied by Nigel Mason (Oxford University) and Stuart Irvine (North East Wales Institute)



Blackbody spectral radiant photon emittance at various temperatures.

Focal Plane Arrays

The first generation of IR imaging systems were linear, scanned arrays, with front-side illumination and a direct connection between each element and its preamplifier. Second generation detectors incorporate FPAs with many thousands of elements and employ either scanning or staring modes of operation.

The most common method to couple the detector array with the readout IC is by direct hybridization. Indium bump-bonds are placed on each element, and the array and IC are aligned and compressed to form the bond. Hybrid arrays are backside illuminated, so steps must be taken to prevent absorption of IR radiation before it reaches the detector material. Another problem is the difference in thermal expansion coefficients between the IR-sensitive material and the silicon readout chip. Some technologies (platinum silicide, silicon microbolometer) permit direct integration of the detector material with the readout circuit.

Raytheon's Wide Array of Capabilities

Ownership of Hughes Aircraft's Santa Barbara Research Center (SBRC) transferred to Raytheon after the merger of Raytheon with Hughes' defense operations. Raytheon Amber, the IR FPA manufacturer acquired by Raytheon in 1992, plans to close its facility in Goleta, CA, and consolidate operations with SBRC. The Hughes Electronics facility in Malibu known as Hughes Research Labs is now owned jointly by Raytheon and Hughes Electronics, effective December 1997. Raytheon also acquired further expertise in focal plane arrays with the acquisition of Texas Instruments' defense business.

The Heat is On - Thermal Detectors

The absorption of IR energy by a thermal detector material causes heating, and ensuing changes in the material's physical properties can be measured and correlated with the scene. Pyroelectric detectors typically contain ferroelectric materials such as lead zirconium tantalate (PZT) or barium strontium titanate (BST), and appear in room temperature cameras as well as in non-imaging heat sensors for fire alarms and similar applications.

Bolometers are a type of thermistor, in which the resistance of the detector element changes with temperature. Silicon microbolometer technology was developed at Honeywell, and has since been licensed to several manufacturers including Raytheon and Boeing. In this integrated technology, the vanadium oxide detector material is deposited directly onto microbridges machined from the same silicon chip holding the readout circuitry.

Although the performance of thermal detectors does not reach the levels of cooled photon detectors, the micro-bolometer and ferroelectric technologies offer the major advantage of operation without cryogenic cooling. Both these technologies are to be found in commercially available, portable cameras which run from conventional camcorder batteries.

Photon Detectors

Intrinsic detectors absorb IR photons up to the cut-off wavelength (λ_c), which corresponds to the bandgap energy. Many compound semiconductor materials are suitable, including $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ alloys, InSb, InGaAs and IV-VI lead-salt compounds. Due to high background noise levels, intrinsic detectors generally need to be cooled to cryogenic temperatures to achieve the desired sensitivity. At long wavelengths (beyond $\sim 12 \mu\text{m}$), the very narrow bandgap involved makes control of material properties and thermal dark currents increasingly difficult.

One option is to use extrinsic devices, such as Hg-doped germanium or arsenic-doped silicon, in which the long wavelength photons stimulate transitions from deep impurity levels within the host-material bandgap. Extrinsic devices need to be cooled well below cryogenic temperatures, but extend the detection wavelength up to around $200 \mu\text{m}$. SBRC manufactures impurity band conduction Si:As arrays for astronomy applications, which operate at 4-12 K in the 2-28 μm region.

QWIPs, in which absorption of IR photons causes transitions between subbands confined within a quantum well, are discussed in detail in a separate article (page 24).

A further device category utilizes the photoelectric effect. The most common example is PtSi (platinum silicide) in which absorption of photons causes emission of electrons in the metallic PtSi detector. These electrons can be detected after crossing a Schottky barrier formed between PtSi and a doped Si layer. The readout ICs for these devices can be integrated alongside the detector elements, or a hybrid design can be used. The quantum efficiency of PtSi is much lower than InSb in the MWIR region, however the pixel-to-pixel uniformity of the metallic material is much better.

Photoconductors and Photodiodes

Early arrays were photoconductive (PC) devices, in which the absorption of photons generates carriers and alters the conductivity of the material, measured as the change in resistance to a current flowing through the device. Focal plane arrays require devices with a low power dissipation (allowing large numbers of elements) and a high impedance, to interface with the FET input of readout multiplexers. These characteristics are provided by photovoltaic (PV) devices, although some high impedance photoconductors such as PbSe, PbS and extrinsic silicon are suitable. Litton manufactures using photoconductive PbS (1-3 μm) and PbSe (1-5 μm) 1x 128 linear FPAs operating at 220 K.

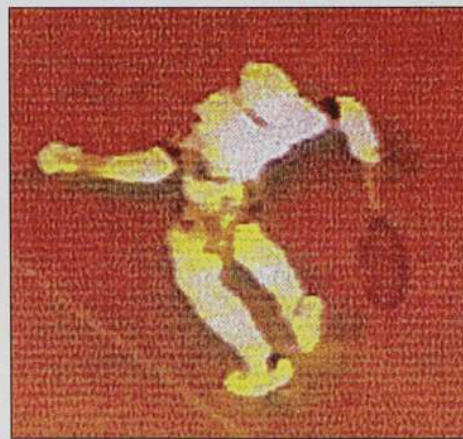
PV detectors are usually p-n photodiodes. Electron-hole pairs generated in (or within one diffusion length of) the depletion region are separated, producing a

measurable photocurrent. Devices are usually operated at a low value of negative bias to suppress the dark current and improve linearity.

HgCdTe Rules?

Since its discovery 40 years ago, HgCdTe has been one of the most widely investigated IR materials. Over the last two decades, the US government has invested several billion dollars in this material. HgCdTe-based detectors have been the mainstay of the scanning imager industry since the 1970's, but large staring arrays are less common, especially at longer wavelengths.

HgCdTe is intrinsically a very good material for IR detection, having a high quantum efficiency, a low thermally generated dark current above 77K, and an adjustable composition to access almost the whole IR region up to $\sim 20 \mu\text{m}$. The lattice parameter shows a very small variation as x is adjusted, which is a huge

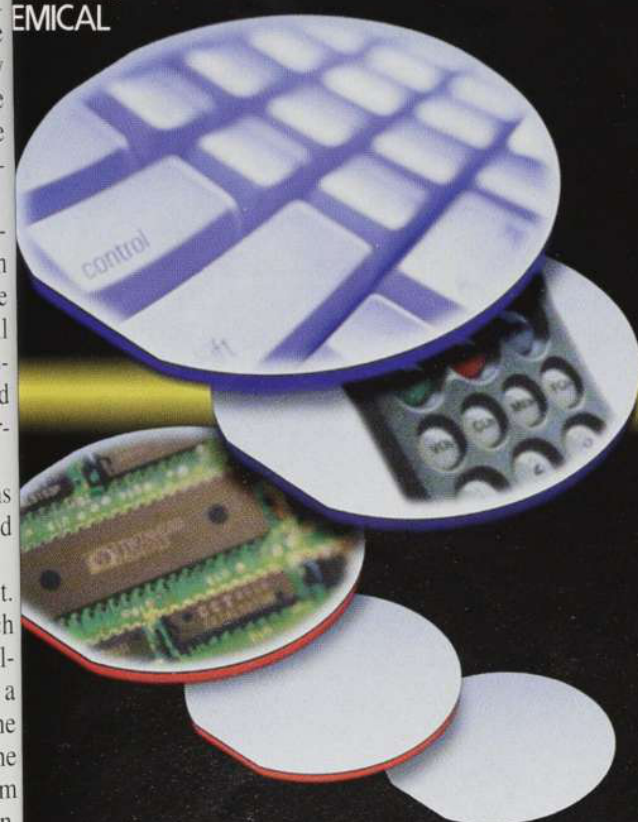


Raytheon Systems (Amber)

advantage for lattice-matching to substrates.

However, $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ is a difficult material to work with; the weak Hg-Te bond is further destabilized by alloying with CdTe, and Hg has a high vapor pressure. At longer wavelengths x has to decrease, growth becomes even more challenging and small variations in x cause large shifts in λ_c . Also, the lower bandgap required for longer wavelength

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InGaAs Camera Sees In The Near-Infrared

Sensors Unlimited of Princeton, NJ, have developed a room temperature camera operating in the 1.0-1.7 μm wavelength band, based on a 320 x 240 element focal plane array of InGaAs detectors. The camera has a very high spatial resolution and a room temperature detectivity (D^*) in excess of $10^{13} \text{ cmHz}^{0.5}/\text{W}$. The absence of cryogenic cooling greatly increases the simplicity of the instrument.

One of the features of the focal plane array is the very high yield arising from the use of an epitaxial structure. Detectors are currently grown by MOCVD on 2-inch n^+ InP substrates, with Epitaxial Products International as the primary epilayer supplier. The device structure consists of a 1 μm -thick InP buffer, an 3 μm active region of lattice-matched InGaAs and a 1 μm InP cap layer. Greg Olsen, President of Sensors Unlimited, reports that the device performance is very sensitive to the substrate quality. 'The dark current relates directly to substrate defects,' he says. 'Also, we see variations which can be attributed to a wafer's rotational symmetry.'

The need for large, high yield FPAs is going to drive the move towards larger substrate sizes, according to Olsen.

'At present, we only get 4 arrays from our 2" wafers, whereas we could get 24 from a 4" substrate,' he says. 'We will be one of the first to make this move in the opto-electronics business. We have already received a 3" wafer from Quantum Epitaxial Designs, which shows promising results. QED uses MBE, which has a slight edge over MOCVD at present as there doesn't seem to be a problem using the larger wafers.'

Sensors Unlimited is likely to be one of the first consumers to benefit from the Title III program, under which AXT and M/A-COM plan to develop 4" InP wafers. The improved yield from larger wafers will be instrumental in reducing the price from around \$25,000 for the current 'laboratory special' camera to around \$5,000.

The InGaAs technology has the best demonstrated capability for room temperature imaging in the 1.0-1.7 μm band. Low light level devices and image intensifiers only extend to about 0.9 μm in the IR. Operation beyond 1.4 μm makes the imager compatible with eye-safe lasers in applications such as range finding and target designation. The camera has also been used to image painted-over areas of famous works of art.

Camouflage clothing designed to blend in with a background under visible light has a different reflectivity in the short-wave IR and can be picked out with the InGaAs camera.

Sensors Unlimited also manufacture a series of linear InGaAs photodiode arrays, for use in scanning applications such as spectroscopy, process control and laser and fiber-optic characterization.



Sensors Unlimited

Room temperature, 1.0-1.7 μm InGaAs camera from Sensors Unlimited. The dimensions in cm are 15.8 x 10.3 x 10.3.

detection means a higher thermally assisted dark current, so that the operating temperature has to decrease.

Substrates are also a major issue; CdZnTe substrates are used most frequently, but are small in size, expensive, and have a very large thermal mismatch with silicon readout ICs in hybrid detector systems.

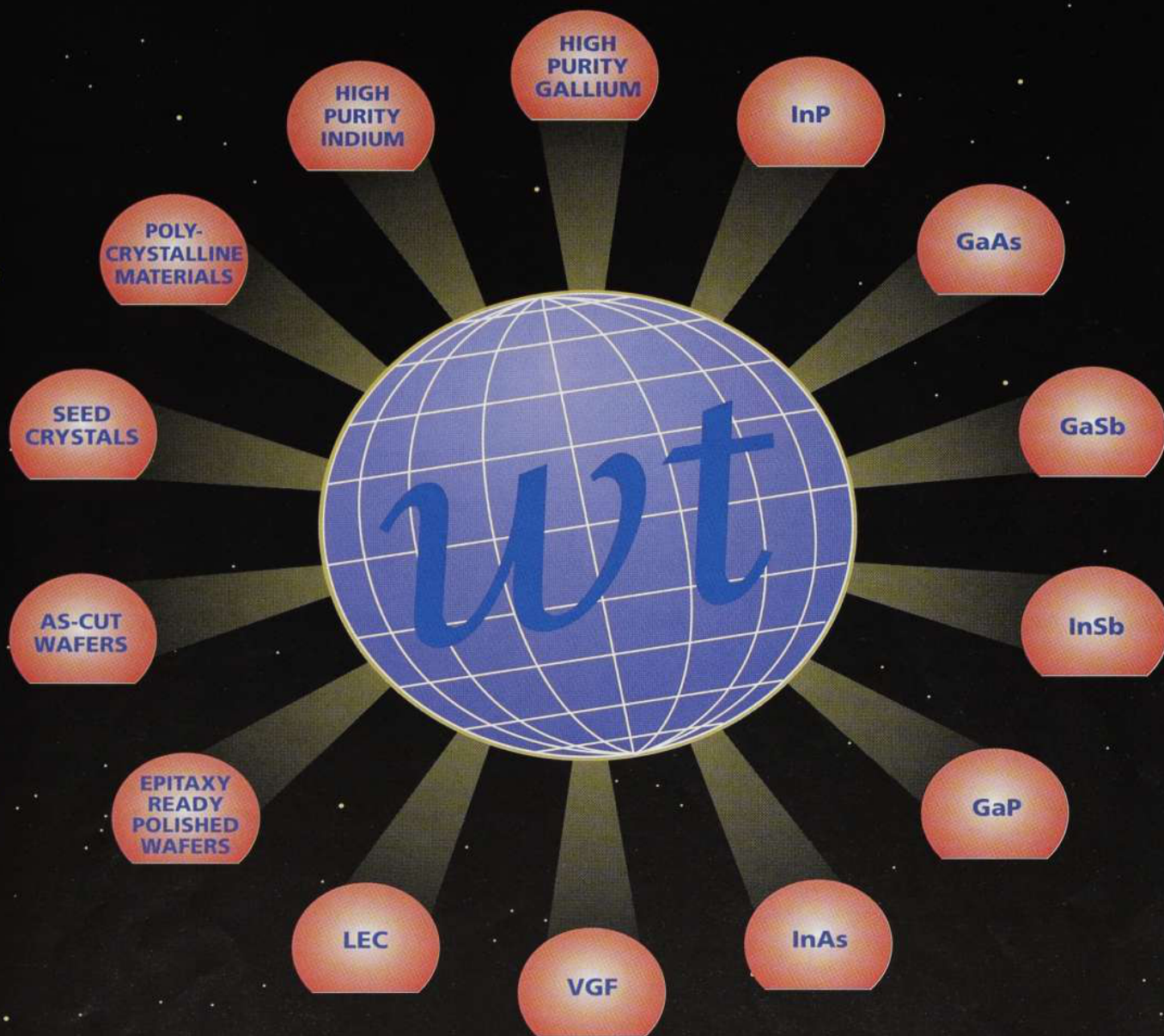
Growth of HgCdTe

LPE from a Hg or Te melt is the most mature and widely used HgCdTe production technique. However, large, high uniformity, long wavelength arrays, and sophisticated device structures such as 2-color arrays require precise control of composition and layer thickness at a level that is difficult to achieve with LPE. The high growth temperature of MOCVD ($\sim 350^\circ\text{C}$) creates problems with p-type doping control, due to the formation of Hg vacancies. In contrast, several groups including those at Hughes Research Labs and Rockwell Science Center made progress in MBE growth of HgCdTe at temperatures of around 200°C . Around 6 years ago, a DARPA-funded US consortium was established to develop MBE growth technology, with two strands to investigate both in-situ doping and ion implantation, led by Hughes and Rockwell respectively.

In a previous issue (CS 2:4, p.26) Owen Wu described Hughes' work. Typical devices are double layer p-on-n heterostructures; two color n-p-p-n devices were also fabricated, in which the bias direction determines the detected wavelength by selecting one or other of the two different p-n diodes.

MOCVD has also continued to develop. Lockheed Martin has fabricated 64 x 64 hybrid arrays of two color n-p-p-n detectors, using HgCdTe grown by MOCVD on CdZnTe substrates. Two bump bonds per pixel allow simultaneous access to the back-to-back MWIR and LWIR photodiodes, which had D^* values of 4.8×10^{11} and $7.1 \times 10^{10} \text{ cmHz}^{0.5}/\text{W}$ respectively at 78 K. [see P. Mitra et al, J.Elec.Mater., 1997, 26, p.482].

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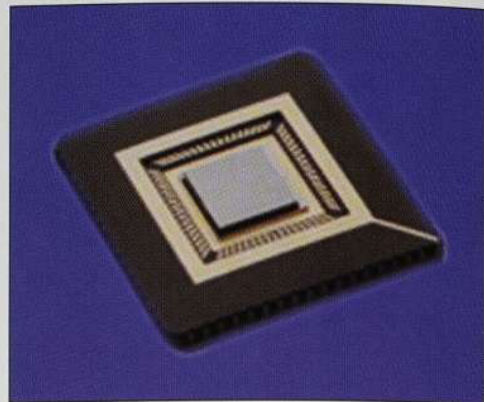
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Indium Antimonide

Several companies, notably Raytheon Systems (both Amber and SBRC), Lockheed Martin (Santa Barbara Focalplane), Cincinnati Electronics and Litton fabricate InSb focal plane arrays, and in some cases manufacture cameras. Epitaxy is not used; instead, the standard manufacturing technique begins with bulk single crystal wafers, and uses either ion implantation or diffusion to form the diodes. After surface passivation and hybridization to a readout chip, the material is thinned to $\sim 10\text{ }\mu\text{m}$ to minimize carrier recombination. Detectors grown by LPE have apparently shown certain advantages in minority carrier lifetime, but performance is actually limited by the ion implantation process rather than by

bulk material properties, so there may be no real benefit. Cincinnati Electronics uses a diffusion process to avoid ion-implantation damage in the IR-sensitive layer, and report that limiting noise in their imaging systems arises from the A-to-D converter in the readout circuit, rather than from the FPA.

According to Jeff Barton of Raytheon Amber, epitaxial techniques may be considered if they are able to offer an increase in operating temperature from 77 K to around 120-150 K - this is a major goal for MWIR imaging. Transparent substrates are also very desirable. 'The difficult backside thinning process for InSb arrays keeps the yields low and the costs high,' says Barton. 'If a technology were developed for growing high quality InSb on an alternative sub-



A 128 x 128 InSb focal plane array.

strate with a wider bandgap, so that InSb did not have to be thinned down, this would be of extreme interest. Unfortunately, there don't appear to be any obvious candidates with good lattice-match.'

Detector Terminology Explained

Quantum Efficiency

Ratio describing the proportion of incident photons converted into an electrical signal.

Responsivity

[A/W or V/W]

The detector signal (either voltage or current) for a given incident photon flux (radiant input power). Depends mainly on quantum efficiency and wavelength, doesn't include noise.

Dark Noise

[A or V]

Signal without incident photon flux. Sources are intrinsic detector noise (e.g. thermal generation of carriers, tunneling currents etc) and stray photon noise e.g. from detector mountings and optics.

Noise Equivalent

Power (NEP) [W]

Noise divided by responsivity, equivalent to minimum detectable radiant input power when the signal to noise ratio (SNR) is 1. Value is small for good detectors, does not take area into account.

Detectivity (D^*)

[$\text{cmHz}^{1/2}/\text{W}^{-1}$]

also called [Jones]

Square root of (detector area in cm^2 multiplied by system bandwidth in Hz), divided by NEP. High D^* is good, but above a certain limit array is limited by pixel-to-pixel uniformity, increasing D^* has no effect on array performance.

Noise Equivalent

Temperature

Difference ($\text{NE}\Delta T$) [K]

Minimum temperature change in the scene required to produce a signal equal to rms noise. Value is a few mK for high performance MCT, 15-30 mK for InSb cameras, 70-100 mK for room temperature (microbolometer, ferroelectric) technologies

Background Limited

Photodetection (BLIP)

Achieved when detector dark noise is less than background photon noise from ambient scene under view. BLIP is performance expected from high quality detector. Depends on field of view and background (scene) temperature. Cooler scene (e.g. deep space, compared to terrestrial) contains less background IR, therefore detector needs to be cooled further to reduce dark current and maintain BLIP conditions. BLIP requirement defines necessary D^* , for given scene temperature and wavelength.

RoA

[Ωcm^2]

Product of dynamic impedance and area, measured at zero bias voltage for PV devices. High value indicates low leakage currents. In LWIR MCT arrays, R_0A falls as λ_c increases (lower bandgap) due to higher thermal carrier generation. impedance matching with readout circuit becomes more difficult.

HgCdTe Epitaxy at Rockwell

Rockwell Science Center produces HgCdTe-based focal plane arrays using two techniques, both involving ion implantation. LPE is used to grow n-on-p HgCdTe-based photodiodes on lattice-mismatched CdTe/sapphire substrates (also known as PACE - Producible Alternative to CdTe for Epitaxy) in the SWIR and MWIR bands. MBE is used to grow p-on-n photodiodes on lattice-matched CdZnTe substrates across all the IR bands. The choice of technique is a trade-off between performance and cost.

In the SWIR band, 1024 x 1024 astronomy FPAs have been made on PACE substrates; in the MWIR, 640 x 480 arrays have been made using both PACE and CdZnTe substrates, and 256 x 256 arrays (PACE) are in continuous production to support several systems applications. At longer wavelengths, 256 x 256 arrays have been developed on CdZnTe substrates with cut-off wavelengths up to 17 μm .

Sapphire Substrates

The older PACE technology takes advantage of the availability of larger, less expensive sapphire substrates. These are prepared with a thin buffer layer of CdTe, grown by MOCVD, followed by LPE growth of p-type HgCdTe. The photodiode is fabricated by boron ion implantation. In the completed hybrid FPA, light has to pass through the sapphire substrate, which is transparent for visible and IR radiation out to about 5.5 μm . By thinning the substrate to <7 μm , this cut-off wavelength can be extended to 6-7 μm . The lattice mismatch results in a relatively high dislocation density but is suitable for a number of tactical applications in the MWIR. In the SWIR band, cooling to 78 K results in a very low dark current (<1 electron/s) compatible with the long exposure times desired for astronomy applications. 1024 x 1024 arrays with a 2.5 μm cutoff were used at an observatory in Hawaii to record the collision of the comet Shoemaker-Levy 9 with Jupiter. The readout circuit for this array, fabricated in 0.8 μm CMOS, contains nearly 3.5 million transistors.

MBE Growth On CdZnTe

Rockwell has three MBE reactors for the production of double layer HgCdTe p-on-n heterostructures (see figure). The active $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ layer, with x chosen to target the wavelength of interest, is capped with a second layer of wider bandgap $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ (higher x). In the final device, this layer eliminates interfaces around the p-n junction at which recombination can occur. After arsenic ion implantation, the HgCdTe surface is stabilized by passivation with a CdTe layer.

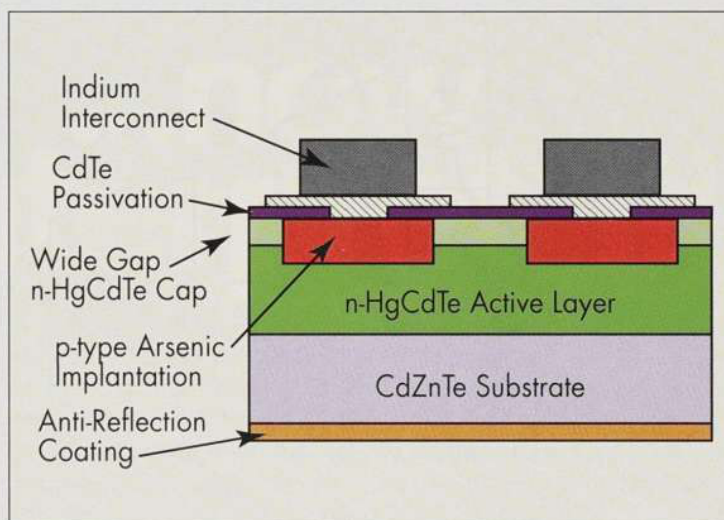
Rockwell reports dark currents for MBE-grown FPAs in the 5 μm region which are about two orders of magnitude lower than PACE in the 50-90 K temperature range. At 50 K, the median dark current was 0.39 electrons/sec for 0.5 V reverse bias,

with 93.8% of pixels below 1 e-/sec. InSb detector arrays must be cooled below 30 K to achieve this performance. The technology, under development for passively cooled space experiments, could therefore provide an alternative to InSb and Si:As detector arrays.

HgCdTe on Silicon

Compared to CdZnTe, silicon substrates offer large area, low cost and the prospect of long-term reliability over many thermal cycles when hybridized to silicon readout circuits. Despite the large lattice mismatch (~19%) between CdTe and Si, both Hughes and Rockwell have investigated growth of CdTe on Si, and subsequent fabrication of HgCdTe detectors. Rockwell prepared Si(211)B wafers by MBE growth of several monolayers of SiTe_2 , followed by a thin layer ZnTe, and finally CdTe(211)B. The detector structures grown on these substrates had the same general structure as the double layer heterostructures grown on CdZnTe. Due to the lattice-mismatch between CdTe and HgCdTe, typical dislocation densities were 1-2 orders of magnitude higher (10^6 - 10^7 cm^{-2}) than for growth on CdZnTe. Further improvements in low temperature detector performance require enhancements in material quality, however the R_0A product of $7 \times 10^6 \Omega\text{cm}^2$ was measured for a cut-off wavelength of 4.8 μm at 77 K, comparable with devices grown on CdZnTe. Rockwell has fabricated 1024 x 1024 arrays on CdTe/Si substrates.

[See J. Bajaj, *Proc. Intl. Workshop Phys. Semicon. Dev.*, 1997; R. Bailey et al, *Proc. SPIE vol. 3354*, 1998; P. Wijewarnasuriya et al, *Proc. US Workshop Phys. Chem. II-VI Mat.*, 1997]



Schematic cross-section through two pixels of a p-on-n HgCdTe photodiode array fabricated by MBE growth, followed by ion implantation.

QWIPs

A Serious Alternative to HgCdTe for Long-Wavelength Infrared Imaging

TIM WHITAKER

At long wavelengths in the infrared, fabrication of focal plane arrays utilizing direct interband transitions in intrinsic semiconductors such as HgCdTe becomes increasingly difficult, due to the very small bandgap required. One approach is to use the transition between subbands within either the conduction or valence band, which are isolated within a quantum well. The transition energy is much lower than the bandgap energy, and can be tailored according to the dimensions of the well and the doping levels used.

About 6 years ago, scientists at the Jet Propulsion Laboratory (JPL) began to investigate possible alternatives to MCT. 'We wanted to see if we could work with a more producible material like silicon or GaAs,' says Carl Kukkonen, head of the Center for Space Microelectronics Technology. Five competing approaches, two in silicon and three in III-V materials, based on either superlattices or quantum wells, were evaluated. Among these was QWIP, or Quantum Well Infrared Photodetector, technology, which was developed by Barry Levine's group at AT&T Bell Labs, and later transferred to JPL

under the leadership of Sarath Gunapala. JPL has a number of interests in long wavelength detection. Molecules such as ozone, water, CO, CO₂ and nitrous oxide have strong absorption lines in the 3-18 μm region, and imaging systems at these wavelengths are being planned for NASA's Earth Observation System for monitoring global atmospheric temperature profiles, relative humidity profiles and cloud characteristics. Also, ballistic missiles have peak emissions in the

8-15 μm region when the hot rocket engine is not burning, and detecting these bodies is a further space-based application for QWIPs.

'The technology behind QWIP production is very mature,' says Kukkonen. 'It won't supplant HgCdTe in all areas, but it will become significant, first in military systems, and also in medicine, where very high resolution imaging is crucial.'

Boxed In

QWIP operation is explained by the particle-in-a-box model found in basic quantum mechanics. When a particle such as an electron is confined within a 2-D box (e.g. a quantum well), the energy states are quantized provided that the well is sufficiently deep and narrow. The potential depth and width of the well can be adjusted so that it holds only two energy states, the ground state and an excited state near the top of the well. (see figure 1). Inter-subband transitions between these two states results in a detector with a very sharp absorption spectrum, and the absorption wavelength can be adjusted by changing the well parameters. Using GaAs/AlGaAs allows the wavelength to be adjusted over the 6-25 μm region, and the accessibility of this material system makes it the most widely studied for QWIP applications. Growth and processing technology is well understood and relatively straightforward compared to HgCdTe, and precise quantum well engineering can be carried out to define the desired structure.

A QWIP functions by detecting electrons which are excited from the ground state to the first excited state, and swept out of the device by an externally applied bias to form a photocurrent. QWIPs are actually photoconductors; there is no p-n junction. A bias voltage is applied to sweep the excited electrons out of the well region.

One of the most critical problems to address in high performance QWIPs is the dark current i.e. the current flowing through a biased detector without illumination. At temperatures above 45 K, the electrons in the ground state have sufficient thermal energy to escape from the well without absorbing IR radiation, and

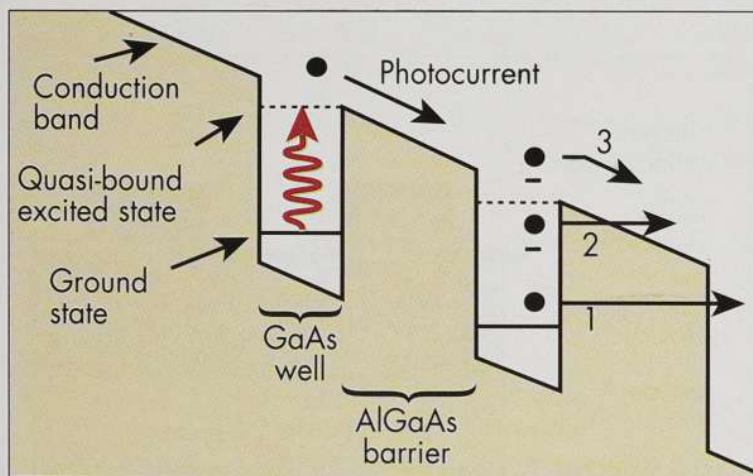


Figure 1: Schematic band structure of a bound-to-quasibound QWIP in an externally applied electric field. IR absorption excites electrons, and the field sweeps them into the continuum, causing a photocurrent. Three dark current mechanisms are shown; (1) ground state tunneling (2) thermally assisted tunneling and (3) thermionic emission.

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Position	Count	29.32028	80.00	30.66057	92.00	32.00085	69.50	33.34114	83.50	34.68143	73.00	36.02171	69.50	37.36200	133.50	38.70229	68.50
28.00000	71.00	29.34029	64.00	30.68057	83.00	32.02086	68.50	33.36115	72.50	34.70143	63.00	36.04172	68.00	37.38200	125.50	38.72229	59.50
28.02000	62.00	29.36029	80.50	30.70058	97.00	32.04086	71.50	33.38115	67.00	34.72144	72.00	36.06172	73.00	37.40201	137.50	38.74229	67.00
28.04001	72.50	29.38029	67.00	30.72058	84.50	32.06087	70.50	33.40115	93.50	34.74144	79.00	36.08173	56.50	37.42201	148.50	38.76230	62.50
28.06001	68.50	29.40030	75.50	30.74059	86.50	32.08087	61.00	33.42116	74.50	34.76144	61.50	36.10173	69.00	37.44202	134.00	38.78230	62.50
28.08002	76.00	29.42030	70.00	30.76059	78.00	32.10088	68.50	33.44116	72.00	34.78145	71.00	36.12173	70.50	37.46202	143.00	38.80231	60.00
28.10002	67.50	29.44031	59.50	30.78059	76.00	32.12088	62.50	33.46117	89.00	34.80145	76.50	36.14174	68.00	37.48203	116.00	38.82231	64.50
28.12003	68.50	29.46031	64.00	30.80060	81.50	32.14088	65.00	33.48117	81.00	34.82146	83.00	36.16174	71.00	37.50203	136.00	38.84232	65.50
28.14003	71.00	29.48032	74.00	30.82060	72.50	32.16089	69.50	33.50117	88.00	34.84146	65.50	36.18175	66.00	37.52203	127.00	38.86232	66.00
28.16003	64.00	29.50032	66.00	30.84061	65.50	32.18089	63.50	33.52118	78.50	34.86147	76.00	36.20175	68.00	37.54204	109.50	38.88232	54.50
28.18004	74.50	29.52032	72.50	30.86061	79.50	32.20090	61.50	33.54118	86.50	34.88147	59.50	36.22176	67.00	37.56204	99.50	38.90233	70.50
28.20004	66.00	29.54033	66.50	30.88062	75.00	32.22090	79.00	33.56119	91.50	34.90147	81.00	36.24176	64.50	37.58205	95.00	38.92233	70.00
28.22005	66.50	29.56033	72.50	30.90062	62.50	32.24091	72.00	33.58119	97.00	34.92148	66.00	36.26176	67.50	37.60205	94.00	38.94234	77.00
28.24005	70.50	29.58034	65.00	30.92062	71.00	32.26091	68.50	33.60120	105.00	34.94148	70.50	36.28177	69.50	37.62206	98.00	38.96234	78.00
28.26006	70.00	29.60034	66.50	30.94063	68.50	32.28091	68.00	33.62120	103.00	34.96149	71.00	36.30177	66.50	37.64206	85.00	38.98235	73.50
28.28006	60.00	29.62035	70.00	30.96063	71.00	32.30092	64.50	33.64120	107.50	34.98149	70.00	36.32178	57.00	37.66206	76.50	39.00235	82.00
28.30006	69.50	29.64035	55.50	30.98064	67.50	32.32092	83.00	33.66121	96.00	35.00150	68.00	36.34178	67.50	37.68207	88.00	39.02235	81.00
28.32007	68.50	29.66035	69.50	31.00064	72.50	32.34093	71.00	33.68121	104.00	35.02150	70.00	36.36179	61.50	37.70207	84.50	39.04236	78.00
28.34007	63.50	29.68036	61.00	31.02065	72.50	32.36093	61.00	33.70122	118.00	35.04150	70.50	36.38179	68.50	37.72208	72.50	39.06236	82.50
28.36008	68.50	29.70036	71.50	31.04065	64.50	32.38094	80.00	33.72122	110.00	35.06151	67.00	36.40179	62.50	37.74208	82.50	39.08237	72.00
28.38008	74.50	29.72037	62.50	31.06065	69.00	32.40094	60.50	33.74123	132.00	35.08151	63.50	36.42180	60.50	37.76208	68.50	39.10237	78.50
28.40009	72.00	29.74037	69.00	31.08066	72.50	32.42094	76.00	33.76123	167.50	35.10152	82.00	36.44180	53.00	37.78209	73.00	39.12238	86.00
28.42009	65.50	29.76038	62.50	31.10066	67.50	32.44095	66.50	33.78123	186.00	35.12152	71.50	36.46181	58.50	37.80209	67.50	39.14238	81.00
28.44009	70.50	29.78038	68.50	31.12067	72.50	32.46095	61.50	33.80124	211.00	35.14153	67.50	36.48181	74.50	37.82210	79.50	39.16238	81.00
28.46010	72.50	29.80038	57.00	31.14067	66.50	32.48096	74.00	33.82124	224.00	35.16153	68.00	36.50182	61.50	37.84210	65.00	39.18239	76.50
28.48010	64.50	29.82039	64.50	31.16068	76.50	32.50096	70.00	33.84125	246.00	35.18153	62.00	36.52182	67.00	37.86211	68.50	39.20239	75.50
28.50011	67.50	29.84039	73.00	31.18068	71.00	32.52097	72.50	33.86125	284.50	35.20154	67.50	36.54182	54.50	37.88211	57.50	39.22240	68.50
28.52011	81.00	29.86040	73.50	31.20068	67.00	32.54097	74.50	33.88126	301.00	35.22154	61.00	36.56183	64.00	37.90211	64.00	39.24240	74.50
28.54012	73.00	29.88040	88.00	31.22069	74.00	32.56097	72.50	33.90126	331.50	35.24155	67.00	36.58183	71.00	37.92212	50.00	39.26241	70.50
28.56012	80.50	29.90041	74.00	31.24069	65.50	32.58098	64.50	33.92127	356.50	35.26155	66.00	36.60184	58.00	37.94212	70.00	39.28241	61.00
28.58012	71.50	29.92041	81.50	31.26070	68.00	32.60098	72.00	33.94127	356.50	35.28156	63.00	36.62184	59.50	37.96213	65.00	39.30241	62.00
28.60013	86.00	29.94041	81.00	31.28070	66.50	32.62099	58.00	33.96127	345.50	35.30156	69.00	36.64185	58.00	37.98213	61.50	39.32242	68.50
28.62013	82.50	29.96042	81.50	31.30070	67.50	32.64099	68.00	33.98128	319.00	35.32156	68.00	36.66185	63.00	38.00214	68.50	39.34242	63.50
28.64014	74.00	29.98042	80.00	31.32071	72.00	32.66100	68.50	34.00128	329.50	35.34157	68.00	36.68185	64.50	38.02214	62.50	39.36243	60.00
28.66014	75.00	30.00043	96.00	31.34071	59.50	32.68100	70.50	34.02129	317.50	35.36157	75.50	36.70186	62.00	38.04214	64.00	39.38243	68.00
28.68015	70.50	30.02043	82.50	31.36072	59.00	32.70100	69.50	34.04129	280.00	35.38158	62.50	36.72186	54.50	38.06215	54.00	39.40244	67.50
28.70015	70.50	30.04044	113.00	31.38072	67.50	32.72101	72.50	34.06129	261.00	35.40158	75.50	36.74187	63.00	38.08215	68.00	39.42244	66.50
28.72015	76.50	30.06044	98.00	31.40073	78.50	32.74101	73.00	34.08130	213.00	35.42159	73.50	36.76187	75.00	38.10216	66.50	39.44244	56.50
28.74016	69.50	30.08044	106.00	31.42073	65.50	32.76102	70.00	34.10130	185.00	35.44159	66.50	36.78188	64.50	38.12216	51.50	39.46245	53.50
28.76016	68.00	30.10045	115.50	31.44073	71.00	32.78102	61.50	34.12131	159.50	35.46159	71.50	36.80188	78.50	38.14217	63.50	39.48245	69.00
28.78017	72.50	30.12045	117.00	31.46074	61.00	32.80103	58.50	34.14131	145.00	35.48160	73.00	36.82188	69.00	38.16217	59.00	39.50246	69.00
28.80017	83.00	30.14046	127.00	31.48074	73.50	32.82103	72.00	34.16132	122.50	35.50160	71.00	36.84189	60.50	38.18217	66.00	39.52246	59.00
28.82018	73.00	30.16046	137.00	31.50075	79.00	32.84103	68.50	34.18132	101.00	35.52161	64.00	36.86189	66.50	38.20218	63.50	39.54247	63.00
28.84018	75.00	30.18047	157.00	31.52075	59.50	32.86104	77.50	34.20132	94.50	35.54161	71.50	36.88190	60.00	38.22218	73.00	39.56247	64.00
28.86018	82.00	30.20047	179.00	31.54076	74.00	32.88104	65.00	34.22133	85.00	35.56161	76.00	36.90190	68.50	38.24219	64.00	39.58247	69.50
28.88019	71.50	30.22047	222.00	31.56076	80.00	32.90105	73.50	34.24133	79.50	35.58162	61.50	36.92191	68.00	38.26219	55.00	39.60248	70.00
28.90019	76.50	30.24048	173.50	31.58076	73.00	32.92105	92.00	34.26134	83.50	35.60162	76.00	36.94191	71.50	38.28220	54.50	39.62248	63.00
28.92020	72.50	30.26048	206.00	31.60077	64.50	32.94106	70.50	34.28134	74.50	35.62163	63.00	36.96191	69.50	38.30220	76.50	39.64249	63.00
28.94020	76.00	30.28049	245.00	31.62077	75.00	32.96106	63.50	34.30135	81.00	35.64163	65.00	36.98192	65.50	38.32220	63.00	39.66249	60.00
28.96021	69.50	30.30049	243.50	31.64078	77.00	32.98106	57.00	34.32135	80.50	35.66164	61.50	37.00192	67.50	38.34221	67.50	39.68250	57.00
28.98021	66.50	30.32050	233.00	31.66078	66.00	33.00107	72.50	34.34135	76.50	35.68164	76.50	37.02193	61.50	38.36221	72.00	39.70250	60.50
29.00021	65.00	30.34050	270.50	31.68079	68.00	33.02107	81.50	34.36136	67.00	35.70164	69.50	37.04193	75.00	38.38222	66.00	39.72250	63.00
29.02022	70.50	30.36050	254.50	31.70079	63.50	33.04108	69.00	34.38136	59.00	35.72165	80.00	37.06194	78.50	38.40222	65.00	39.74251	66.50
29.04022	77.50	30.38051	237.50	31.72079	65.50	33.06108	68.00	34.40137	67.00	35.74165	65.50	37.08194	69.50	38.42223	61.00	39.76251	56.50
29.06023	64.50	30.40051	246.50	31.74080	71.50	33.08109	78.50	34.42137	72.00	35.76166	64.50	37.10194	76.50	38.44223	66.50	39.78252	68.00
29.08023	75.00	30.42052	270.50	31.76080	56.00	33.10109	74.00	34.44138	73.00	35.78166	75.50	37.12195	78.50	38.46223	59.00	39.80252	71.00
29.10023	65.00	30.44052	244.50	31.78081	64.50	33.12109	75.50	34.46138	66.00	35.80167	60.00	37.14195	74.50	38.48224	58.00	39.82253	58.00
29.12024	82.50	30.46053	198.00	31.80081	73.00	33.14110	74.00	34.48138	59.00	35.82167	63.50	37.16196	94.50	38.50224			

this thermionic emission explains the need to operate QWIPs at cryogenic temperatures. The first QWIPs were bound-to-continuum devices, in which the first excited energy state is a continuum level about 10 meV above the well top. JPL designed quantum wells with the excited state positioned exactly at the top of the well. In these bound-to-quasibound QWIPs, the barrier to thermionic emission is increased by approximately 10 meV compared to the bound-to-continuum variety, causing the dark current to drop by a factor of ~ 6 at a temperature of 70 K. Other dark current mechanisms such as tunneling through the barriers can be reduced by increasing the barrier width.

Stacking Up

Photon absorption in QWIPs can be increased by stacking together many identical quantum wells. The detector arrays used by JPL are grown by Quantum Epitaxial Designs (QED), using the precise thickness and composition control available from MBE. For detectors with a peak responsivity at 14.2 μm , the layer structure shown in figure 2 was used. The IR-sensitive region has 50 periods of 65 Å GaAs wells doped at $n = 2 \times 10^{17} \text{ cm}^{-2}$, separated by 600 Å $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ barriers. Doping is required to provide electrons to undergo the inter-subband transition; the IR absorption energy is not sufficient to create electron-hole pairs. Since a high doping level will increase the contribution to the dark current, doping has to be optimized for the required operating temperature.

QWIPs with p-type doping, in which transitions occur between hole states in the valence band, can also be fabricated. The low hole mobility results in low dark currents, so that devices with high detectivity can be made, but also results in low photocurrents, so that the detector output is easily swamped by system noise when incorporated into a camera.

Detectors with a peak responsivity at 8.4 μm were also fabricated, using a 50-period structure with 45 Å GaAs wells doped at $n = 4 \times 10^{17} \text{ cm}^{-2}$ and separated by 500 Å $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barriers. The narrower wells increase the transition energy and lower the absorption wavelength relative

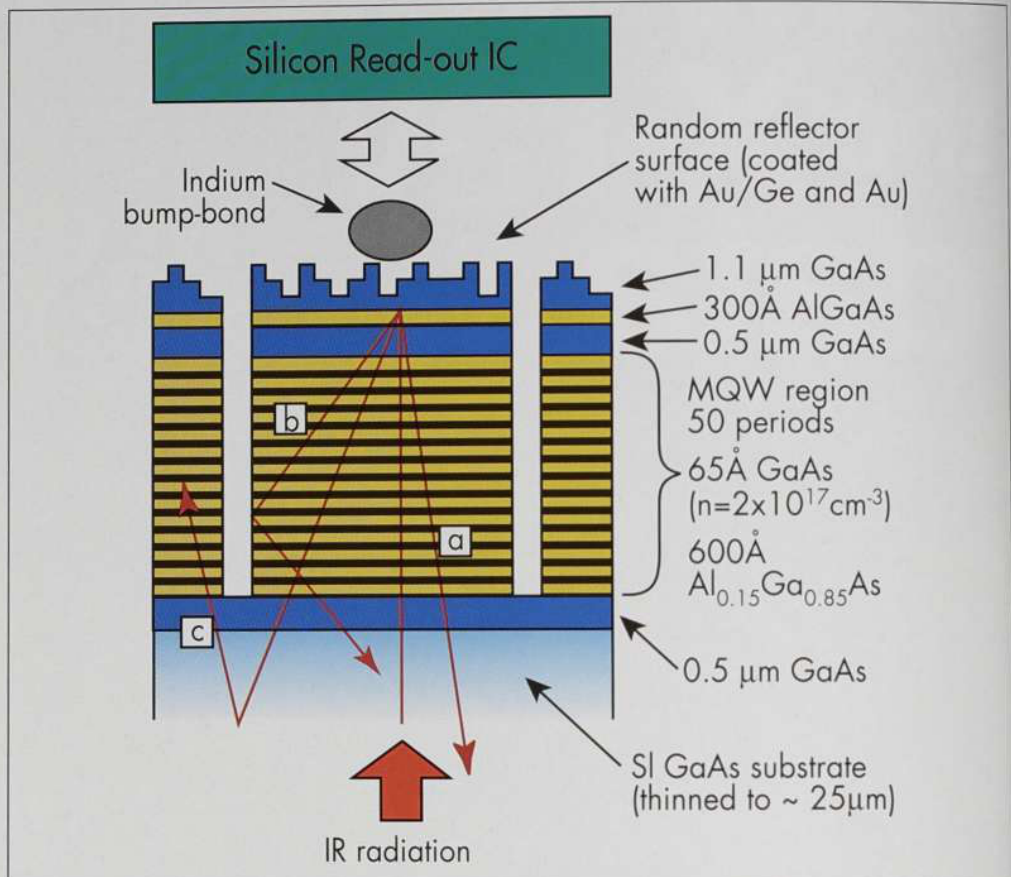


Figure 2: Schematic showing the constituent parts of a QWIP hybrid array. The random reflector surface is etched into the uppermost GaAs layer. Three reflection paths are shown; (a) light escapes after two passes (b) internal reflection trapping light in the detector (c) optical cross-talk between neighboring pixels.

to the 14.2 μm detector; a higher Al content is also required to confine the states in the well.

On Reflection

Due to quantum selection rules, the incident radiation must have an electric field component parallel to the MQW superlattice growth direction (normal to the layers) for absorption by the confined carriers. As the electric field component of electromagnetic radiation is perpendicular to the direction of propagation, this means that radiation normal to the detector surface cannot be absorbed, presenting a major stumbling block for the formation of FPAs using QWIP technology. Illumination through a 45° polished facet creates the desired component but this solution is only suitable for linear arrays.

For 2-D arrays, surface gratings have been used but the most successful approach, developed at JPL, incorporates a randomly reflecting surface. Light pass-

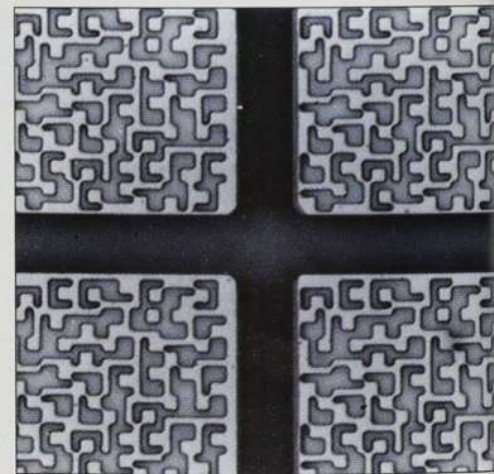


Figure 3: Two-level random reflector on pixels (38 $\mu\text{m} \times 38 \mu\text{m}$) of a QWIP array. Light coupling efficiency is increased by a factor of eight when the substrate is thinned down to $< 1 \mu\text{m}$.

ing through the detector is reflected by the back surface and will escape from the device after only two optical passes if the angle of reflection is less than about 17° from the normal. The random reflector results in random angles of reflection de-

which both creates a component parallel to the growth direction, and minimizes the probability of reflection within the escape cone, thus trapping light within the detector for multiple passes. The reflector surface is fabricated by standard lithography and selective dry etching, and the surface pattern produced has a repeating unit cell, to ensure pixel-to-pixel uniformity in imaging cameras (see figure 3).

QWIP Imaging Cameras

The components of a hybrid FPA imaging system incorporating a QWIP detector with peak responsivity at $14.8\text{ }\mu\text{m}$ are shown in figure 2. The MQW stack, sandwiched between $0.5\text{ }\mu\text{m}$ thick n-type contact layers, is capped with an AlGaAs etch-stop layer and a $1.1\text{ }\mu\text{m}$ GaAs cap. After fabrication of the random reflector surface on top of the detectors, pixels are defined by wet-etching through the IR-sensitive MQW stack to the lower GaAs contact layer. In this case, 128×128 arrays are fabricated with pitch of $50\text{ }\mu\text{m}$ and an actual pixel size of $38\text{ }\mu\text{m} \times 38\text{ }\mu\text{m}$. The random reflectors are covered with Au/Ge and Au, both for reflection and to form ohmic contacts. Indium bumps are evaporated onto the detector surface for hybridization to the silicon CMOS multiplexer, supplied by Raytheon Amber. The substrate is thinned from $\sim 630\text{ }\mu\text{m}$ to $\sim 25\text{ }\mu\text{m}$, to reduce the optical cross-talk between neighboring pixels. (When light is internally reflected at the substrate/air interface, it can reflect back into a neighboring pixel if the substrate is not sufficiently thin - see figure 2). The initial array gave excellent images with 99.9% of the pixels working, demonstrating the high yield of GaAs technology.

Imaging cameras in the $8\text{--}9\text{ }\mu\text{m}$ region were fabricated from 256×256 arrays using a similar procedure. The pitch in this case was $38\text{ }\mu\text{m}$, with an actual pixel size of $28\text{ }\mu\text{m} \times 28\text{ }\mu\text{m}$. The substrate was thinned to a membrane $\sim 1300\text{ }\text{\AA}$ thick. This eliminates thermal mismatch between the FPA and the readout IC because the membrane is able to adapt to the thermal expansion and contraction of the silicon multiplexer. Typically, around 10-20 of the 65536 pixels in each array are dead. The best such array had an NEAT

value of 15 mK , measured at an operating temperature of 68 K and a 300 K background, with $f/2$ optics. The peak quantum efficiency was 3.3% as a result of the optical fill factor of only 54% . The FPA-readout IC hybrid was mounted with a Stirling cooler and installed in an Amber RADIANCE 1 body to produce a hand-held LWIR camera. A palm-size camera, weighing just 2.5 pounds and consuming 5.5 W has also been made. (see figure 5). The cameras incorporate Ge lenses which are transparent in the $8\text{--}12\text{ }\mu\text{m}$ region of interest.

640×486 QWIP arrays have also been fabricated in the $8\text{--}9\text{ }\mu\text{m}$ band, and these are among the largest arrays ever fabricated in the LWIR. The NEAT of this FPA was 36 mK , measured at an operating temperature of 70 K , with 300 K background and $f/2$ optics. Due to the small pixel size ($18\text{ }\mu\text{m} \times 18\text{ }\mu\text{m}$), random reflectors proved unsuitable and were replaced with a two dimensional grating surface. The high sensitivity of this device is demonstrated by figure 4.

Broadband and Dual-band QWIPs

JPL have fabricated broadband QWIPs with a broad spectral response in the $10\text{--}16\text{ }\mu\text{m}$ region. The devices consisted of 33 repeat units separated by $575\text{ }\text{\AA}$ thick AlGaAs barriers. The repeat units each contain three QWs separated by $75\text{ }\text{\AA}$ thick AlGaAs barriers. The thicknesses of the 3 QWs in each unit are tuned to 13 , 14 and $15\text{ }\mu\text{m}$ respectively, and broadening is further enhanced by wavefunction overlap due to the thin barriers.

Dual-band, or two-color, detectors are of particular interest for military target recognition purposes. Two-color, voltage-tunable QWIP detectors have been fabricated, but these require two voltage sources, high bias to access long wavelength detection and do not allow simultaneous detection in both bands. JPL have fabricated structures with different MQW stacks to absorb in different regions of the spectrum,



Figure 4: Image from a 640×486 LWIR ($8\text{--}9\text{ }\mu\text{m}$) QWIP staring array camera taken at around midnight. The places where cars were parked during the day are clearly visible as cooler, dark areas.



Figure 5: A palm-sized LWIR camera manufactured by Inframetrics incorporating a 256×256 QWIP array made at JPL.

including devices offering simultaneous detection at $8.3\text{ }\mu\text{m}$ and $15.2\text{ }\mu\text{m}$. If a single indium bond per pixel is used, an interlace readout scheme is required i.e. odd rows for one color, even for the other. This allows simultaneous readout but greatly reduces the optical fill factor per band. The JPL structure allows the fabrication of three terminals per pixel for hybridization to a multicolor readout with two readout cells per detector pitch.

Applications of QWIP Cameras

The QWIP RADIANCE 1 has been utilized in many situations where the high sensitivity at long wavelengths offers many advantages. A Los Angeles news team used the camera to broadcast nighttime pictures of lingering hotspots during

the Malibu fires of October, 1996. These could not be observed by visible CCDs and were viewed through smoke. (figure 6). QWIP cameras have also been used to observe underground lava tubes and other geothermal features in Hawaii. A number of medical applications have been investigated, including measurements of skin temperature variation, and heart imaging at the Texas Heart Institute which was able to show the build-up of arterial plaque during heart surgery experiments.

The Ballistic Missile Defense Organization has a strong interest in identifying missile launch vehicles by being able to discriminate the relatively cold (250°C) vehicle body from the hot (950°C) exhaust plume (figure 7). At 4 (m, the exhaust will dominate the infrared scene, whereas the colder vehicle generates a significant fraction of the total photon flux at longer wavelengths e.g. 8.5 μm or above. A further application is astronomy, where QWIP cameras in the Mt. Palomar observatory have observed a multitude of IR sources deep in space which are dim or undetectable in the visible.

Comparing QWIPs with HgCdTe

The major drawbacks of QWIP technology are a low conversion efficiency, especially compared to direct gap HgCdTe alloys, and a high thermal generation rate above 77 K. 'The D^* parameter is usually a factor of 2 worse than HgCdTe in this temperature regime, just comparing pixels,' says Carl Kukkonen. 'However, because QWIPs don't have tunneling defects, you can cool them down and get big improvements in D^* .'

A major advantage of QWIPs is the uniformity which comes from a well-understood material system and mature fabrication techniques. Fabrication of HgCdTe arrays is relatively mature at MWIR wavelengths but does not transfer easily to LWIR and beyond. Development of VLWIR and multicolor FPAs using HgCdTe will require significant improvements in reproducibility and yield. MBE growth of HgCdTe should solve some of the control problems, but is likely to be more expensive than QWIP production,

which is developing from the established III-V manufacturing base.

'The technology behind QWIP production is very mature,' says Kukkonen. 'It won't supplant HgCdTe in all areas, but it will become significant, first in military systems, and also in medicine, where very high resolution imaging is crucial.' In the long and very long wavelength IR regions, and for low temperature and low background applications, HgCdTe arrays now have a serious challenger.

(see 'Recent Developments in QWIPs', S. Gunapala et al, *Thin Films*, 1995, 21, p.113; 'Progress in QWIP Research and Development at JPL', S. Gunapala et al, *Proc. SPIE* 3286, 1998)



Figure 6: Helicopter news footage of homes on fire in Malibu taken with a camera incorporating a 256 x 256 QWIP array. The scene is black when viewed through a visible CCD camera. The QWIP camera is able to see through smoke and pinpoint lingering hotspots, not normally visible with the naked eye, which could flare up at any time.

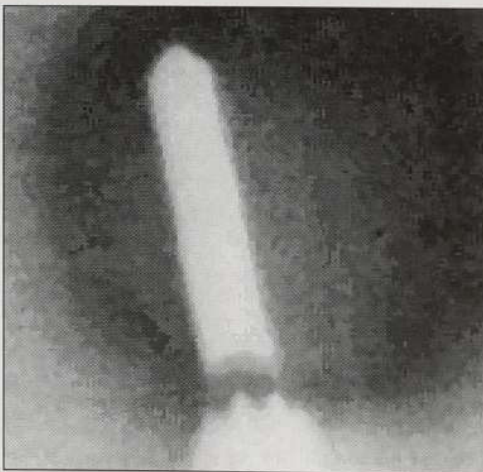


Figure 7: Image of a Delta-II launch vehicle. The QWIP camera allows discrimination of the cold rocket body from the hot exhaust plume.

QWIPS in Other Material Systems

QWIPs with GaAs wells and AlGaAs barriers are limited to detection above 5.6 μm by the maximum value of the conduction band offset. Shorter wavelengths can be accessed by replacing GaAs in the wells with a smaller bandgap material, such as InGaAs. Also, the use of deeper wells at longer wavelengths can reduce the amount of Al required in the barriers, improving transport properties. This enhances the observed photocurrent. Ternary barriers can be replaced with binary materials such as GaAs or InP to considerably improve electron transport properties. Using GaAs as the barrier layer has resulted in very long wavelength (> 14 μm) $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}/\text{GaAs}$ QWIPs. Results from QED suggest that introducing small amounts of P (~2%) into the GaAs barriers is effective in compensating the strain in these structures and reducing the dark current by a factor of 4, while maintaining the photocurrent.

QWIPS have been formed from other material systems, including $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ on InP, in the 3-5 μm band, and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ in the 6-9 μm band. A binary material such as InP used as the barrier material has excellent electron transport properties for improved responsivity, and using InGaAsP as the well material moves the absorption peak out to around 12 μm . $\text{GaAs}/\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$ QWIPs at around 8 μm and $\text{GaAs}/\text{Al}_{0.5}\text{In}_{0.5}\text{P}$ QWIPs at around 3.25 μm have also been fabricated. JPL have combined InGaAs/AlGaAs MQW stacks with a peak absorption at 4.2 μm , with 8.5 μm GaAs/AlGaAs stacks to form a mid/long wave dual-band detector.

QWIPs have also been demonstrated with p-type doping; here, InP-based devices have a higher responsivity than GaAs-based alternatives. $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ p-QWIPs have the shortest wavelength response of any such device, at 2.7 μm .

Magnetic Sensors - Indium Antimonide in Pole Position

TIM WHITAKER

Magnetic position and speed sensors, which transfer mechanical movement into an electrical signal using a permanent magnet and a magnetic field sensor, are finding widespread use in many applications, especially where contact resistance or contamination prevent the use of potentiometers or optical sensors. There is a huge demand for position sensors to control brushless DC motors in audio, video and computer electronics. Asahi Chemical, the leading supplier of InSb Hall elements largely for these types of application, estimates a world market well in excess of 1 billion units a year. However, these are low performance devices based on polycrystalline InSb thin films.

There is also an increasing range of automotive applications, such as crankshaft position sensing for ignition timing, where the operating environment places more stringent demands on sensor performance. General Motors now incorporates InSb magnetoresistive sensors in all their vans, pick-ups and sport utility vehicles totalling some 4-5 million devices up to the present time. The desired performance of these devices necessitates the use of epitaxial material.

Choosing the Right Technology

Magnetic position sensors generally consist of a magnetic field sensor, a permanent magnet and a moving magnetic circuit. The sensor registers a response which is dependent on its position relative to the permanent magnetic field. The two main types of field sensor are the Hall element, which measures the change in Hall voltage with magnetic field, and the magnetoresistive (MR) sensor, which measures geometrical magnetoresistance. When a current-carrying conductor is placed within a magnetic field having a

direction normal to the current flow, the Lorentz force acts on the carriers. The carrier pathway is deflected normal to both magnetic field and current direction, and this sets up a potential difference across the material. Typical Hall elements measure this Hall voltage as a function of magnetic field.

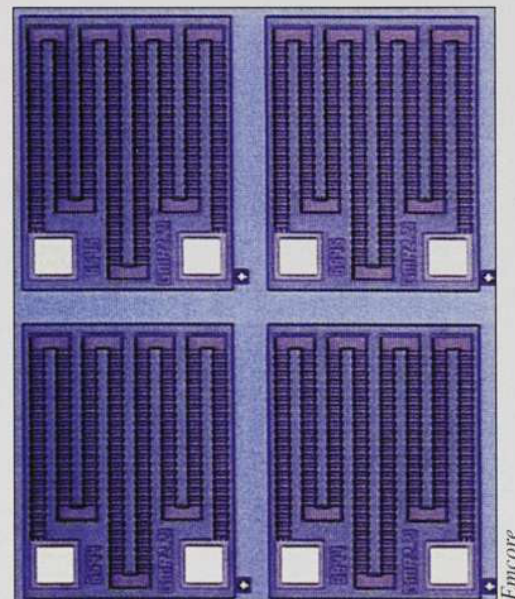
If the conducting slab is not sufficiently long, the Hall voltage does not develop fully. The path traveled by carriers is much longer than at zero field, leading to an increased resistance (the geometrical magnetoresistance). Typical MR devices consist of many elements connected in series; these can be fabricated by overlaying the sensor material with metal shorting bars at regular intervals to short out the Hall voltage.

High mobility semiconductors are most responsive to magnetic field variations, so that the largest values of Hall voltage or magnetoresistance are generated by thin films of materials such as indium antimonide. However, in InSb and other narrow bandgap materials the intrinsic carrier density is strongly dependent on temperature. This causes a strong variation of device response with temperature for single, undoped elements, and can limit narrow bandgap devices to operation close to room temperature.

Magnetic sensors are commonly doped n-type to compensate for their temperature-dependent behavior. However, as the doping level is increased, scattering by ionized impurities reduces the mobility, and therefore the device sensitivity. This can be counteracted in MR devices by optimizing the device element geometry and utilizing multiple elements in series.

Consumer Electronics

Asahi Chemical produces huge quantities of undoped, polycrystalline InSb



InSb magnetoresistive sensors manufactured by Emcore under license from General Motors.

Hall elements, but these are only suitable for operation at or near room temperature (CS 2(5), p.38). GaAs Hall elements operate at higher temperatures, due to the wider bandgap in this material, but they lack sufficient sensitivity.

Si-doped InAs Hall elements also have a smaller Hall output voltage than InSb devices, but have improved stability over a wider operating temperature range, and are manufactured by Asahi. The sensitivity can be increased using ultra-thin InAs films, but the lattice mismatch with GaAs makes this very difficult. Asahi has also investigated the use of quantum well heterostructures consisting of an InAs QW between insulating AlGaAsSb layers.

On the Road

Many automotive systems rely on electronic feedback and control, including position sensing in fuel pumps, windshield wipers, window motors, fan motors; wheel speed sensors and anti-lock braking; speedometers, and accelerator pedal and throttle valve position. A typical example is a position sensor measuring the crankshaft angle, which is used by the engine controller to calculate ignition timing i.e. the correct time to fire a spark in each cylinder. It is now also mandatory to

detect engine misfires, which can be achieved by picking up small angular velocity changes in the crankshaft using the same sensor.

The demands of automotive applications can be very severe. Due to the harsh operating environment - sensors may be fully immersed in engine oil and need to run between -40°C and $+200^{\circ}\text{C}$ in some cases - highly accurate, solid state sensors are required with a wide operating temperature range. A permanent magnet with a stable field in this temperature regime is also required. The magnetic material SmCo is commonly used, so that the field experienced by an MR sensor is typically

in the range 0.2-0.4 T¹. At this field strength, MR sensors are relatively impervious to stray magnetic fields, such as those arising from the earth's permanent field, spot welds, loudspeakers introduced by the customer, or driving over electric railroad tracks.

An extensive study by Joseph Heremans of General Motors Research compared different sensor types capable of operating up to temperatures as high as 200°C . The technologies evaluated in this study were GaAs² and silicon Hall elements, GMR and AMR³ devices, and InSb MR sensors based on GM's own designs. For position sensing applications at

around 0.3 T, the field-dependent output voltage as a function of input current was 270 mV/mA for an InSb MR sensor, compared to only 11 mV/mA for a GaAs Hall element.² Si Hall elements and GMR and AMR³ sensors were saturated, although a Si Hall element integrated with a lower gain amplifier than the one used in the study could work (see graph).

As the sensitivity of any sensor can be increased by using an appropriate amplifier, a key parameter is the sensor resolution i.e. the smallest amount of magnetic field modulation that the sensor can detect in the presence of noise and drift. In the range 200 to 800 mT and between tempera-

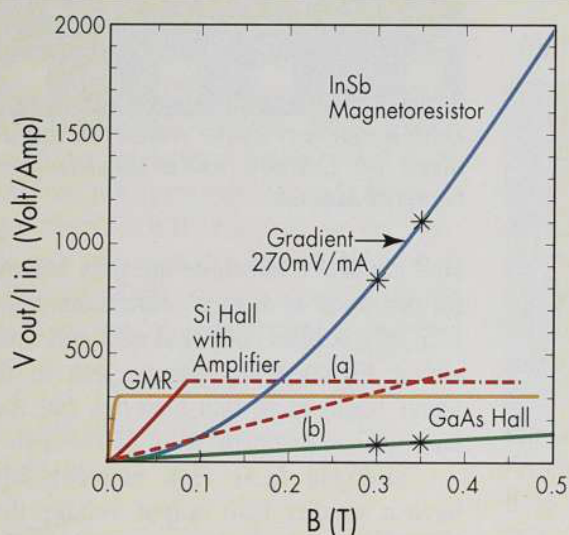
ture extremes of -60°C and 200°C , InSb MR sensors showed a resolution of 1.2 mT, some 30 times better than the other sensor types assessed.

The InSb MR technology developed by GM is based on $\sim 1.5\text{ }\mu\text{m}$ thick InSb films grown by MOCVD on GaAs substrates. The devices are fabricated by etching a mesa and covering it with shorting bars to prevent the Hall voltage from developing. Each device contains 172 active elements with a length of $20\text{ }\mu\text{m}$ and a width of $50\text{ }\mu\text{m}$. (see figures). The change of magneto resistance with field is proportional to the number of elements and inversely proportional to the thickness. Increasing the number of elements is expensive in terms of semiconductor real estate, while very thin layers have a low mobility due to a high density of defects.

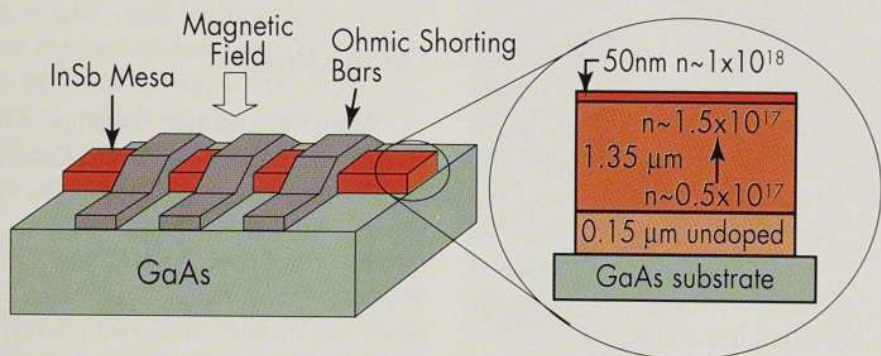
The devices are presently employed in dual-element configurations, where a differential measurement between the pair of sensors further reduces the effect of temperature-induced sensitivity variation (see box next page). In practice, the drift is limited largely by the mismatch between MR sensors, due to non-uniformities in electron density and mobility across the wafer, or to variations in contact resistance. Using a two-sensor system makes alignment and testing difficult, as well as being more expensive than using a single Hall or MR element.

Doping Profiles

As mentioned previously, n-type doping is necessary in such devices to control the mobility variation with temperature,



Output characteristics of various sensors, measured at room temperature. Between 0.3 and 0.35 T, the InSb MR output is 270mV/mA, compared to 11 mV/mA for the GaAs Hall element. GMR saturates at low fields. Replacing the Si Hall amplifier in (a) with a lower gain device (b) prevents saturation but significantly reduces the output.



Schematic showing shorting bars laid across an InSb mesa to form a multi-element MR device, together with a cross-section showing the generic epitaxial structure. Thicknesses and doping levels can be varied to achieve desired performance characteristics.

¹ The Tesla (symbol T) is the unit of magnetic flux density (symbol B). B measures the effect of a magnetic field on a medium. One gauss (G) is 10^{-4} T.

² The GaAs Hall elements used in this study were manufactured by Siemens using ion implantation. Siemens also sells InSb MR sensors, and GMR devices.

³ AMR (anisotropic magnetoresistive) materials such as permalloy (Fe/Ni) are ferromagnetic and demonstrate resistivity with components both parallel and perpendicular to the field. GMR (giant magnetoresistive) materials are alternating layers of magnetic and non-magnetic metals eg Co/Cu. An external field changes the magnetic orientation of the layers with respect to one another, thus changing the resistivity of the multilayers.



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and extend the operating temperature range. To maximize the sensitivity of the device, it is necessary to keep the mobility as high as possible, and the solution involves an optimized doping profile, rather than a uniform concentration throughout. 'It's not a matter of choosing a magic level,' says Dale Partin of GM Research. 'We need to determine the desired doping profile through the entire thickness of the film.'

InSb layers with a uniform n-type doping level throughout were found to have an electron mobility varying from a very low value at the substrate interface, up to around $36,000 \text{ cm}^2/\text{Vs}$ at the surface. This is attributed to the large substrate-epilayer lattice mismatch, resulting in a large number of dislocations that degrade the mobility near the interface. A substantial improvement in mobility was achieved by growing a nominally undoped buffer layer at the interface.

The surface contact region is doped at $n \sim 1 \times 10^{18} \text{ cm}^{-3}$ to provide a tunneling dominated, low-resistance contact, which is only a small fraction of the total resistance ($\sim 5 \Omega$) of each MR element. This is essential to allow the MR device to be driven at a fairly large current, and thus maximize the output voltage. Again, the doping level has to be optimized, as any undepleted part of the contact layer will create a parallel conductance in the active layer. Another feature of these devices is that there is a substantial increase in sensitivity to magnetic field in samples including a

doping gradient through the active region, so that the active layer is more highly doped near the surface. The most likely reason for this observed effect is that the spreading resistance, i.e. the distribution of current from the contacts into the rest of the device, is reduced by concentrating the current nearer to the surface of the device.

Partin reports that ongoing research at GM is targeting wider operating temperature ranges, and sensors that work well at lower magnetic fields. 'That would allow us to use cheaper materials for the permanent magnets,' he says. 'Also, we're looking at smaller chips to help reduce costs, and future plans include integrating 10 or more devices on a single substrate for various advanced functions.' In terms of MOCVD growth, GM has also been investigating heterojunction devices, alternative Sb precursors such as tris(dimethylamino) antimony, and looking into the effect of replacing Te with Sn as the n-type dopant.

Large Scale Production

To meet GM's production demand, the InSb MR design was licensed to Emcore, and the sensor became the first product of Emcore's Pegasus division in January 1997. The first generation product was a matched pair on a single substrate; a sort of magnetic ASIC. A more recent version allows the distance between the two sensors to be varied, according to different user requirements; this is about one quar-

ter the size of the ASIC, and correspondingly much cheaper.

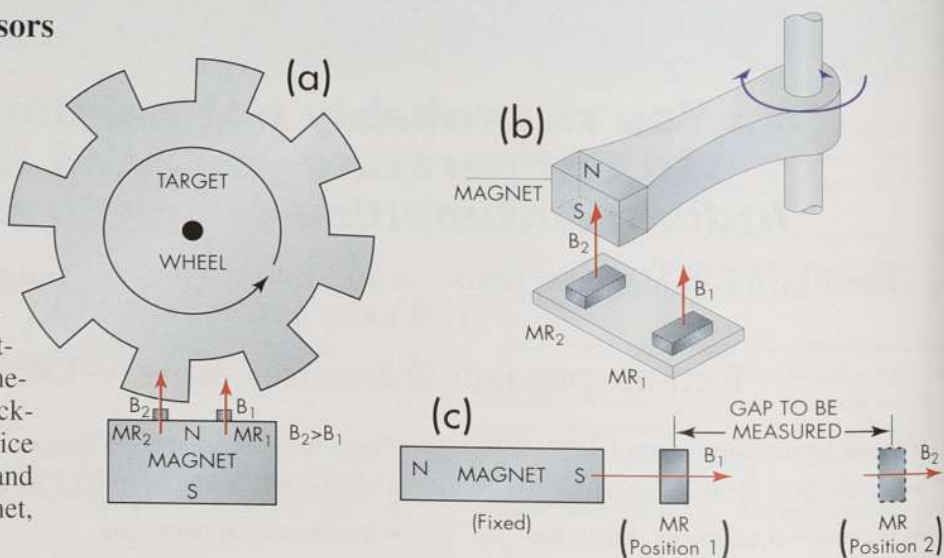
Pegasus produces die based either on new or customized designs generated internally, or in accordance with external designs on a foundry basis. On the MR sensor product line, Pegasus is using the technology licensed from GM to offer products tailored to a customer's requirements, and can for example trade-off sensitivity and cost. 'We are in the process of forming strategic alliances with OEM suppliers in the automotive markets,' says Lou Koszi, the VP in charge of Pegasus. 'Our license with GM gives other suppliers direct access to a design capability at the die level. Our custom engineering meets their needs, so they don't have to look for a compromised off-the-shelf product.'

Emcore is considering other products, such as MR sensors optimized for use as single elements rather than as a differential pair. 'This type of product could be a direct replacement for Hall elements,' says Koszi. 'By using only one die, and making better use of the epitaxial layer, we would be able to reduce the price significantly, and open up a much larger market.'

An excellent overview of solid state magnetic field sensors is given in J. Heremans, J. Phys. D: Appl. Phys. 1993, 26, p.1149. See also J. Heremans, Proc. MRS Spring meeting, 1997; and D. Partin et al, 'Doping profiles in InSb magnetoresistors', 1998, to be published in Sensors

Common Configurations for MR Sensors

In the toothed wheel configuration (a), the permanent magnet causes the two MR sensors to experience a flux density B_0 (typically 0.2-0.4 T). The motion of the wheel causes the fluxes B_1 and B_2 in the MR sensors to vary around the value B_0 , where $B_2 > B_1$ in the position shown in the diagram. The contactless potentiometer (b) measures the rotational position of the permanent magnet mounted on a shaft, as the change in differential magneto-resistance of the MR pair. A simple gap or thickness monitor (c) uses a single, movable MR device to measure the change in field close to (B_1) and further from (B_2) the fixed permanent magnet, where $B_1 > B_2$.



Research Review

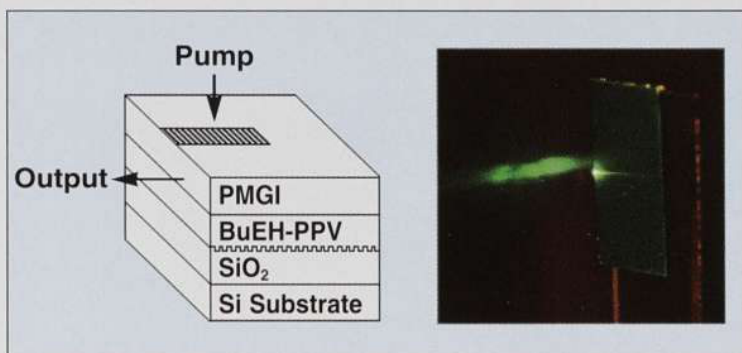
The following is a sampling of recent papers from a variety of international journals, compiled by the staff of Compound Semiconductor.

Compound Semiconductor Materials

Semiconducting Polymer DFB Lasers

M. McGehee et al, Appl. Phys. Lett., 1998, 72(13), p.1538

Photopumped DFB lasers fabricated using a semiconducting polymer had a lasing wavelength tunable from 540 - 583 μm by adjusting the period of the grating. The lasing medium was BuEH-PPV, an alkyl-substituted PPV derivative suitable for spin casting from solution. 150-350 nm thick films were deposited onto gratings (period 170-185 nm) etched into a 1 μm thick SiO_2 layer. The top, polymeric PGMI layer acts as a cladding layer. Two closely spaced modes were observed with 0.1-0.3 nm spacing, characteristic of DFB lasers with a periodic variation in refractive index. Above threshold, the light was fully polarized parallel to the substrate. The lowest threshold value ($\sim 1 \text{ kW/cm}^2$) was still too high to allow electrical pumping, or optical pumping by placing the structure monolithically onto a blue InGaN LED, but straightforward improvements in film quality should permit this. [Work carried out at the University of California at Santa Barbara]



Schematic of the DFB laser structure (stripe dimensions were 0.2 mm wide by 0.5-2 mm long) and photograph showing edge emission onto a white screen 5 mm from the edge.

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Individual Dopant Identification Using STM

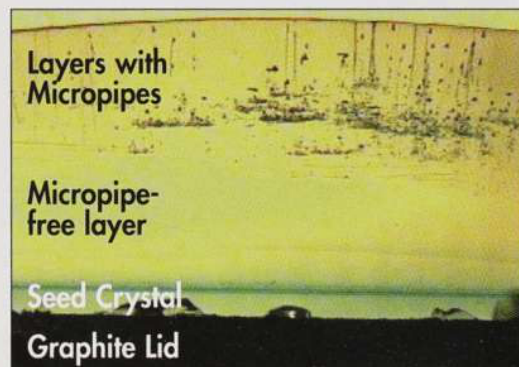
K-J, Chao et al, J. Vac. Sci. Tech., 1998, B16(1), p.453

Scanning Tunneling Microscopy (STM) exhibits a clear contrast between p and n regions in cleaved GaAs samples containing p-n junctions, but the same results cannot easily be achieved for silicon. This paper reports a spectroscopic technique (Scanning Tunneling Spectroscopy, STS) which samples the I-V characteristics of each pixel in a 64 x 64 2D grid. During measurement, there exists a metal-insulator-semiconductor (MIS) tunnel junction between the tip, the vacuum region and the surface. Since the I-V characteristics of p-MIS and n-MIS junctions are expected to be very different, this technique is able to image the p-n junction on a 10 nm scale for both GaAs and silicon. Also individual Zn dopants were observed as bright 'hillocks' on a cleaved GaAs (110) surface. The intrinsic surface states lie outside the bulk bandgap, and the tip-induced band-bending effect causes the p-type dopants to be negatively ionized. This produces an attractive coulombic potential for the free-carrier holes, resulting in the hillock features observed in the STM image. [Work carried out at the University of Texas at Austin]

Micropipe-free 6H-SiC Single Crystals

N. Schulze et al, Appl. Phys. Lett., 1998, 72(13), p.1632

SiC single crystals may be prepared by sublimation physical vapor transport (the so-called Lely technique). The growth crucible contains a 3C-SiC charge, and a seed crystal is attached to the underside of the graphite lid. Annealing with both source and seed at 2150°C under an argon pressure of 820 mbar resulted in the disappearance of surface defects (e.g. polishing scratches) from the seed crystal. At 30 mbar and a source temperature of 2180°C, and hence a thermal gradient of 5°C/cm, defect-free material was grown. However, reducing the pressure and increasing the thermal gradient resulted in a high density of micropipes. Using a micropipe-free seed and near-equilibrium (low thermal gradient) conditions, single crystal growth without micropipes was achieved at a maximum growth rate of 0.27 mm/hour. [Work carried out at the University of Erlangen-Nurnberg, Germany]



Optical micrograph, parallel to the c-axis of a 6H-SiC crystal, showing regions both with and without micropipes.

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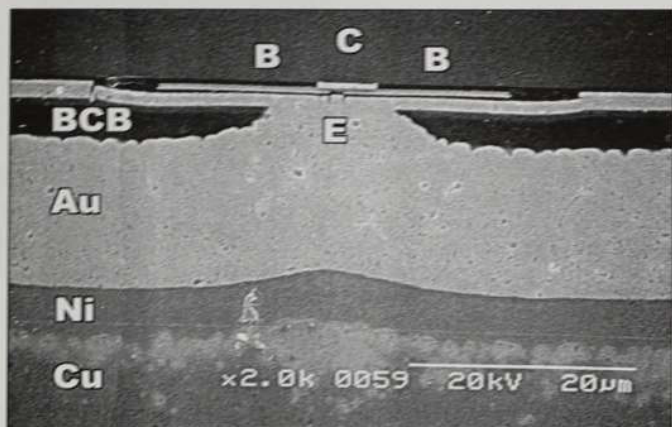
Microelectronic Devices and Circuits

HBTs Transferred to GaAs or Cu Substrates

Q. Lee et al, IEEE Elec. Dev. Lett., 2998, 19(3), p.77

J. Guthrie et al, Elec. Lett., 1998, 34(5), p.467

Use of HBTs in high bandwidth, high clock rate applications can require $f_{\max}$ and f_T to be several hundred GHz. The interconnect must have small inductance and capacitance per unit length, and wire lengths (and hence transistor spacings) must be small. Use of microstrip transmission lines over the wafer back surface can eliminate parasitic inductance, but the widely used through-wafer via processes can create other problems relating to thinning, and subsequent handling, of wafers. To maximize bandwidths, HBTs are biased at current densities in the order of 10^5 A/cm² so that efficient heat sinking becomes an issue. Both these papers from the



SEM photograph showing an InAlAs/InGaAs HBT transferred to a Cu substrate (BCB = benzocyclobutene, B = base, C = collector, E = emitter).

University of California at Santa Barbara describe transferred-substrate processes as alternative HBT IC fabrication technologies. The HBTs are conventional InGaAs/InAlAs structures grown by MBE on InP substrates. A low millimeter-wave loss polymer, BCB (benzocyclobutene) is used as the microstrip dielectric. Transistor heat sinking is provided by electro-plated gold thermal vias.

In the structure described by Lee et al, the gold ground plane is soldered to a GaAs carrier wafer before removal of the InP substrate, and formation of contacts and interconnects. An HBT with a $0.6 \times 25 \mu\text{m}$ emitter and a $0.8 \times 29 \mu\text{m}$ collector exhibited an f_T of 134 GHz and $f_{\max}$ in excess of 400 GHz. An alternative approach is to transfer to a Cu substrate, which provides enhanced thermal performance. After interconnect deposition on top of the device emitter and BCB spin deposition, the Au ground plane is formed. Sufficient electro-plated Cu is added to make the structure mechanically robust, and the InP is again removed. Both approaches present desirable wiring environments and efficient heat sinking.

Delta-doped InAs/AlSb HEMTs

C. Bolognesi et al, IEEE Elec. Dev. Lett., 1998, 19(3), p.83

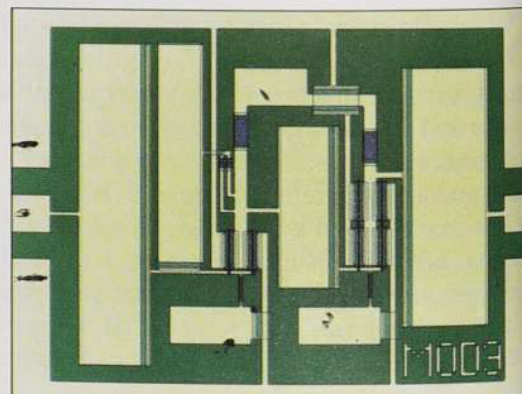
J. Boos et al, Elec. Lett., 1998, 34(4), p.403

The AlSb/InAs material system is promising for high speed, low power HEMTs due to the high electron mobility and velocity, high sheet charge density and good carrier density. Typically, Te is used as a dopant because Si is p-type in AlSb. Alternatively, Si delta-doping of ultrathin InAs layers provides an effective donor layer for the InAs channel. The doped and undoped InAs layers are separated and confined by AlSb. Bolognesi et al (Simon Fraser University, Canada, and Hughes) demonstrated $0.6 \mu\text{m}$ gate InAs/AlSb HEMTs with a transconductance of 800 mS/mm at V_{DS} of 0.8 V, with $f_T = 60$ GHz and $f_{\max} = 87$ GHz. The slightly different structure reported by Boos et al (Naval Research Labs) had $f_T = 75$ GHz and $f_{\max} = 100$ GHz for $V_{DS} = 0.5$ V and a $0.4 \mu\text{m}$ gate length.

Transimpedance Amplifiers in SiGe/Si

M. Saxarra et al, Elec. Lett., 1998, 34(5), p.499

Transimpedance amplifiers have important roles in front-end photoreceivers or low-noise amplifiers in communication systems. This work, from Ruhr-University Bochum, Daimler-Benz and Multilink, describes the first SiGe/Si transimpedance amplifiers. The MBE-grown MODFET structures have a relaxed SiGe graded buffer, an Sb-doped SiGe layer, an undoped spacer, a strained Si QW as the 2 DEG channel, a SiGe spacer, an Sb-doped SiGe layer, and cap layers. Devices were fabricated with 150 nm gate length and 120 nm gate width, and had a transconductance of 150 mS/mm. On-wafer S parameter measurements to evaluate circuit performance showed a high transimpedance of up to 72 dB Ω and a maximum bandwidth (at lower transimpedance) of 1.8 GHz. Further steps towards the modeled value of 4.84 GHz at 64.7 dB Ω are expected. The figure opposite shows a micrograph of the 2-stage transimpedance amplifier.



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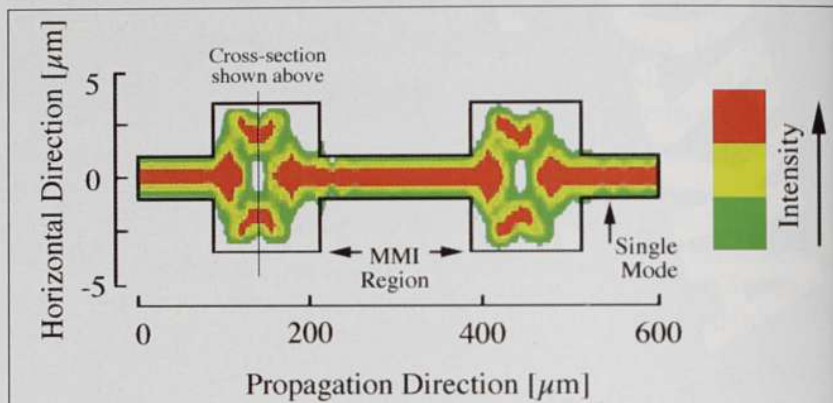
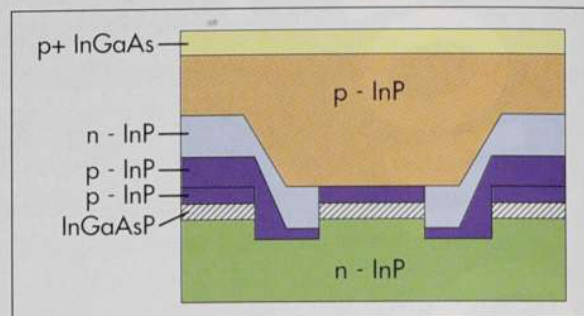
Creating the Right Chemistry

Optoelectronic Devices

High Power, Single Mode Lasers

K. Hamamoto et al, Elec. Lett., 1998, 34(5), p.462

High output power, single transverse mode lasers are attractive for long distance transmission and local area access. This work, carried out by the Institute of Quantum Electronics, Zurich, describes a buried heterostructure InGaAsP/InP laser diode incorporating two multi-mode interferometer (MMI) regions. The top figure shows a cross-section of the layer structure through the MMI region. The bottom figure shows a top-down view of the simulated intensity within the active waveguide structure. The MMI region is designed to effectively increase the active area of the diode while ensuring the output remains single mode. Compared to a conventional $2 \times 600 \mu\text{m}$ laser stripe with the same structure, the incorporation of MMI regions increased the output power by 90% to 27mW/facet, and also increased the slope efficiency by 20% to 0.12 W/A, for CW operation. The higher output power was also successfully coupled into single mode fiber.



10-Stage, Cascaded InAsSb QW laser

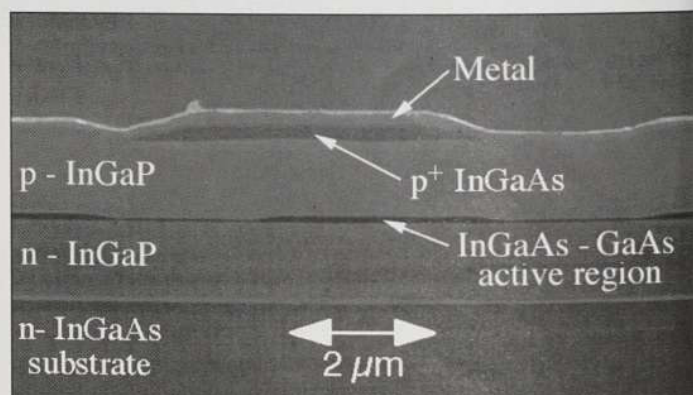
A. Allerman et al, Elec. Lett., 1998, 34(4), p.369

Multi-stage or cascaded structures in several material systems have been implemented to improve the performance of mid-IR ($2\text{--}6 \mu\text{m}$) lasers and LEDs. The Auger-limited lifetimes of interband devices are orders of magnitude longer than optical phonon lifetimes in unipolar devices. The laser reported here is among the most complex structures ever grown by MOCVD, incorporating not only 3 group III elements but also 3 group V elements, and consists of 10 stages. Each stage has a semi-metal layer formed from an n-InAs/p-GaAsSb heterojunction. This acts as a source of electrons and holes, which radiatively recombine in nearby quantum wells. Each active region contains 3 $\text{InAs}_{0.88}\text{Sb}_{0.12}$ QWs separated by $\text{InAs}_{0.76}\text{P}_{0.24}$ barriers, and there is a wide bandgap AlAsSb layer between each stage to prevent electrons escaping. Under pulsed conditions, lasing was observed at 80-170 K at a wavelength of 3.8-3.9 μm . The threshold current density at 80 K was 1 kA/cm² with a slope efficiency of 93 mW/A, corresponding to a differential quantum efficiency of 29%, or 2.9% per stage. [Work carried out at Sandia National Labs].

1.15 μm Al-free Lasers on Ternary InGaAs Substrates

A. Jones et al, IEEE Photon. Tech., 1998, 10(4), p.489

Lasers grown on InP substrates emitting at around 1.3 μm have a low characteristic temperature (T_0) due to the poor carrier confinement, whereas lasers on GaAs substrates are limited to about 1.1 μm . Using InGaAs substrates with a larger lattice-constant than GaAs increases the critical thickness of InGaAs QWs, hence increasing the wavelength and allowing high values of optical gain and T_0 . This report describes the growth of Al-free lasers on InGaAs substrates with a 3.03% molar composition of InAs. Following MOCVD growth of an InGaAs buffer and InGaP cladding layer, SiO_2 stripes were deposited. Selective area growth of the single strain-compensated InGaAs QW and GaAs barriers was followed by stripe removal, and growth of the upper cladding (InGaP) and contact layers. The measured wavelength of 1.15 μm exceeds the capability of InGaAs QW lasers grown on GaAs. Further improvements are expected using ternary substrates with a higher In composition. [Work carried out at the University of Illinois, Urbana, Crytsar Research, EG&G Canada, and Crystallod].



SEM photograph of a buried-heterostructure laser grown on a ternary InGaAs substrate.

New Products/New Literature

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Which GaAs Technology is Best for the Next Generation of Cell Phones?

DALE PFAU AND EARL LUM
CIBC OPPENHEIMER CORPORATION

It seems rather quaint now, but the first cellular phones (circa 1980) were 12V systems - they were designed to work off car batteries. Things have certainly changed since then. From the early 1990's onward 6V designs were dominant; but that technology has been almost entirely obsolesced by 4.8V designs.

This transition has been very good for the GaAs industry, as it has created significant demand for high efficiency power amplifiers (PAs). The next step in the evolution of wireless handsets is operation at 3.6V. Motorola and other phone manufacturers predict that this standard will dominate the rest of this decade and the beginning of the next.

The Next Generation

We are starting to see some differentiation within GaAs semiconductor technologies due to performance issues at 3.6V and below. The two key parameters for 3.6V battery technology are the nominal voltage (operating voltage) and the end voltage (or cutoff voltage). The end voltage is where the battery is at the voltage where it no longer discharges. For Li⁺ (lithium ion) technology, this is typically 3.0V but can be as low as 2.7-2.8V depending on battery construction. In the case of NiMH (nickel metal hydride) batteries, the nominal voltage per cell is 1.2V and the end voltage is typically 1.0V but can go as low as 0.9V.

The efficiency of the PA between 2.7V to 3V becomes a critical factor in terms of system level performance for the handset at the end of the battery discharge. Each handset supplier will specify different power, efficiency, voltage requirements to semiconductor suppliers,

depending upon the system level criteria and performance.

GaAs MESFET vs. Epi-Based Devices

Table 1 outlines efficiency performance of each of the three competing GaAs semiconductor technologies and how they perform at different battery voltages under CDMA modulation. Efficiency is one of the most crucial parameters to meet. Current CDMA specifications for

"Despite the fact that MESFETs are undoubtedly cheaper on a per wafer basis, we believe that the OEM handset industry will slowly but surely move away from MESFET technology and towards the more seemingly more "exotic" solutions of HBT and PHEMT. The compelling factors will be the intrinsic performance advantages of these device types, coupled with their advantageous die area cost - the latter factor being especially favorable for HBTs."

PA efficiency are concentrated at high power performance at $P_{out}=28.5\text{dBm}$, however, in a CDMA handset, the typical operational RF power level is between 15-18dBm, 10dB backed off from the high power level. By backing off from the high

power level, power added efficiency is greatly reduced and the idle current starts to play a more significant role in terms of overall current consumption of the PA. It is very important to note that efficiency, power gain, and linearity can be traded off against each other in order to customize performance to a particular system and this can be accomplished through the tuning of the output and through adjusting biasing currents.

Overall, we do not see any significant advantages or disadvantages between the different GaAs technologies at 3V operation in terms of efficiency. While the data for HBT does look slightly worse than PHEMT and MESFET, we believe that typical datasheet performance does not correlate to actual performance in a particular OEM handset.

One very important factor which affects PA efficiency and current drain in the battery is the quiescent current or bias current.

This is a constant DC current for the PA and therefore translates to constant power consumption of the battery, regardless of whether or not the PA is transmitting RF signals. The ideal situation would be zero quiescent or bias current when the PA is

Table 1

	MESFET	PHEMT	HBT
Digital CDMA Mode [1]			
$V_s = 3.6\text{ V}$	42% [3]	42% [4]	42% [5]
$V_s = 3.0\text{ V}$	42% [3]	40% [4]	42% [5]
Idle Current (mA)	100	60	40
Analog AMPS Mode [2]			
$V_s = 3.6\text{ V}$	70% [3]	63% [4]	64% [5]

Note [1] : $P_{out} = 28.5\text{dBm}$, $F = 1.9\text{GHz}$

Note [2] : $P_{out} = 31.5\text{dBm}$, $F = 800\text{ MHz}$

Note [3] : $I_{dq} = 100\text{mA}$, $F = 800\text{ Mhz}$

Note [4] : $I_{dq} = 60\text{mA}$, $F = 1900\text{ MHz}$

Note [5] : $V_s = 3.4\text{ V}$, $I_{cq} = 90\text{mA}$, $F = 800\text{ MHz}$

Source : Celeritek, RF Micro Devices, Anadigics Company Datasheets

not transmitting, therefore zero power consumption. In examining Table 1, HBT performance seems to have a much lower quiescent current bias than MESFET or PHEMT, but again, device performance will vary substantially across different applications and systems.

GaAs Device Technology Trends

Given the apparent equivalency of the three technologies in terms of efficiency, other factors become more important. In Table 2 we can see that the cost of MESFET wafers are 66% lower than PHEMT and HBT wafers, and that the cost per unit area of finished processed material is 32% lower for MESFETs. The mask steps are slightly lower for MESFET and PHEMT than HBT for a normal active device process but we expect that all three technologies are about the same for total mask steps when you add in the different mask steps for passive components.

Despite the fact that MESFETs are undoubtedly cheaper on a per wafer basis, we believe that the OEM handset industry will slowly but surely move away from MESFET technology and towards the more seemingly more "exotic" solutions of HBT and PHEMT. The compelling factors will be the intrinsic performance advantages of these device types, coupled with their advantageous die area cost - the latter factor being especially favorable for HBTs.

The knee voltages of all three technologies - shown in Table 3 - are sufficiently low that they should not adversely affect device performance at 3.0V. Also shown in Table 3 is a factor which is greatly in favor of HBT technology: MESFETs and HEMTs require the use of a negative supply generator - typically supplied either within the GaAs IC, or by adding a silicon charge pump IC. Also, MESFETs and HEMTs cannot be fully 'turned-off' during stand-by operation, due to their leakage characteristics. Therefore a PMOS switch is usually required in the handset, to fully turn off the current drain of the FET in order to prevent battery drain during standby. But HBTs can operate off a single supply and do not require the PMOS switch.

Table 2

GaAs Technology	Wafer Cost (100mm) [2]	Mask Steps	Unit Area Price (\$/mm ²) [1]
MESFET	\$200	10-12	0.25
PHEMT	\$750	10	0.33
HBT	\$750	14	0.33

Note 1 : Assumes 100% die yield

Note 2 : Assumes volume production quantities

Source : CIBC Oppenheimer Corp., Industry Sources

Table 3

GaAs Technology	Knee Voltage	Negative Gate Voltage
MESFET	0.5V	Yes
PHEMT	0.5V	Yes
HBT	0.6V	No

Source : CIBC Oppenheimer Corp., Industry Sources

Table 4

GaAs Technology	Relative Die Size	Die Area Cost (\$/mm ²)[2]
MESFET	1.00 [1]	0.25
PHEMT	0.65	0.21
HBT	0.33	0.11

Note 1 : Assumes MESFET die size as reference point for comparison

Note 2 : Assumes Unit Area Price x Relative Die Size

Source : CIBC Oppenheimer Corp., Industry Sources

Moreover, when we look at the relative die size, we begin to see some advantages to HBT and PHEMT technology. The data in Table 4 reflects a typical die size for a PA and uses MESFET die size as a figure of merit by which to compare PHEMT and HBT technologies. We believe that both PHEMT and HBT device structures can offer a smaller overall die size (active and passive components) than MESFET device structures and we believe that the relative die size of HBT and PHEMT technology may allow for more die per wafer and a lower overall die cost, assuming that device packaging and testing are technology independent. Of course, die size will vary widely depending on how much integration is used, including both active and passive components. Tradeoffs can be made to reduce die size including the elimination of most of the passive components in order to maximize the gross number of die per wafer. While actual die costs will vary substantially depending on die size and process variations, the data in Table 4 shows that it is possible that HBT technology may ultimately be the lowest cost.

Overall, we predict a general trend away from MESFETs, even though they have lower wafer costs and lower unit area prices. Even though MESFET performance is still acceptable and competitive against PHEMT and HBT, we believe that the higher electron mobility offered in PHEMT technology for power efficiency and the single supply voltage and smaller die size of HBT offer compelling value to the handset manufacturer. It is important to note that most major GaAs semiconductor suppliers have either PHEMT or HBT technologies in development or already in production. This trend is very significant in supporting the industry shift towards PHEMT and HBT.

About the Authors

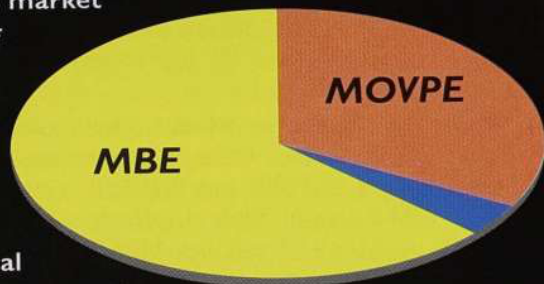
Dale Pfau is the executive director of wireless equipment research for CIBC Oppenheimer in San Francisco. Earl Lum is an equity analyst at Oppenheimer specializing in GaAs companies. Prior to joining Oppenheimer, he was a GaAs Industry analyst for Dataquest.

MBE or MOVPE? ...the choice has never been easier

Chances are you've read the claims made by MOVPE equipment manufacturers. They would like to turn the semiconductor world on its head and ignore some of the realities of the high-performance III-V device market.

The plain truth is that MBE is simple, reliable and cost-effective. It delivers on time, every time. Compared to MOVPE running costs are lower, operator training costs are lower and it is more reproducible. And it's comforting to know that MBE is safer and more environmentally friendly.

If you're involved in the rapidly growing wireless market you already know that MBE is the technology of choice for high performance microwave and mm wave devices. More than two thirds of the world's microwave epi is produced by MBE. VG Semicon's VI00 production MBE system revolutionized the pHEMT business, providing high yield, cost-effective epi at a critical time in the growth of the market. That's why with over twenty-seven multiple 4" systems installed and more on the way it's the system of choice for the world's leading GaAs companies. Put simply, it's not just the world standard for MBE, it's the world standard for Production Epitaxy.



SI Epitaxy Market

So if you value performance over rhetoric and your process needs throughput, reliability, performance and reproducibility, the choice has never been easier. Talk to VG Semicon, The MBE Company.

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USA	(1) 800 888 7007
	(1) 978 524 1041
Japan	(81) 3 3639 9652
France	(33) 1 6092 3610
Korea	(82) 2 548 2983
Taiwan	(88) 63 535 9771
Benelux	(31) 184 490909
Nordic	(46) 8 629 2400
Australia	(61) 2 898 1244



VG Semicon
The MBE Company

mbesales@vgsemicon.com



The following is our first directory of compound semiconductor-related materials suppliers. Included are 24 companies that deal in materials such as gases for use in epitaxy (hydrides, metalorganics, and others) and solid sources for MBE. Also included are several companies that deal in recycling and reclaiming III-V scrap.

In our last issue, which contained a directory of epiwafer vendors (CS 4(3), p. 24), we noted that several companies were expanding their capacity. The same is true for many -

perhaps all - of the materials suppliers, who are scrambling to keep up with the increasing production for III-V devices. This trend is most notable in the process gas area, where both Morton and Epichem have recently expanded their production of metalorganics, and Solkatrionic has set up a second plant for the production of arsine, phosphine and dopant mixtures.

Our next issue will include a directory of compound semiconductor substrate suppliers.

Akzo Nobel Chemicals Inc.

Deposition Chemicals
730 Battleground Road
P.O. Box 600
Deer Park, TX 77536 USA

Contact: Dick Pearce
TEL: [1] 281 479 8100 x299
FAX: [1] 281 479 4517
dick.pearce@akzo-nobel.com

Atlantic Metals & Alloys Inc.

PO Box 386
Old Greenwich, CT 06870 USA

Contact: Robert Knopf
TEL: [1] 203 359 8881
FAX: [1] 203 359 9948
atlmetal@ix.netcom.com

Atramet Inc.

222 Sherwood Avenue
Farmingdale, NY 11735-1718 USA

Contact: Gary Newman
TEL: [1] 516 694 9000
FAX: [1] 516 694 9177
BABL28h@prodigy.com

CMK Ltd.

Sandricka 30
Zarnovica 966 81 Slovakia

Contact: Alex Murin
TEL: [421] 858 412 141
FAX: [421] 858 412 125
cmk@psgnetzv.sk

Dowa Mining Co. Ltd

8-2 Marunouchi 1-Chome
Chiyoda-ku, Tokyo 100 Japan

Contact: Kishu Okuda
TEL: [81] 3 3201 1067
FAX: [81] 3 3201 1098
okudak@dowa.co.jp

Eagle-Picher Technologies LLC

P.O. Box 47
Joplin, MO 64802 USA

Contact: Bill Harsch
TEL: [1] 417 623 8000
FAX: [1] 417 781 1910
bharsch@epi-tech.com

Electron Transfer Technologies

155 Campus Plaza
PO Box 5812
Edison, NJ 08818 USA

Contact: William Ayers
TEL: [1] 732 225 3995
FAX: [1] 732 225 3580
wmaett@aol.com

Elemental/ Solid Sources	Hydrides & Alternative	Metalorganics	Recycling/ Reclaiming
		●	
●			●
●			
●			●
●			
●		●	●
	●		

Offers oxygen-free low silicon TMI TMG and TMAI select semiconductor grade OMVPE metalorganic sources. Users confirm very low oxygen and silicon levels via SIMS in AlInGaP and like layers. Certified NMR and ICPE analysis help insure purity. Other III-V sources and dopants available. World-wide distribution.

Offers high purity gallium metal with purity up to 7N. Also purchases Ga and GaAs scrap. Also a supplier of Pt group metals including Pt thermocouple wire.

Manufacturer of ultra high purity chemicals and metals including high purity beryllium, arsenic, red phosphorus and other MBE-grade chemicals.

Offers 4N Ga metal plus recapture of Ga from any GaAs scrap.

Producer of high purity Ga metal.

Over 45 years experience in the production of electronic grade materials. Producing UHP precursors high purity Ga & Ge metal. Also recycles GaAs and Ge-containing scrap.

Offers on-site AsH₃ and PH₃ gas generators which provide the highest purity gas available while eliminating the hazards of compressed gas cylinders. Gas generators available for MOCVD, GSMBE and doping applications.

EMF Limited
Winfor Church Road
Wentworth
Ely Cambridge CB6 3QE
United Kingdom

Contact: Jim Dixon
TEL: [44] 1223 364 080
FAX: [44] 1223 354 701
jd@emf.co.uk
Hydrides

Epichem Ltd.
Power Road
Bromborough
Wirral, Merseyside L62 3QF
United Kingdom

Contact: Lesley Smith
TEL: [44] 151 334 2774
FAX: [44] 151 334 6422
lesley@epichem.co.uk

Indium Corporation of America
1676 Lincoln Ave.
Utica, NY 13502 USA

Contact: David Minckler
TEL: [1] 315 853 4900
FAX: [1] 315 853 1000
askus@indium.com

Japan Energy Corporation
Compound Semiconductor Marketing
Dept.
10-1 Toranomon 2-chome
Minato-ku, Tokyo 105-8704 Japan

Contact: Hiroshi Miura
TEL: [81] 3 5573 6592
FAX: [81] 3 5573 6779
h.miura@j-energy.co.jp

Marketch International
4750 Magnolia Street
Port Townsend, WA 98368 USA

Contact: J.A. Spieckerman
TEL: [1] 360 379 6707
FAX: [1] 360 379 6907
mkt@olympus.net

Mining & Chemical Products
The Mill House
Laverstoke
Whitchurch, Hampshire RG28 7NS
United Kingdom

Contact: Malcolm Harrower
TEL: [44] 1256 897 226
FAX: [44] 1256 895 259

Morton International Inc.
150 Andover St
Danvers, MA 01923 USA

Contact: Robert Stennick
TEL: [1] 978 750 9490
FAX: [1] 978 750 4298

NIMTEC Inc
125 North Price Rd
Chandler, AZ 85224 USA

Contact: Kurt Williams
TEL: [1] 602 732 9857 x107
FAX: [1] 602 899 0779
nimteccs@ix.netcom.com

Picopolish
Route des Michels
Peynier F-13790 France

Contact: Gerard Gilles
TEL: [33] 442 291 979
FAX: [33] 442 291 970
picopolish@compuserve.com

Elemental/ Solid Sources	Hydrides & Alternative	Metalorganics	Recycling/ Reclaiming
●	●		
		●	
●			
●			
●			
●		●	
●			
●			●

Utilizes the proprietary DEOXTM process for the manufacture of metalorganics. This ensures high quality and eliminates oxygen impurities. Unique ultrapurge bubbles with 3 valve configuration eliminates contamination on bottle changes.

Offers UHP metalorganics. Proprietary adduct purification technology yields volatile compounds including those of Al, Ga, In, As, P, Zn, S, Sb, N and Mg. New facility in USA provides dual production capability and assures customers of uninterrupted delivery of critical metalorganic needs.

World's leading producer, refiner & fabricator of indium and indium chemicals. Indium is refined in Utica, NY where the company makes epitaxy sources and precursor materials.

Provides high purity In, Cd and Te metal.

Offers solid elemental sources and metalorganic precursors for compound semiconductors

Supplies high purity indium and gallium made to customer specific parameters in a variety of quantities and forms up to a purity level of 7N+. Production by fully equipped modern purpose built facility. Worldwide distribution.

Leading manufacturer of high purity metalorganic sources for MOCVD and related growth techniques. Our exclusive MorPure™ quality system is ISO-9001 certified and encompasses all aspects of our operations. Morton's new manufacturing plant located in North Andover, MA will use state-of-the-art production and analytical equipment to ensure the highest quality, most consistent sources available.

Provides high purity metals and source materials, including 7N & 6N In, 7N & 6N Cd and 7N & 6N Te

Recycling/repolishing GaAs wafers from 3 - 6" by unique patented process which produces ultra-pure clean epi-ready substrates. State-of-the-art facility in the heart of the French Silicon Valley in Provence. US\$7 million investment and a staff of 30 people highly skilled in semiconductor manufacturing.

PPM Pure Metals GmbH
Am Bahnhof 4
Langelsheim D-38685 Germany

Contact: Karl H. Pormann
TEL: [49] 5326 507 160
FAX: [49] 5326 507 151
ppm@ppmpuremetals.de

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Richardson, TX 75082

Contact: Mark McClear
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FAX [1] 972 479 8631
mark_mcclear@praxair.com

Promecome Electronics
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68 Ave. General Michel Bizot
75560 Paris Cedex 12 France

Contact: Dr. E. Prudhommeaux
TEL: [33] 1 4473 1070
FAX: [33] 1 4473 1053
s83325@a-arnaud.fr

Rhodia, Inc.
3 Enterprise Drive
Box 881
Shelton, CT 06484 USA

Contact: Nick Sullo
TEL: [1] 203 925 3391
FAX: [1] 203 925 8182

Solkatronic Chemicals, Inc.
30 Two Bridges Road
Fairfield, NJ 07004 USA

Contact: Nancy McGrath
TEL: [1] 973 882 7900
FAX: [1] 973 882 7967
info@solkatronic.com

Strem Chemicals
7 Muliken Way
Newburyport, MA 01950 USA

Contact: Ephraim Honig
TEL: [1] 978 462 3191
FAX: [1] 978 465 3104
ephraimhonig@strem.com

United Mineral & Chemical
1100 Valley Brook Ave
Lyndhurst, NJ 07071 USA

Contact: Irwin Drangel
TEL: [1] 201 507 3300
FAX: [1] 201 507 1506
inquiry@umccorp.com

Wafer Technology Ltd.
34 Maryland Road
Tongwell
Milton Keynes, Bucks MK15 8HJ
United Kingdom

Contact: Karen Lamb
TEL: [44] 1908 210 444
FAX: [44] 1908 210 443
klamb@wafertech.co.uk

Elemental/ Solid Sources	Hydrides & Alternative	Metalorganics	Recycling/ Reclaiming
●			●
	●		
●			●
	●		
		●	
●			
●			

Offers Ge, In, Ga, As, Sb, Cd, Cu, Zn, Sn, Pb, Te, Hg, Bi, Se and their compounds in 5N to 7N purity. Particular customer requirements regarding certain impurities are also taken into account. A workforce of ~100 people develops and manufactures >50 standard products; all product lines are certified under DIN EN ISO 9001.

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Offers several elemental sources including Furukawa As, Rhone-Poulenc Ga, VMC Al, Rasa In and P, Atomergic Be, Bi, Cd, Pb, Sb, Sn, Te, Zn, Se, and Th. Also gallium recycling, GaAs, InP reclaiming

Rhodia Chimie (formerly Rhone-Poulenc) is the world's largest manufacturer of gallium metal.

World's largest producer of Megabit & Megabit II arsine and phosphine. Also offering the newly developed Blue Ammonia for blue LED production. The only company with two separate manufacturing sites for arsine and phosphine, guaranteeing the security of your supply.

Manufactures MOCVD precursors including metalalkyls, alkylamides, alkoxides, betadiketates, volatile organometallics and metal carbonyls, fluorinated derivatives and single source precursors.

UMC has supplied the finest high purity materials for MBE and crystal growth for over 25 years. Furukawa As, Rasa Ga, In, Red P, B2O3, and Dow Sb in purities to 7N5 each supplied with GDMS lot certification from stock, in a variety of forms and packaging. Our rapid customer response is well known.

Offers polycrystalline granules of GaP or GaAs for use as solid MBE source materials.

Losses Mounting at SLI

MARIE MEYER

The annual report filed by Semiconductor Laser International (SLI) for the year ended December 31, 1997 proves that the company has continued to fail to find customers for its semiconductor laser diodes.

SLI reported a \$7.68M loss on sales of \$478,924. The cost of those sales was \$1.48M. SLI's losses have more than doubled over each of the past three years - the loss in 1995 was \$1.15M, and the loss in 1996 was \$3.38M. Their accumulated deficit is \$12.8M. No prediction of when the company might turn the corner on profitability was offered.

How much longer can the company go on? Cash on hand has declined to \$1.9M, compared to \$4.2M in 1996. SLI received just over \$3M of new financing but it was offset by the use of \$5.4M for the company's operations. Accounts receivable are \$201,070, and current liabilities are \$710,386. The company has available an unused, secured line of credit

for \$1M.

The best solution is, of course, to ship some products. But although the company claims a sales order backlog of \$3.2M as of April 1, past history suggests much of this won't be turned into income anytime soon. Case in point: SLI claimed to have a \$4M backlog on August 1, 1997 - but sales for the subsequent two quarters were just \$147,916 and \$152,008.

The company will likely rely on more financing to keep its doors open. A private placement in December which netted \$2.8M has kept the company afloat until now, but at the cost of seriously diluting the value of the existing shareholders' investments. And now there is more to come. According to the annual report, the company is planning to sell 1,650,000 additional shares at \$0.75, which should net around \$1M for SLI. Investors that participated in the initial public offering paid as much as \$5 per share just two years ago, and the stock was trading at

around \$9 at one point in 1997 - see chart, next page.

The company's strategic vision - at least insofar as it is described in the annual report - does not inspire a great deal of confidence in their future prospects. SLI chooses to emphasize the claimed superiority of their epigrowth process - basically, MBE growth with in-situ monitoring & real-time feedback control. Experienced observers will note that this is not a revolutionary approach. Several other companies - including Sharp, Uniphase Laser Enterprise (the former IBM Research in Zurich) and Coherent - are already in volume production of lasers using MBE-grown material. Other aspects of laser manufacturing, such as post-growth processing, packaging, and testing, are hardly mentioned, even though they are equally or more important than the epigrowth technique.

The company also touts its tie-up with Northwestern University that gives it access to some Al-free technology and related patents. But that R&D work was done using MOCVD, which creates an inconsistency in the company's basic "story". And despite SLI's claims for the exclusivity of their Al-free technology, they have plenty of competitors in this area, including Coherent, which is actually making and shipping Al-free lasers in higher volumes than SLI.

Most surprising is the company's choice of markets: apparently, they intend to focus on the production of red lasers for DVD, targeting an 8% market share in year 2000. But DVD player production is dominated by Japanese companies. Does

Company	Symbol	52 - Week		Closing Price		Change	Volume (000's)	P/E Ratio
		Hi	Lo	Jan 2	May 1			
Alpha Ind.	AHA	20 5/8	6 1/4	15 3/4	18 4/9	17%	87	18
Anadigics	ANAD	54 1/4	11 3/4	29 2/3	16 2/3	-44%	306	23
APA Optics	APAT	9 1/4	5 3/8	8 5/8	5 7/8	-32%	4	♦
ATMI	ATMI	42 1/4	16 3/8	23 1/8	27 1/4	18%	444	79
Celeritek	CLTK	18 3/8	9 1/2	13 1/2	10	-26%	45	17
Cree Research	CREE	29 1/2	10 5/8	17 3/4	16 4/5	-5%	234	43
Emcore	EMKR	25 1/4	11	19 1/4	13 7/8	-28%	58	♦
Kopin	KOPN	29	10 1/2	16 2/3	18 1/8	9%	52	♦
Ortel	ORTL	25	10 2/3	15 3/4	13 5/8	-13%	111	27
RF Micro Devices	RFMD	23 1/2	9 3/4	13	15 4/5	22%	136	♦
SDL	SDLI	27 3/4	12 5/8	15 1/8	24 3/8	61%	81	♦
SLI	SLIC	6 1/2	1/2	1 3/4	3/4	-57%	72	♦
Spire	SPIR	24 3/4	4 1/2	14 5/8	11 1/2	-21%	19	21
TriQuint	TQNT	45 1/2	17 3/8	20 1/4	23	14%	128	♦
Vitesse	VTSS	59 1/4	31 3/8	35 5/16	58 3/8	65%	690	54

♦ = loss in most recent 4 quarters



SLI really have the resources and skills needed to compete in Japan? Especially when their competition will be captive laser manufacturing capabilities which would presumably have the inside track? SLI plans to concentrate on the higher power models (>30mW) that are need for rewritable systems. But they will have

formidable competition. Sharp and Mitsubishi are already shipping such devices, and Hitachi, Matsushita, and Sanyo are known to be developing products (See CS 3(5), p. 24).

Moreover, the DVD market has, in fact, turned out to be something of a disappointment. The Electronic Industry Association of Japan has scaled back its forecast for DVD players to a little more than 10 million units per year by 2001. If this holds true, SLI's target would equate to less than 1 million units per year. Unless SLI has more to offer than their annual report reveals, it seems that the red ink will continue to flow.

Anadigics Update

As expected, Anadigics reported sharply lower sales, leading to a loss of \$1.1M for the first quarter. Net sales were \$18.8M, compared to \$28M for the previous quarter and \$22.9M for the year ago period. These results reflect a significant decrease in sales of power amps for wireless applications, as Anadigics loses market share to its competitors (see CS 4(3), p. 4). Wireless sales were just \$9.0M, down 48% from the \$17.4M reported for the previous quarter. And there may be worse yet to come: around 25% of Anadigics' wireless sales during the first three months of this year were for phone models which have been terminated. A \$1M charge was taken for obsolete inventory related to end of life products.

What is the way forward for Anadigics? On a recent conference call with investors, Ron Rosenzweig, President and CEO, said the key actions to increase wireless revenue were "first, to develop more efficient linear power amplifiers for the CDMA market, and second, sampling highly efficient 3V power amplifiers for all the major standards." He went on to say that the company was getting positive feedback from CDMA hand-

set manufacturers, and that Anadigics was in the running - but had not yet actually landed contracts - for 3V CDMA and TDMA phones at two OEMs for products that will be launched in 1999.

Anadigics is not considering switching away from its GaAs MESFET technology base. Because of the performance and low cost of the MESFET process, he said, "we haven't seen a need to accelerate PHEMT development or to really consider HBT development. We're very, very comfortable with the performance and cost of our products, and we think that they're going to be very, very competitive in the marketplace. As far as SiGe is concerned, we don't see that as a threat for the power amplifier business at all." He also said that they see the strongest competition from Si in GSM, because of the lower duty cycle and lower requirements for linearity. But in the more linear standards such as CDMA and TDMA, he said "we see less Si competition and more GaAs competition".

He also denied rumors that the company was for sale. No firm forecast was given for when the company would return to profitability.

1st Quarter Earnings

Alpha Industries reported income for the first quarter of \$3.7M, compared with a loss of \$5.3M for the year-ago period. Sales were \$31.9M, up 40%. Sales of GaAs ICs for wireless have increased 99% over the past 12 months. However, the company says that sales for the second quarter will be relatively flat.

Cree Research reported sales of \$10.6M for the first quarter of 1998, which represents a 53% increase over the year-ago period. Product revenue, which includes sales of LEDs, SiC wafers, and display products increased 60%. Net income was \$1.75M, up 217%. (For more on Cree, see page 13).

RF Micro Devices reported net revenues of \$12.6M for the quarter, after taking into account a revenue reduction of \$2.8M due to previously announced package-related product returns. This represents an increase of 38% over the corresponding quarter in 1997. GaAs HBTs comprised 81.5% of total revenues. Net loss for the quarter was \$3.6M, compared to a net income of \$864,000 for the year-ago period. The loss was due primarily to the packaging problems, which the company believes have been contained and corrected.

TriQuint revenues were a record \$23.7M, boosted by its newly acquired MMIC business (the former TI GaAs operation), resulting in a 41% increase over the comparable period of 1997. As anticipated, the company reported a net loss for the quarter of \$12.3M, due to three factors: one-time charges of \$8.8M for the acquisition of the MMIC business from Raytheon TI Systems; charges of \$1.4M related to the settlement of shareholder lawsuit dating from 1994; and "unexpected difficulties" encountered when transitioning to its new site in Hillsboro, OR.

Vitesse turned in yet another record-breaking quarter. Revenues were \$40.2M, up 64% over the year-ago period, and income was \$12.1M, compared to \$7.8M in the year-ago period. Vitesse has announced a 2-for-1 stock split, effective May 29.

In Our Next Issue:

More earnings reports, and coverage of the pending IPO from wafer maker AXT.

PATENTS

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

Sources:

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

"WO..." = World Intellectual Property Organization



Now
includes
International
Patents

Electronics

**05734183 / 1998 03 31 / Canon
Morishita, Masakazu**

Heterojunction Bipolar Transistor

Structure. A semiconductor device is provided with an emitter area and a collector area of a first conductive type and a base area of a second conductive type, arranged in a horizontal structure. The semiconductor device comprises an area constituting at least a part of the base area, being in contact with a part of the base area at least positioned between the emitter and collector areas, and having a narrower forbidden band than in the base area.

**05726463 / 1998 03 10 / GE
Brown, D. M et al.**

SiC MOSFET Having Self-Aligned Gate

Structure. A SiC MOSFET having a self-aligned gate structure is fabricated upon a monocrystalline substrate layer, such as a p type conductivity 6H silicon carbide (SiC) substrate. An SiC n+ type conductivity layer, epitaxially grown on the substrate layer, includes a steep-walled groove etched through the n+ SiC layer and partially into the p SiC layer. The groove is lined with a thin layer of silicon dioxide which extends onto the n+ type conductivity layer. A filling of gate metal over the layer of silicon dioxide is contained entirely in the groove. The silicon dioxide layer includes a first window extending to the filling of gate metal in the groove, and second and third windows extending to the n+ type conductivity layer on either side of the groove, respectively. A gate contact extends through the first window to the filling of gate metal in the groove while drain and source contacts extend through the second and third window, respectively, to make contact with the n+ type conductivity layer in drain and source regions on either side of the groove.

**05733805 / 1998 03 31 / Hitachi
Fujisaki, Y; Takano, Y; Ishiba, T**

Method Of Fabricating Semiconductor Device Utilizing a GaAs Single Crystal.

By exploiting an intense correlation exhibited between the distribution of lattice distortions in a wafer and the distribution of the threshold voltages of field effect transistors, the distribution of the lattice distortions in the wafer is reduced, thereby to mitigate the distribution of the characteristics of the semiconductor elements in the wafer. The difference between the maximum value and minimum value of the lattice distortions of a

GaAs single crystal at a normal temperature is set to at most 4×10^{-5} , and the density of Si atoms contained in the GaAs single crystal is set to at most $1 \times 10^{16} \text{ cm}^{-3}$, whereby the characteristics of semiconductor elements whose parent material is the GaAs single crystal can be made uniform.

**05729033 / 1998 03 17 / Hughes Electronics
Hafizi, Madjid**

Fully Self-Aligned Submicron

Heterojunction Bipolar Transistor. A submicron emitter heterojunction bipolar transistor and a method for fabricating the same is disclosed. The fabrication process includes lattice matched growth of subcollector, collector, base, emitter, and emitter cap layers in sequential order on a semi-insulating semiconductor substrate. An emitter cap mesa, an emitter/base/collector mesa and a subcollector mesa are formed. Dielectric platforms are formed extending the base/collector layers laterally. Sidewalls are formed on the sides of emitter cap mesa and the sides of the extended base/collector layers and undercuts are etched into the emitter layer and the upper portion of the subcollector layer. This forms an overhang on the emitter cap mesa with respect to the emitter layer and an overhang on the base/collector layers with respect to the upper portion of the subcollector layer. Emitter, base and collector contacts are simultaneously formed, the base contact aligned to the edge of the emitter cap overhang and the collector contact aligned to the edge of the base/collector layer overhang.

**EP0829906 / 19980318 / Hughes Electronics
Junction High Electron Mobility Transistor-Heterojunction Bipolar Transistor Monolithic Microwave Integrated Circuit.**

A highly uniform, planar and high speed JHEMT-HBT MMIC is fabricated using a single growth process. A multi-layer structure including a composite emitter-channel layer, a base-gate layer and a collector layer is grown on a substrate. The composite emitter-channel layer includes a sub-emitter/channel layer that reduces the access resistance to the HBT's emitter and the JHEMT's channel, thereby improving the HBT's high frequency performance and increasing the JHEMT's current gain. The multi-layer structure is then patterned and metallized to form an HBT collector contact planar HBT base and JHEMT gate contacts, and planar HBT emitter and JHEMT source and drain contacts.

**EP0829908 / 19980318 / Matsushita Electric
Kubo, Minoru et al**

Field-Effect Transistor And Method Of Producing The Same.

Si and SiGeC layers are formed in an NMOS transistor on a Si substrate. A carrier accumulation layer is formed with the use of a discontinuous portion of a conduction band present at the heterointerface between the SiGeC and Si layers. Electrons travel in this carrier accumulation layer serving as a channel. In the SiGeC layer, the electron mobility is greater than in silicon, thus increasing the NMOS transistor in operational speed. In a PMOS transistor, a channel in which positive holes travel, is formed with the use of a discontinuous portion of a valence band at the interface between the SiGe and Si layers. In the SiGe layer, too, the positive hole mobility is greater than in the Si layer, thus increasing the PMOS transistor in operational speed. There can be provided a semiconductor device having field-effect transistors having channels lessened in crystal defect.

**05729030 / 1998 03 17 / Mitsubishi Denki
Yamamoto, Y; Hayafuji, N**

Semiconductor Device (HEMT with AlGaAsPSb Electron Supply Layer).

A semiconductor device includes an InP substrate; a channel layer in which electrons, as charge carriers, travel; and an AlGaAsPSb electron supply layer for supplying electrons to the channel layer. The electron supply layer has an electron affinity smaller than that of the channel layer and is doped with a dopant impurity producing n type conductivity. Since n type AlGaAsPSb is thermally stable, its electrical characteristics are not changed by heat treatment at about 350°C ., resulting in a thermally stable and highly reliable HEMT in which the characteristics hardly change with the passage of time during fabrication and operation. Further, a heterostructure including an electron supply layer and a channel layer and having a desired energy band structure is easily produced with a wide degree of freedom in designing the device.

**05734670 / 1998 03 31 / Mitsubishi Denki
Ono, Kenichi & Motoda, Takashi**

Semiconductor Device, Semiconductor Laser, And High Electron Mobility Transistor.

A semiconductor device includes a semiconductor substrate having a surface; and a strained superlattice structure

Electronics, con't

including first semiconductor layers having a first strain in a direction with respect to the semiconductor substrate and second semiconductor layers having a second strain in the same direction as and different in magnitude from the first strain, the first semiconductor layers and the second semiconductor layers being alternately laminated. The difference in strains between the first semiconductor layers and the second semiconductor layers is reduced, so that the crystalline quality of the strained superlattice structure is improved.

**05726467 / 1998 03 10 / Rohm
Nakagawa, Yoshikazu**

Multiple Narrow-Line-Channel FET Having Improved Noise Characteristics. Insulating layers are formed, for instance, by ion injection, in a multilayer of compound semiconductor layers in regions spaced at predetermined intervals, to leave a plurality of narrow

channel layers between the insulating layers. A gate electrode is formed on the insulating layers and channel layers so as to traverse those layers.

**EP0833379 / 9980401 / Sanyo
Fujii, Emi et al**

Semiconductor Device And Manufacturing Method Thereof. An SiN anneal protection film is formed on a GaAs epitaxial growth substrate. A dummy gate 3 is formed with photoresist to form n+ layers and the dummy gate length is reduced. An SiO₂ film is formed all over the SiN anneal protection film and the dummy gate, and the SiO₂ film attached to the sidewall of the dummy gate is selectively etched, and a reverse dummy-gate pattern is formed by a lift-off process. Annealing is applied for a short time to activate the n+ layers. After that, mesa etching is performed for device isolation.

VCSELs

**05727014 / 1998 03 10 / Hewlett-Packard
Wang, S-Y et al**

VCSEL Generating Light With A Defined Direction Of Polarization. A VCSEL that generates light having a fixed direction of polarization. The laser has a plane light-generating region sandwiched between a first conductive mirror region and a second conductive mirror region. The light emission port and/or the core region has first and second dimensions in orthogonal directions in a plane parallel to the light-generating region. The first dimension is greater than the second dimension to set the direction of polarization of the light to the direction of the first dimension.

**05729567 / 1998 03 17 / Hewlett-Packard
Nakagawa, Shigeru**

Multilayer Film Structure And Vertical Cavity Surface Emitting Lasers. First and second layers are alternately laminated on the semiconductor substrate, providing a multilayer structure in which the resultant residual stress in the layered structure is significantly decreased. One embodiment of the invention is applied to a vertical cavity surface emitting laser having a dielectric multilayer mirror comprised of pairs of a first layer (SiO₂ layer) and a second layer (TiO₂ layer).

**05732103 / 1998 03 24 / Motorola
Ramdani, J; Lebby, M; Jiang, W.**

Long Wavelength VCSEL. A VCSEL for emitting long wavelength light including a first mirror stack lattice matched to the surface of a substrate and including mirror pairs in a II-VI material system, an InP based active region lattice matched to a surface of the first mirror

stack, and a second mirror stack lattice matched to a surface of the active region and including mirror pairs in a II-VI material system. An electrical contact is coupled to a surface of the active region and an electrical contact is positioned on another surface of the active region. In a specific embodiment the II-VI material system includes ZnCdSe/MgZnCdSe.

**05732101 / 1998 03 24 / Samsung
Electronics
Shin, Hyun-kuk**

VCSEL Device And Optical Pickup Apparatus Adopting The Same. The present invention relates to a vertical cavity surface emitting laser (VCSEL) device and to an optical pickup apparatus adopting the same, and more particularly, to a VCSEL device in which an optical source and a photodetector are integrally formed on a semiconductor substrate, and an optical pickup apparatus adopting the same.

**EP0829933 / 19980318 / Xerox
Guerin, Jean-Michel**

VCSEL Integral Feedback Assembly. There is disclosed a raster output scanner which utilizes a vertical cavity laser diode (VCSEL) assembly with an integral set of detectors for the purpose of individually monitoring and adjusting the output power each laser diode. A semi-transparent and semi-reflective plate is positioned to allow a portion of each light beam to pass through and reflects the remaining portion of each light beam back onto the detectors of the VCSEL assembly to provide a feedback to adjust the output power of its respective laser diode.

Other Laser Diodes

**05734771 / 1998 03 31 / Lucent Technologies
Huang, Sun-Yuan**

Packaging Assembly For A Laser Array Module. An optical subassembly comprises a two-dimensional semiconductor laser array having a plurality of laser diodes arranged in rows and columns. The laser diodes are configured to provide laser lights at a first and a second direction. A first lenslet module is disposed adjacent the semiconductor laser array, such that light emitted from the laser array in the first direction is collected by the lenslet module. The lenslet module is further configured to focus the collected light at a given first focal point that may be disposed on a receiving end of a fiber optic. A second lenslet module is disposed adjacent the semiconductor laser array, such that light emitted from the laser array in the second direction is collected by the second lenslet module. The second lenslet module is further configured to focus said collected light at a given second focal point disposed at the receiving end of a photodetector.

**05729561 / 1998 03 17 / Mitsubishi Denki
Hironaka, Misao**

Semiconductor Laser Device. A semiconductor laser device includes a semiconductor laser chip; a heat sink; a solder layer adhering the semiconductor laser chip to the heat sink; a lower electrode on the semiconductor laser chip including a non-alloying layer not alloyed with the solder layer and opposite the heat sink and directly opposite to a center line in a longitudinal direction of a light emitting region of the semiconductor laser chip and alloying layers on regions of the lower electrode, except for the region of the non-alloying layer, alloyed with the solder layer. Internal stress due to the difference in coefficients of thermal expansion of the semiconductor laser chip and the heat sink and applied to the light emitting region is reduced, and GaAs destruction at the light emitting region is prevented.

**WO9812779 / 19980326 / Northwestern Univ.
Razeghi, Manijeh**

Method Of Making An InAsSb/InAsSbP Diode Laser. InAsSb/InAsSbP/InAs Double Heterostructures (DH) and Separate Confinement Heterostructure Multiple Quantum Well (SCH-MQW) structures are taught wherein the ability to tune to a specific wavelength is possible by varying the ratio of As:Sb in the active layer.

**05727015 / 1998 03 10 / Sharp
Takahashi, K; Kounushi, F; Taneya, M**

DFB Semiconductor Laser. A gain coupled distributed feedback semiconductor laser includes an active layer and a diffraction grating provided in the vicinity of the active layer and having a plurality of light absorption layers periodically arranged along a resonator

Other Laser Diodes

length direction. The order of the diffraction grating is one, a duty of the diffraction grating is in the range of about 0.4 to about 0.8, and a thickness of the light absorption layer is in the range of about 6 nm to about 30 nm.

**05732099 / 1998 03 24 / Sony
Kawasumi, Takayuki et al**

Semiconductor Light Emitting Device.

A p-type GaAs current block layer is stacked on a (100)-oriented n-type GaAs substrate, and a stripe-shaped groove is formed in the p-type GaAs current block layer to extend in the <01-1> direction. Side surfaces of the groove has the maximum inclination not larger than 60°. The thickness of the p-type GaAs current block layer is 1.5 micron or more. Stacked on the structured substrate having the current narrowed mechanism via an n-type ZnSe buffer layer are an n-type ZnMgSSe cladding layer, n-type ZnSSe waveguide layer, active layer, p-type ZnSSe waveguide layer, p-type ZnMgSSe cladding layer, and others, to establish an index-guided inner-stripped semiconductor laser having SCH structure and CSPW structure.

**05734671 / 1998 03 31 / Sumitomo Electric
Katsuyama, Tsukuru et al**

Semiconductor Laser Diode.

A semiconductor laser diode which can be applied to optical fiber amplifiers to attain a high reliability and can generate light having a wavelength of about 1 micron is provided. This semiconductor laser diode is formed on a GaAs substrate and has an active layer comprising a GaInAsP strained quantum well whose energy band gap is smaller than that of GaAs. Barrier layers each comprising GaInAsP whose band gap is greater than that of the active layer are bonded to the active layer through heterojunction. According to this structure, when the active layer and the barrier layers are grown, the amounts of supply of a Ga material and an In material can be controlled in a simple manner and a semiconductor laser diode having a high reliability can be realized.

**05727013 / 1998 03 10 / Wisconsin Alumni
Research Foundation
Botez, D. & Kasraian, M.**

Single Lobe Surface Emitting Complex Coupled DFB Semiconductor Laser. A high power monolithic surface emitting semiconductor laser provides a single lobe far-field radiation profile which is emitted normal to the plane of a surface of the semiconductor laser structure. The semiconductor laser includes an active region layer at which light is emitted and a complex-coupled distributed feedback grating positioned to act upon light from the active region. The adjacent elements of the distributed feedback grating differ from one another in both refractive index and gain/loss. The grating period, or the combined width of the two adjacent grating elements, is selected to be equal to a full wavelength in the semiconductor structure of the light emitted from the active region. Lasing occurs in a symmetric mode, resulting in emission of light from a planar surface of the semiconductor structure perpendicular to the surface, the grating layer and the active region layer as long as the modal-gain difference between symmetric and antisymmetric modes due to optical-field overlap with the gain/loss grating overcomes the modal-gain difference based on radiation losses.

GaN LEDs

**05734182 / 1998 03 31 / Nichia Chemical
Nakamura, S; Mukai, T; Iwasa, N**

Light-Emitting Gallium Nitride-Based Compound Semiconductor Device.

A light-emitting gallium nitride-based compound semiconductor device of a double-heterostructure is disclosed. The double-heterostructure includes a light-emitting layer formed of a low-resistivity $\text{In}_x\text{Ga}_{1-x}\text{N}$ ($0 < x < 1$) compound semiconductor doped with p-type and/or n-type impurity. A first clad layer is joined to one surface of the light-emitting layer and formed of an n-type gallium nitride-based compound semiconductor having a composition different from the light-emitting layer. A second clad layer is joined to another surface of the light-emitting layer and formed of a low-resistivity, p-type gallium nitride-based compound semiconductor having a composition different from the light-emitting layer.

**EP0828302 / 1998 03 11 / Sharp
Hata, Toshio**

GaN LED. A gallium nitride group compound semiconductor light-emitting device comprises substrate and a layered structure provided on the substrate. The layered structure includes: an active layer; an upper cladding layer and a lower cladding layer which is located closer to the substrate than the upper cladding layer, the active layer interposed between the cladding layers; an internal current constricting layer having an

opening for constricting a current within a selected region of the active layer, the internal current constricting layer being provided on the upper cladding layer; a surface protecting layer for covering the internal current constricting layer and an exposed surface of the upper cladding layer in the opening of the internal current constricting layer; and a regrowth layer provided on the surface protecting layer. The surface protecting layer serves as a protecting layer for the upper cladding layer and the internal current constricting layer in a step of forming the regrowth layer.

**05733796 / 1998 03 31 / Toyota Gosei
Manabe, Katsuhide et al**

Light-Emitting Semiconductor Device Using Gallium Nitride Group Compound.

A light-emitting semiconductor device using a gallium nitride compound semiconductor (AlGaIn) having an iL-layer of insulating gallium nitride compound semiconductor containing a low concentration of p-type impurities. An iH-layer of insulating gallium nitride compound semiconductor containing a high concentration of p-type impurities is adjacent to the iL-layer. An n-layer of n-type gallium nitride compound semiconductor of low carrier concentration is adjacent to the iL-layer. An n+ -layer of n-type gallium nitride compound semiconductor of high carrier concentration doped with n-type impurities is adjacent to the n-layer.

Other Optoelectronics

**EP0828299 / 1998 03 11 / Matsushita
Electric
Wada, Takahiro et al.**

Compound Semiconductor And Thin Film Solar Cell.

This invention provides a compound semiconductor which can be used for an absorbing layer of a thin-film solar cell. The compound semiconductor is characterized in that it belongs to a I2m space group with a stannic structure and is from the CuInGaSeS material system. It has a larger band gap than the corresponding compound semiconductor having a chalcopyrite structure.

**05733689 / 1998 03 31 / Oki Electric
Ogihara, M et al**

Led Array Fabrication Process With Improved Uniformity.

A method of fabricating an LED array includes (a) forming a first insulating film composed of aluminum oxide on a semiconductor substrate of a first conductive type; (b) patterning the first insulating film by photolithography to form a plurality of first windows; (c) diffusing an impurity of a second conductive type through the plurality of first windows into the first insulating film, thereby forming a plurality of diffusion regions of the second conductive type below the plurality of first windows; (d) forming a second insulating film on the first insulating film and the plurality of first windows; (e) patterning the second insulating film by photolithography to remove the second insulat-

Other Optoelectronics

ing film from the plurality of first windows, using an etchant that does not etch the first insulating film; (f) forming a metal film on the second insulating film and the plurality of first windows; and (g) patterning the metal film by photolithography to form a plurality of electrodes which make electrical contact with respective diffusion regions.

**05734494 / 1998 03 31 / Oki Electric
Xu, Chang Qing & Okayama, Hideaki**

Wavelength Conversion Device And Wavelength Conversion Method. A wavelength conversion device includes a wavelength conversion element. The wavelength conversion element includes a ridge waveguide layer made of nonlinear optical crystals as being a zinc-blend material. The waveguide layer is provided on a GaAs substrate made of the zinc-blend material. The waveguide layer is made of InGaAsP and interposed between clad layers made of InGaP. With this arrangement, signal light and pumping light are incident upon the wavelength conversion element (DFG or SFG element) while the pumping light is fixed in a TE polarization direction. Alternatively, the signal light may be fixed in the TE polarization direction.

**05726465 / 1998 03 10 / Temic
Gerner, J.; Gillesen, K.; Marshall, A**

Light Emitting Diode. An light emitting diode of indium gallium aluminum phosphide with a substrate, an electrical contact to the substrate, a dual hetero structure as a active zone comprising a first cladding layer, an active layer and a second cladding layer to which, a window layer is applied, and to which in turn, an electrical contact is applied. This window layer is made of gallium aluminum phosphide.

**05729020 / 1998 03 17 / Toshiba
Matsushita, K; Shigenaka, K; Fukuda, K**

Hybrid Type Infrared Detector. The hybrid type infrared detector includes a plurality of photodiodes constructed by p-n junctions made of compound semiconductor material on a silicon substrate, a signal processing portion formed on another substrate, and a connecting member for electrically connecting the plurality of photodiodes with the signal processing portion, and for injecting carriers generated by the photodiodes into the signal processing portion, and is characterized in that partitioning portions are formed along the cleavage plane of the compound semiconductor material.

**05731213 / 1998 03 24 / Toshiba
Ono, Reiji**

Semiconductor Light Receiving Device And Method Of Manufacturing The Same. The present invention relates to a semiconductor light receiving device and a method of manufacturing the same and, more particularly, to a semiconductor light receiving device having a return light blocking mechanism and a method of manufacturing the same.

**05732098 / 1998 03 24 / Toshiba
Nisitani, Katsuhiko et al**

LED Display Device. A semiconductor light emitting device has a double heterostructure. The device is composed of an active layer and clad layers that sandwich the active layer. At least one of the clad layers has a multilayer structure having at least two element layers. The Al mole fraction of an element layer, which is proximal to the active layer, of the multilayer structure is smaller than that of the other element layer thereof distal from the active layer. This arrangement improves the crystal quality of an interface between the active layer and the clad layer of multilayer structure and effectively confines carriers in the active layer.

Materials

**05725659 / 1998 03 10
Sepehry-Fard, Fareed**

Solid Phase Epitaxy Reactor, The Most Cost Effective GaAs Epitaxial Growth Technology. Apparatus for performing SPE deposition for growing layers of semiconductive material includes a reaction chamber and means for mounting a substrate wafer and a source wafer in the reaction chamber. The substrate wafer and the source wafer are maintained at a predetermined distance which is less than the mean free path of the reactive species of the oxido-reduction of the semiconductive material. A heater for heating the wafers maintains a temperature difference of 20°C to 40°C between the wafers.

**05728425 / 1998 03 17 / Fujitsu
Ebe, H; Sawada, A; Takigawa, H**

Method for CVD of Semiconductor Films (Including HgCdTe). A method and apparatus in which separate steps are used between feeding source gases and growing films in a process of chemical vapor deposition (CVD) for compound semiconductor films. In one embodiment, a CVD reactor chamber has a piston which can change the volume of the chamber to control the pressure of the source gases therein. After source gases are fed to the chamber having a substrate under the condition that no CVD

takes place due to an insufficient vapor pressure, the chamber is kept closed for a few seconds, and then pressurized by the piston to start CVD. A typical result indicates that a Hg_{1-x}Cd_xTe (where x=0.2) film on a 3-inch CdTe wafer has only 1% (or x=0.002) inhomogeneity in composition.

**05729029 / 1998 03 17 / Hewlett-Packard
Rudaz, Serge L.**

Maximizing Electrical Doping While Reducing Material Cracking in III-V Nitride Semiconductor Devices. N-type doping in III-V-nitride semiconductor compounds, i.e. GaN-based compounds such as GaN, AlGaIn, AlInN, InGaIn, or AlGaInN, can be optimized to improve N-contact electrical resistance, carrier injection, forward voltage, and recombination characteristics without inducing cracking of the device layers. The N-type layer is constructed of sub-layers such that an N-type sub-layer is provided for each desired characteristic or property. The thickness of each sub-layer is carefully selected to avoid material cracking: the higher the required doping, the smaller the corresponding thickness. In illustration, the buffer layer of a light emitting device (LED) has three sub-layers. The first sub-layer is lightly doped to avoid cracking and is grown to the desired thickness for good material quality. The second sub-layer is heavily doped to provide good N-contact and electrical resistivity char-

acteristics and is kept correspondingly as thin as necessary to avoid material cracking. The third sub-layer is doped to the desired level to provide optimum carrier injection and pair recombination in the active layer of the device.

**05726494 / 1998 03 10 / NEC
Nashimoto, Y. & Tsutsui, H.**

Semiconductor Device Having A Plated Heat Sink. A semiconductor device having a plated heat sink structure is provided, in which an Au layer high in thermal expansion coefficient is formed on the lower surface of a GaAs substrate having a source electrode, a gate electrode and a drain electrode of a field effect transistor on the upper surface, and, a W layer low in thermal expansion coefficient is formed on the lower surface of the Au layer. Warping of the device after mounted on a package is reduced on the ground of such a plated heat sink structure.

**05728623 / 1998 03 17 / NEC
Mori, Kazuo**

Method of Bonding a III-V Layer on a Silicon Substrate. Prior to a heat treatment for bonding a III-V group compound semiconductor layer on a silicon substrate, a thermal stress relaxation layer is provided between the silicon layer and the III-V group compound semiconductor layer thermal stress

Materials, con't

relaxation layer, having a thermal expansion coefficient equal or near to the thermal expansion coefficient of the III-V group compound semiconductor layer and having a rigidity coefficient being sufficiently large to suppress generation of any crystal defects in the III-V group compound semiconductor layer due to a thermal stress generated in the heat treatment and subsequent cooling stage by the difference in the thermal expansion coefficient between the III-V group compound semiconductor layer and the silicon layer.

**05726462 / 1998 03 10 / Sandia
Spahn, O & Lear, K.**

Semiconductor Structures Formed From an AlSb-Alloy Layer. The semiconductor structure comprises a plurality of semiconductor layers formed on a substrate including at least one layer of a III-V compound semiconductor alloy comprising Al and Sb, with at least a part of the AlSb-alloy layer being chemically converted by an oxidation process to form superposed electrically insulating and electrically conducting portions. The electrically insulating portion formed from the AlSb-alloy layer comprises an oxide of Al (e.g. Al₂O₃), while the electrically conducting portion comprises Sb. A lateral oxidation process allows formation of the superposed insulating and conducting portions below monocrystalline semiconductor layers for forming many different types of semiconductor structures having particular utility for optoelectronic devices such as light-emitting diodes, edge-emitting lasers, vertical-cavity surface-emitting lasers, photodetectors and optical modulators (waveguide and surface normal), and for electronic devices such as heterojunction bipolar transistors, field-effect transistors and quantum-effect devices. The invention is expected to be particularly useful for forming light-emitting devices for use in the 1.3-1.6 micron wavelength range, with the AlSb-alloy layer acting to define an active region of the device and to effectively channel an electrical current therein for efficient light generation.

**05727008 / 1998 03 10 / Sanyo
Koga, K.**

Semiconductor Light Emitting Device. A semiconductor light emitting device and a semiconductor laser device having an epitaxial growth layer composed of a III-V group nitride semiconductor. An AlN buffer layer, an n-type GaN intermediate layer, an n-type AlGaIn cladding layer, an InGaIn active layer and a p-type AlGaIn cladding layer, and a p-type GaN contact layer are successively formed on an n-type 6H-SiC substrate having a {0001} crystal growth plane. A p-side electrode is formed on the upper surface of the p-type GaN contact layer, and an n-side electrode is formed on the lower surface of the n-type 6H-SiC substrate, after which the n-type 6H-SiC substrate is cleaved along a {1120} plane to form a cavity facet.

**05731209 / 1998 03 24 / Shin-Etsu
Yamada, M; Yanagisawa, M; Higuchi, S**

Method For The Determination Of Nitrogen Concentration In Compound Semiconductor. An efficient method is proposed for the determination of the concentration of nitrogen in an indirect-transition compound semiconductor such as gallium phosphide added as an isoelectronic trap. The method utilizes the fact that a good correlation of proportionality is held between the nitrogen concentration and the difference in the absorption coefficient of light of a wavelength identical with the wavelength due to the excitons under constraint in the isoelectronic trap between the semiconductors and without addition of nitrogen.

**05725658 / 1998 03 10 / Sumitomo Electric
Sawada, Shin-ichi**

Heat-treatment Method of III-V Materials. It is an object to prepare a wafer in which no slips are generated when the epitaxial growth is carried out. In order to achieve this object, a method is provided in which; an ingot is heated and cooled in a range between an upper limit temperature Th, and a lower limit temperature Tl where the upper limit temperature ranges from more than 800°C to less than a melting point of a material of the ingot, and the lower limit temperature ranges from more than 800°C to less than the upper limit temperature Th. The reciprocating changing between of heating and cooling steps is repeated a plurality of times at a speed A of raising temperature and a speed B of lowering temperature where the speed A of raising temperature is lower than the speed B of lowering temperature. The residual stress is excluded by this heat-treatment method, and, consequently, no slips occur in the peripheral part of a wafer obtained by this invention.

**05731224 / 1998 03 24 / Temic
Gerner, Jochen**

Method For Manufacturing Ohmic Contacts For Compound Semiconductors. A method for manufacturing ohmic contacts on an n-doped semiconductor layer of a III-V compound semiconductor. An AuGeNi layer is formed on the n-type III-V compound semiconductor, where the thickness of the AuGeNi layer is between 50 and 200 nm and both the germanium and the nickel concentration in the AuGeNi layer are less than 1 percent by weight. An Au layer with a thickness of between 250 and 1000 nm is applied to the AuGeNi layer. These layers are not alloyed but tempered either at a temperature between 430 and 480 °C. for a period between 5 and 20 seconds or at a temperature between 360 and 400°C. for a period between 40 and 180 minutes. The metal semiconductor contact produced in this way has a low contact resistance and is free from the inhomogeneities of alloyed AuGeNi contacts.

Misc.

**05728215 / 1998 03 17 / Mitsubishi Denki
Itagaki, T; Takemi, M; Hayafuji, N**

Method For Forming A Film By Selective Area MOCVD Growth. A method for forming a film by selective area growth by MOCVD technique includes forming a mask on a semiconductor substrate having a (100) plane, the mask having a mask opening to selectively growing a compound semiconductor layer, and a slit which is narrower than the mask opening in width and controls the growth rate of the compound semiconductor layer at the mask opening; and selectively growing the compound semiconductor layer at a growth rate which is on the mask in the mask opening and the slit.

**05730802 / 1998 03 24 / Sharp
Ishizumi, T & Kaneiwa, S**

Vapor Growth Apparatus And Vapor Growth Method Capable Of Growing Good Productivity. A vapor growth apparatus and a vapor growth method is capable of growing a compound semiconductor layer having an evenness and an interfacial sharpness in units of atomic layers with a good productivity. A growth chamber has a cylindrical portion and an end plate which closes an upstream end of the cylindrical portion. The end plate is provided with a cation gas material supply inlet and an anion material gas supply inlet, while an exhaust device is provided on the downstream side of the cylindrical portion. A substrate holder having a substrate support surface is provided in the cylinder portion. A gas separating member separates flow paths of material gases from each other, thereby forming on the substrate support surface a plurality of material gas supply areas to which the material gases are independently supplied. A drive device rotates the substrate holder with a substrate set on the substrate support surface thereof around the center line of the cylindrical portion. Then a cation material and an anion material gas are alternately supplied to the surface of the substrate.

**05728212 / 1998 03 17 / Sumitomo Electric
Inoue, T & Hagi, Y**

Method Of Preparing Compound Semiconductor Crystal. A method which can prepare a compound semiconductor crystal doped with an impurity and having a prescribed carrier concentration with excellent reproducibility comprises the steps of melting a raw material for the compound semiconductor crystal in a crucible, and controlled cooling the obtained raw material melt, thereby growing a crystal. The time required for cooling the raw material melt from the melting point T of the raw material to 2/3T is so controlled as to adjust the carrier concentration to a prescribed level.

1998 MTT-S International Microwave Symposium

MTT '98 will be held June 7-12, 1998 at the Baltimore Convention Center in Baltimore, MD.

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1998 IEEE Radio Frequency Integrated Circuits Symposium

RFIC '98 will be held Jun. 07, 1998 - Jun. 12, 1998 at the Baltimore Convention Center in Baltimore, MD (in conjunction with MTT '98).

Contact: Dr. Vijay Nair
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European MRS 1998 Spring Meeting

The 1998 E-MRS Spring Meeting will be held June 16 - 19, 1998 in Stasbourg, France. Symposia include Growth, Characterization and Applications of Bulk II-VI's; Thin Films, Epitaxial Growth and Nanostructures; and Nitrides and Related Wide Band Gap Materials.

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4th International Workshop on Expert Evaluation and Control of Compound Semiconductor Materials and Technologies

EXMATEC 98 will be held June 22-24, 1998 in Cardiff, Wales, UK. This conference aims to bring together research, development, and production specialists involved in compound semiconductor material physics, chemistry, process technology, and device fabrication.

Contact: Cherrie Summers
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1998 Device Research Conference

The 1998 DRC will be held at the University of Virginia in Charlottesville, VA on June 22-24, 1998

Abstract Submission Deadline:
March 2, 1998
Contact: Emmanuel Crabbe
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crabbe@watson.ibm.com

Third European GaN Workshop

EGW-3 will be held June 22-24, 1998 in Warsaw, Poland. This meeting will encompass all areas of research related to physical properties, crystal growth, epitaxy, doping, processing, device manufacturing and applications of nitride semiconductors.

Abstract Submission Deadline:
March 1, 1998

Contact: Conference Secretariat
EGW-3
High Pressure Research Center
01-142 Warsaw, Sokolowska 29/37
Poland
TEL [48 22] 632 5010
FAX [48 22] 632 4218
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stach@unipress.waw.pl or
http://www.unipress.waw.pl/
/egw-3/info.html

1998 Electronic Materials Conference

The 40th EMC will be held at the University of Virginia in Charlottesville, VA on June 24-26, 1997. This conference provides a forum for topics of current interest and significance in the areas of preparation and characterization of electronics materials. Individuals actively engaged or interested in electronic materials research and development are encouraged to attend this meeting, and papers in this general subject area are solicited.

Abstract Submission Deadline:
February 6, 1998
Contact: Barbara Loitwood
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1998 IEEE Photovoltaics Specialist Conference

Wien, Austria July 6-10, 1998
Abstract Submission Deadline:
December 1, 1997
Contact: JRC-Ispra

WCN2

Ispra (VA) Italy I-21020
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OE Expo '98

The 1998 International Optoelectronics Exposition will be held July 11 - 14, 1998 in Taipei, Taiwan. The only annual optoelectronics exhibit in Taiwan, this conference provides an excellent introduction to this rapidly expanding market. Areas of interest in include materials, optoelectronic components, equipment and systems, and processing equipment related to the optoelectronic industry.

Contact: Photonics Industry & Technology
Development Association
Taipei, Taiwan
FAX [886] 2 396 8513

ICCG-12 & ICVGE-10

The Twelfth International Conference on Crystal Growth in conjunction with the Tenth International Conference on Vapor Growth and Epitaxy will be held July 26 - 31, 1998 at the Renaissance Jerusalem Hotel in Jerusalem, Israel
Abstract Submission Deadline:
November 1, 1997

Contact: Conference Secretariat
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FAX [972] 3 5160604
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http://www.technion.ac.il/~iccg12

China-US Workshop on GaN

The China-US Workshop on GaN sponsored by the Chinese Department of Education and Chinese Natural Science Foundation will be held at Peking University, Beijing, China August 17-22, 1998. The workshop is co-organized by Peking University in China and Kansas State University in US. The workshop provides a forum for topics of current interest and significance on the areas of GaN and related wide bandgap semiconductors. Several key researchers in this fields are expected to attend and give lectures on the workshops. Individuals actively engaged or interested in GaN and related materials research and development are encouraged to attend this meeting.

Contact: Prof. H. X. Jiang
Department of Physics
Kansas State University

Manhattan, KS 66506-2601

TEL [1] 785 532 1627
FAX [1] 785 532 5636
Net or Web: Jiang@phys.ksu.edu

10th Int'l Conference on Molecular Beam Epitaxy

MBE-X will be held August 31 - September 4, 1998 in Cannes, France. This conference will cover the full spectrum of MBE-related topics, in the pleasant surroundings of the south of France. Topics of interest include: MBE growth of semiconductors, metals, insulators and other materials; applications and devices; alternative sources and methods; novel in-situ process control; nanostructure engineering; control of surfaces and interfaces; production technology and manufacturability issues.

Abstract Submission Deadline:
March 15, 1998

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

6th Int'l Conf. on Terahertz Electronics

THz 98 will be held September 3-4, 1998 in Leeds, England. This conference has established itself as the pri-

Conference Notes New Entries

- China-US Workshop on GaN, August 17-22, 1998, Beijing, China
- II-VI Workshop, October 20-22, 1998, Charleston, SC
- 1999 Photonics West Conference, January 23-29, 1999, San Jose, CA
- 1999 Int'l Solid-State Circuits Conference, February 15-17, 1999, San Francisco, CA
- OFC 1999, February 21 - 26, 1999, San Diego, CA.

mary meeting for the terahertz electronics research community. Its main goal is to provide a forum for the exchange of information on the theory, technology and application of the emerging and interdisciplinary field of terahertz electronics, and to foster an appreciation of the capabilities and future directions of this technology.

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

First Int'l School on Crystal Growth Technology

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

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

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

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

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

First Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems

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

high frequency circuits, passive device development, reliability and yield, and applications. Three copies of a full-length paper (up to 10 pages) are expected by the deadline.

Abstract Submission Deadline:
May 15, 1998.

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

1998 IEEE Bipolar/BiCMOS Circuits and Technology Meeting

BBCTM '98 will be held Sep. 27 - Sep. 29, 1998 in Minneapolis, MN. This meeting provides a forum for technical communication focused on the needs and interests of bipolar and BiCMOS engineers. Papers covering the design, performance, fabrication, testing and application of bipolar, BiCMOS and BiFET ICs, bipolar phenomena, and discrete devices are solicited.

Abstract Submission Deadline:
March 16, 1998

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

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

The 2nd ISBLLED Conference will be held September 29 - October 2, 1998 in Chiba, Japan. The main objective of this symposium is to provide a joint forum for both the GaN community and the ZnSe community to discuss common problems extending from the growth and characterization of materials to device performance and reliability. Papers are solicited in many areas, including, but not limited to, the following: substrate issues; epitaxy; p-type doping; material characterization; device degradation mechanism; device processing; ohmic contacts; device design; laser oscillation mechanism; detectors; and new materials.

Abstract Submission Deadline:
May 15, 1998

University of Tsukuba
Institute of Materials Science
1-1-1 Tennodai
Tsukuba, Ibaraki 305 Japan
TEL [81] 298 53 5287
FAX [81] 298 55 7440
Net or Web: hasegawa@mat.ims.

tsukuba.ac.jp or http://www.etl.go.jp/etl/divisions/material/isblled2/isblled2.html

17th North American MBE Conference

NAMBE-17 will be held Oct. 4-7, 1998 on the Penn State campus in State College, PA. Researchers from all fields who use MBE in their work with all types of materials are invited to attend. Papers presented at this conference describe recent advances associated with MBE in materials growth technology for research and production, measurement and control, materials characterization, electronic, photonic, and novel devices, and quantum structures.

Abstract deadline: May 30, 1998.

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

1998 IEEE/LEOS Semiconductor Laser Conference

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

Abstract Submission Deadline:
May 8, 1998

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

European Microwave Week (Including GAAS '98)

The new "European Microwave Week" event will be held October 5 - 9, 1998 in Amsterdam, The Netherlands. This event incorporates three previously existing conferences: The European GaAs Applications Symposium (GAAS '98), The European Microwave Conference (EuMC '98), and The MTT-S European Topical Congress on Technologies for Wireless Applications (MTT-S European Wireless '98).

Contact: David Roberts
Miller Freeman Plc
Microwave Engineering Europe
30 Calderwood Street
London SE18 6QH UK
TEL [44] 181 855 777 x 5953
FAX [44] 181 316 3174
Net or Web: droberts@unmf.com

25th Int'l Symp. on Compound Semiconductors

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

Abstract Submission Deadline:
May 18, 1998

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

3rd Int'l Workshop on Novel Index Surfaces

NIS '98 will be held October 6 - 9, 1998, 1998 in La Casona (San Rafael), Spain. The scope of this conference is the growth, characterization and exploitation of epitaxial compound semiconductors on novel index surfaces. All communications in close relation with the topics of the workshop are welcome: growth mechanism of III-V and II-VI compounds on high index planes; patterned growth and regrowth; relaxation of pseudomorphic layers; self assembling quantum wires and dots; doping and defect incorporation; spontaneous ordering and composition modulation; piezoelectric effects and applications; structural, optical and electronic properties; devices using above novel physical properties; and theoretical aspects

Abstract submission deadline:
May 15, 1998

Contact: Mariano Gonz-lez
ETSI Telecomunicaci3n-UPM
Ciudad Universitaria
28040-Madrid, Spain
FAX [34] 1 336 73 23
Net or Web: mariano@die.upm.es
http://www.die.upm.es/research/nis98.htm

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

The 1998 II-VI Workshop will be

The 1998 Electronic Materials Conference (EMC) will be the 40th in a series of conferences intended to provide a forum for topics of current interest and significance in the area of preparation and characterization of electronic materials. Sponsored by the Electronic Materials Committee of The Minerals, Metals & Materials Society (TMS), the conference will be held on the campus of University of Virginia, Charlottesville, Virginia, June 24–26, 1998.

The EMC is again being coordinated with the Device Research Conference of the Institute of Electrical and Electronics Engineers (IEEE), which will be held at the same location, June 22–24, 1998. This coordination is made in recognition of the strong interaction between electronic materials and device research, and should provide for a maximum exchange of information between attendees of both conferences.

In addition to the very strong technical program, the EMC will sponsor an exhibit of electronic materials technology and services.

PLAN TO ATTEND

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West Lafayette, IN 47907-1285
Telephone: (765) 494-3528
Fax: (765) 494-6441
E-mail: melloch@ecn.purdue.edu

For complete up-to-the-minute information on this and all TMS-sponsored and -cosponsored meetings visit the TMS World Meetings Calendar on the World Wide Web at <http://www.tms.org/Meetings/Meetings.html>.

held October 20-22, 1998 in Charleston, SC. The purpose of this workshop is to bring together the universities and industrial and governmental communities that work with II-VI materials, including HgCdTe and other IR materials, II-VI semiconductor alloys used for X-ray and gamma-ray detectors, ZnSe-based II-VU photonic materials, and II-VI photorefractive materials.
Abstract Submission Deadline: May 8, 1998

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

1998 IEEE GaAs IC Symposium

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

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

194rd Meeting of the Electrochemical Society

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

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

45th National AVS Symposium

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

Abstract Submission Deadline: May 1, 1998

Contact: Marion Churchill
AVS
120 Wall Street
New York, NY 10005 USA
TEL [1] 212 248 0200
FAX [1] 212 248 0245
Net: marion@vacuum.org
Web: http://www.vacuum.org

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

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

Abstract Submission Deadline: September 1, 1998

Contact: Dr M Missous
UMIST, EE& E Dept.
PO Box 88
Manchester M60 1QD UK
TEL [44] 161 200 4797
FAX [44] 161 200 4770
Net or Web:
missous@fs4.ee.umist.ac.uk or
http://www.ee.umist.ac.uk/new
ledmo98.html

1998 Fall MRS Meeting

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

Abstract Submission Deadline: June 8, 1998

Contact: Materials Research Society
506 Keystone Drive
Warrendale, PA 15086-7573 USA

TEL [1] 412 779-3003
FAX [1] 412 779-8313
Net or Web: webmaster@mrs.org
or http://www.mrs.org

1998 IEEE International Electron Devices Meeting

The 1998 IEDM will be held Dec. 06-Dec. 09, 1998 in San Francisco, CA.

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

Conf. on Optoelectronic and Microelectronic Materials and Devices

COMMAD '98 will be held December 14-16, 1998 in Perth, Australia.

Abstract Submission Deadline: August 31, 1998

Contact: Lorenzo Faraone
Univ. of Western Australia
EEE Department
Nedlands, WA 6907 Australia
TEL [61] 8 9380 3104
FAX [61] 8 9380 1095
Net or Web:
faraone@ee.uwa.edu.au
http://www.ee.uwa.edu.au/
~COMMAD98

Photonics West

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

Abstract Submission Deadline: June 29, 1998
Contact: SPIE

PO Box 10
Bellingham, WA 98227 USA
TEL [1] 360 676 3290
FAX [1] 360 647 1445
Net or Web: spie@spie.org or
http://www.spie.org

1999 Int'l Solid-State Circuits Conference

ISSCC '99 will be held February 15-17, 1999 in San Francisco, CA. Original papers are solicited in several areas. The theme for this year is High-Bandwidth Systems. Papers targeting high-speed, high-bandwidth applications in all of the above areas are solicited. Examples of IC technologies and circuits related to products and prototypes that leverage and exploit the use of increased bandwidth in processors, memory architectures, wireless systems, data communications, networks, multimedia and video systems are especially encouraged.

Abstract Submission Deadline: September 11, 1998

Contact: ISSCC '99
Diane Suiters
Courtesy Associates
2000 L Street N.W. Suite #710
Washington, DC 20036 USA
TEL [1] 202 973 8667
FAX [1] 202 331 0111
NET isscc@courtesyassoc.com

OFC 1999

The 1999 International Conference on Integrated Optics and Optical Fiber Communication will be held February 21 - 26, 1999 in San Diego, CA.

Contact: Ms. Lisa Myers
OSA Conference Services
2010 Massachusetts Ave., NW
Washington, DC 20036-1023
TEL [1] 202 416-1980
FAX [1] 202 416-6100
Net or Web: ofc.info@osa.org
http://www.osa.org

If you would like your conference to be included in future issues, send the appropriate information by E mail to calendar@compsem.com, or by FAX to [1] 978 750 9740, attention "Calendar"
Contributions must be received by June 5 to appear in our next issue.

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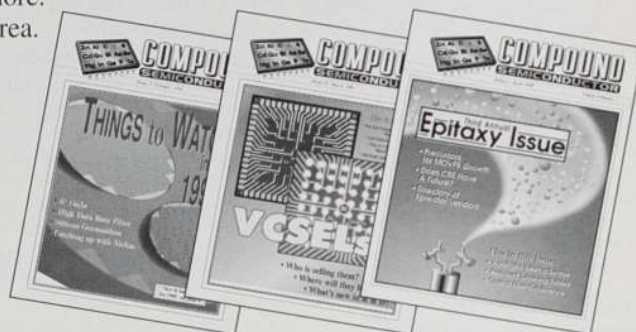
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