GALLIUM

By Deborah A. Kramer

Domestic survey data and tables were prepared by Carolyn F. Crews, statistical assistant.

Gallium imports, which had fallen significantly from 2001 to 2002, began to recover in 2003, increasing by 8% from the level in 2002. An upturn in the wireless communications market and a growing U.S. economy helped to propel the increase in gallium consumption. Gallium arsenide (GaAs) wafers, however, continued to be manufactured in such countries as China, the Republic of Korea, and Taiwan, and imports of undoped GaAs wafers into the United States increased by 89% from the level in 2002. Gallium nitride (GaN) continued to be the focus of research and development activities. Some new devices with GaN components were introduced in 2003, but significant commercial shipments of GaN were expected to begin in 2004, particularly with the introduction of digital video disk (DVD) recorders with GaN laser diodes. More than 95% of the gallium consumed in the United States was in the form of GaAs, which was principally used in integrated circuits (ICs) and optoelectronic devices [mostly laser diodes and light-emitting diodes (LEDs)].

Estimated crude gallium production was 70 metric tons (t) in 2003. Principal world producers were China, Germany, Japan, and Russia. Gallium also was recovered in Hungary, Kazakhstan, Slovakia, and Ukraine. Refined gallium production was estimated to be about 98 t; this included some new scrap refining. France was the largest producer of refined gallium using gallium produced in Germany as feed material. Japan and the United States also refined gallium. Gallium was recycled from new scrap in Germany, Japan, the United Kingdom, and the United States.

Legislation and Government Programs

The U.S. Department of Energy released two studies that analyzed and estimated energy savings of solid-state lighting (mainly LEDs). One study estimated the energy savings potential if solid-state lighting can achieve certain price and performance criteria. The report considered two scenarios—one where the technology receives a moderate national investment of $50 million per year and an accelerated scenario based on an investment of $100 million per year. Under the moderate investment scenario, in 2025, the energy savings associated with solid-state lighting could total approximately 114 terawatthours (TWh) or the equivalent annual electrical output of about 14 large powerplants. Under the accelerated investment scenario, in 2025, the total energy savings could be about 326 TWh, representing the output of more than 40 large powerplants (Navigant Consulting Inc., 2003b§[1]).

The second study that looked at LED use in niche applications concluded that LED traffic signals use only 10% of the electricity consumed by the incandescent lamps they replace, and they last much longer, allowing for additional savings through reduced maintenance costs. Exit signs were identified as another important niche application, where an estimated 80% of U.S. exit signs now use LEDs. LEDs also have made inroads into mobile applications, such as brake and signal lights on automobiles, buses, and trucks. To date, 41 million gallons per year of gasoline and 142 million gallons per year of diesel fuel have been saved because of LED use on these vehicles. (Fuel savings were calculated based on the lower accessory load on the engine.) If all automobiles, buses, and trucks were to convert to LED lighting, 1.4 billion gallons per year of gasoline and 1.1 billion gallons per year of diesel fuel could be saved (Navigant Consulting Inc., 2003a§).

Production

No domestic production of primary gallium was reported in 2003 (table 1). After Eagle-Picher Technologies LLC exited the gallium business in 2002, a group of former executives from the company purchased Eagle-Picher's gallium assets and formed a new company Gallium Compounds LLC in March 2003. The new company's products will remain high-purity gallium trichloride and gallium metal, but it will not recover gallium from GaAs or other scrap material (Evans, 2003). This leaves Recapture Metals Inc. in Blanding, UT, as the only gallium reprocessor in the United States. Recapture Metals recovered gallium from scrap materials, predominantly those generated during the production of GaAs. Recapture Metals facilities have the capability to produce about 40 metric tons per year of high-purity gallium. The company recovered gallium from its customers' scrap on a fee basis and purchased scrap and low-purity gallium for processing into high-purity material.

Gold Canyon Resources Inc. did not report any progress on its Cordero gallium project in Humboldt County, NV, in 2003, nor did Win-Eldrich Mines Ltd. progress on its Painted Hills gallium deposit in Humboldt County. Both companies continued to develop their gold properties.

Consumption

More than 95% of the gallium consumed in the United States was in the form of GaAs. GaAs was manufactured into optoelectronic devices (LEDs, laser diodes, photodetectors, and solar cells) and ICs. ICs and optoelectronic devices each accounted for 41% of domestic consumption, 18% was used in research and development, and less than 1% was used in other applications (table 2).

Gallium consumption data were collected by the U.S. Geological Survey from a voluntary survey of U.S. operations. In 2003, there were 14 responses to the consumption of gallium

[1]References that include a section mark (§) are found in the Internet References Cited section.

survey, representing 74% of the total canvassed. Data in tables 2 and 3 were adjusted by incorporating estimates to reflect full industry coverage. Many of these estimates were based on the companies' 2003 10-K reports submitted to the Securities and Exchange Commission.

Gallium Arsenide.—In July, Agilent Technologies Inc. announced that it would close its fiber-optic-component manufacturing plant in Ipswich, United Kingdom, transfering the epitaxy and wafer processing activities for lasers and photodetectors to its new $92 million facility in Yishun, Singapore, which opened in February 2003. The vast majority of Agilent's optoelectronic devices already were fabricated in Singapore. Agilent also had transferred its entire vertical-cavity surface-emitting laser (VCSEL)-component manufacturing business to Singapore from California. Therefore, with the exception of Lumileds (Agilent's joint venture with Philips Lighting) Agilent had moved all its optoelectronic device manufacturing out of the United States (Compound Semiconductor, 2003a). Agilent operated a manufacturing plant for 6-inch-diameter GaAs wafers in Ft. Collins, CO.

Because it was unable to find a buyer for its Colorado Springs, CO, GaAs-wafer manufacturing facility, Vitesse Semiconductor Corp. wrote down its equipment, facilities, and inventory in the third quarter. The company had announced that it was exiting the GaAs business in 2002 (Compound Semiconductor, 2003t).

In October, AXT Inc. sold its optoelectronics business to Lumei Optoelectronics Corp. for $9.6 million. AXT produced VCSELs, edge-emitting lasers, and nitride-base LEDs at its facilities in California and China (Compound Semiconductor, 2003c). AXT continued to produce GaAs substrates at a plant in China.

In June, RF Micro Devices Inc. (RFMD) announced that it had successfully completed its first major customer qualification of its 6-inch-GaAs-wafer manufacturing capabilities. RFMD's 6-inch-wafer production began at its second facility in Greensboro, NC, in the first quarter of 2003 after a conversion from 4-inch processing that began in late 2002. The company's first facility, which continued to process 4-inch wafers, had a capacity of 60,000 wafers per year (Compound Semiconductor, 2003i).

In January, TriQuint Semiconductor Inc. completed the acquisition of a substantial portion of the Agere Systems (formerly Microelectronics Group of Lucent Technologies) optoelectronics business for $40 million. The transaction included the products, technology, and some facilities related to Agere's optoelectronics business. Within 3 months of signing the deal, TriQuint Semiconductor consolidated Agere's manufacturing facilities into two operations—a wafer- and chip-fabrication plant in Breiningsville, PA, and a component- and module-assembly production line in Matamoros, Mexico (Compound Semiconductor, 2003c§). Agere Systems had sold its U.S. west coast optoelectronics business to EMCORE Corp. in January for $25 million.

In November, EMCORE sold its TurboDisc® metal-oxide chemical vapor deposition (MOCVD) business to Veeco Instruments Inc. for about $80 million. The transferred MOCVD business included the assets necessary for design, engineering, and manufacturing of the MOCVD systems; a manufacturing facility in Somerset, NJ; and EMCORE's MOCVD intellectual property. The acquisition made Veeco the only company to offer both MOCVD and molecular beam epitaxy (MBE) systems. After the divestiture, EMCORE's business would be based on communications products for the cable television, fiber-optic, satellite, and wireless markets (EMCORE Corp., 2003§).

Fairchild Semiconductor International Inc. purchased the commercial unit of Raytheon Co.'s RF Components division in October. The purchase added GaAs monolithic molecular integrated circuits (MMICs) to Fairchild's portfolio of compound semiconductor devices that included LEDs and optocouplers. Fairchild also acquired Raytheon's foundry partnership agreement for the supply of GaAs wafers and an equity stake in Taiwanese firm WIN Semiconductor Corp. as well as access to foundry and support services at Raytheon's Andover, MA, facility (Fairchild Semiconductor International Inc., 2003§).

Motorola Inc. announced plans to separate its Semiconductor Products Sector (SPS) into a publicly traded company. Although details of the transaction were not finalized, the company expected an initial public offering of a portion of SPS, followed by a distribution of remaining shares to Motorola shareholders in a tax-free manner. The company expected to continue purchasing chips for its handsets, which include components manufactured from GaAs and silicon germanium, from its semiconductor business after the spin off (Compound Semiconductor, 2003g).

Celeritek, Inc. announced that it would exit the wireless handset power amplifier business and would focus on GaAs-base subsystems for the defense market and standard GaAs semiconductors for the defense and communications markets. The company cited excess capacity and increasing competition in the handset market as the principal reason for its decision (Celeritek, Inc., 2003§).

In December, Global Communication Semiconductors Inc., a compound semiconductor wafer foundry based in Torrance, CA, and Global Communication Technology Corp., a GaAs wafer manufacturer in Hsinchu Science-Based Industrial Park, Taiwan, agreed to combine their operations into one company. The new company, Global Compound Semiconductors Corp., will be established in the first quarter of 2004. The boards and shareholders of both companies approved the agreement. The merger combined a 6-inch-wafer manufacturing facility in Taiwan with the Torrance facility, which produced heterojunction bipolar transistors (HBTs) and pseudomorphic high-electron-mobility transistors (pHEMTs) (Whitaker, 2003b).

Bandwidth Semiconductor LLC, which was formed in 1999 with Stratos Lightwave Inc.'s purchase of Spire Corp.'s Optoelectronics Division, was repurchased by Spire in May. Bandwidth Semiconductor designed, developed, and manufactured optoelectronic devices at its Hudson, NH, facility (Compound Semiconductor, 2003o).

In September, IXYS Corp., a manufacturer of high-performance power semiconductors and specialized ICs, acquired GaAs IC manufacturer, Microwave Technology Inc. Microwave Technology, a privately held company based in

Fremont, CA, designed and manufactured high-performance GaAs field-effect transistors (FETs), pHEMTs, and MMICs. The company's products were used in defense applications, industrial applications, medical equipment, and wireless telecommunications infrastructure (Compound Semiconductor, 2003e).

Skyworks Solutions Inc. introduced the world's first complete handset radio system that fit into a single dime-sized package about one-third the size of a package created from discrete components. Two separate HBT power amplifier blocks were fabricated on a single GaAs die to provide maximum performance in the smallest possible footprint. This radio system can be used in handsets of cellular telephones. Skyworks began mass production of the module in the third quarter of 2003 (Compound Semiconductor, 2003l).

Indigo Systems Corp., a supplier of infrared cameras, developed a new method for processing standard indium gallium arsenide (InGaAs) detector material that enhances the short-wavelength spectral response. The company called the material produced by the new methods VisGaAs, and it enables both visible and near-infrared imaging on a single photodetector. The new detector allows images to be captured in both the visible and near-infrared spectra, making it easier to perform tasks that previously required two separate detectors or cameras. The company's test results indicated VisGaAs could operate in a broad range of 400 nanometers (nm) (short wavelength visible) to 1,700 nm (near-infrared). Standard InGaAs detectors operate from 900 to 1,700 nm. Simultaneous imaging using ambient visible illumination and near-infrared laser illumination and daytime-nighttime covert surveillance operations are two potential applications for the new material (Indigo Systems Corp., 2003§).

Spectrolab (a unit of Boeing Co.) began large-scale production of its next generation of space solar cells in June. When new, the cells have an average maximum power efficiency of 28%. The ultra triple-junction space solar cell is made of gallium indium phosphide ($GaInP_2$)/GaAs/germanium layers on a germanium substrate. The company claims that it is the highest performing space solar cell in the world (Compound Semiconductor, 2003h§). In addition, Spectrolab and several other solar cell manufacturers have made advances in the efficiency of their multijunction terrestrial solar cells. Spectrolab reported that it had produced terrestrial photovoltaic cells that could convert 36.9% of the Sun's energy into electricity; the terrestrial solar cell is a modified version of Spectrolab's improved triple junction space solar cell. In May, Japan-based Sharp Corp. announced the development of its 36.5% conversion efficiency indium gallium phosphide (InGaP)/InGaAs/germanium cell. In October, Emcore produced terrestrial triple-junction cells with an efficiency of 30% at 200 suns concentration and won a contract to supply the solar panels for the two STEREO satellites being built by Johns Hopkins University (Hatcher, 2003b).

Gallium Nitride.—APA Optics Inc. planned to begin commercial production of GaN-base photodetectors and transistors following its purchase of an MOCVD reactor in November. The Veeco Instruments system is capable of handling six 2-inch-diameter wafers at a time. The new system will increase production capacity for wafers used in APA's ultraviolet light monitor as well as the company's heterostructure field-effect transistor (HFET) power transistor wafers (Compound Semiconductor, 2003a§).

ATMI Inc. reported that it reduced the uniform dislocation density (crystal defects) in its GaN substrates by an order of magnitude and that it shipped these improved 2-inch-diameter GaN substrates to major consumer electronics companies (Compound Semiconductor, 2003b). In the first quarter of 2003, ATMI sold its GaAs epitaxial wafer business to Sumitomo Chemical Co. Ltd. for $0.9 million. Sumitomo Chemical formed a new company, Sumika Electronic Materials, to run the former ATMI operation in Phoenix, AZ (Compound Semiconductor, 2003p).

In April, Sony Corp. began selling a DVD recorder that uses a violet laser and stores up to 23 gigabytes (GB) of data. The recorder uses the Blu-ray format and will be sold in Japan for about $3,800. (Conventional DVD recorders using red lasers are priced at about $420 to $590 universally.) The new recorder can record a 2-hour high-definition television (HDTV) program onto a single Blu-ray disc that can hold up to 23 GB of data and will be priced at about $30 (Compound Semiconductor, 2003n).

Light-Emitting Diodes.—Many LED manufacturers introduced new LEDs based on GaAs and GaN technology that offer improvements from currently produced LEDs. In many cases, the new LEDs are brighter, last longer, and/or can be used in new applications. Some of the new applications include green high-brightness LEDs (HB-LEDs) used at three U.S. airports as runway threshold lamps and as surgical lamps that can last 25 times longer than a comparable halogen product while using only one-third of the power.

Cree Inc. announced its latest product line, the XThin™ series of indium gallium nitride (InGaN) on silicon carbide (SiC) LEDs. The vertically structured LED chips are about 115 microns in height, less than one-half of the typical height of Cree's LEDs. Target applications for this product include white LEDs for use as liquid crystal display (LCD) backlights and digital camera flashes in next-generation mobile appliances. Cree also demonstrated a record 35% quantum efficiency at 20 milliamperes for blue LEDs based on the company's XBright® chip technology. According to Cree, these are the highest known efficiencies publicly reported for LEDs emitting in the blue and white wavelength spectrum (Cree Inc., 2003§). In October, Cree announced a new product, the XLamp™, which is the company's first packaged LED. Until this introduction, Cree's LED business centered on the sale of LED dies that were packaged by its customers.

Osram Opto Semiconductors GmbH developed blue thin-film LEDs that have an extraction efficiency of up to 75%. Unlike the company's standard LEDs, which are grown on SiC, the thin-film LEDs are grown on sapphire. After layer growth, the sapphire is removed by a laser liftoff procedure; a pulsed ultraviolet laser separates the InGaN-base layers from the sapphire substrate. The company expected to begin producing blue thin-film LEDs in 2004 (Compound Semiconductor, 2003f§). In June, Osram GmbH (the parent of Osram Opto Semiconductors) signed a patent license contract with Everlight Electronics Co. Ltd. of Taiwan, which gave Everlight a royalty license to manufacture and sell surface mountable LEDs for white and colored light and for other white LEDs with conversion technology for which Osram held patents. Typical applications for the white LEDs include backlighting for mobile telephone and car radio displays. Osram had signed similar agreements with Japanese firms Nichia Corp. and Rohm Co., Ltd. in 2002 (Osram GmbH, 2003§).

Toshiba America Electronic Components Inc. (a subsidiary of Japan's Toshiba Corp.) announced that the company had added bluish-green and reddish-purple LEDs to its line of high-luminosity LEDs. The LEDs provide ultraviolet emission based on InGaN and red-green-blue (RGB) phosphors in the transparent resin; these differ from conventional white LEDs that typically provide blue emission with yttrium aluminum garnet yellow phosphors. The LED emission does not directly determine the color, which is controlled by the RGB balance of the phosphor layer. The new devices can be used in automotive lighting and were developed in response to demands from specific customers (Compound Semiconductor, 2003r).

Seiwa Electric Manufacturing Co. Ltd. reportedly increased its production capacity of blue LEDs to 10 million units per month in September. At the end of 2002, the company began expanding the production facilities at its plant in Kyoto Prefecture, which had a capacity of 2 million units per month. Once the expansion is completed, Seiwa expects to supply LEDs for use in mobile telephones and plans to expand orders for traffic signals that use LEDs. The company entered the blue LED market in April 2002 and developed its own manufacturing processes to avoid patents held by Nichia and other competitors (Compound Semiconductor, 2003j).

The NorLux subsidiary of Uniroyal Technology Corp., which manufactured LEDs, was purchased by two of its founders in August and was operated as a separate firm—NorLux Corp. Uniroyal Technology filed for bankruptcy in 2002 and was selling all its assets according to a court order. In addition to NorLux, the company owned a Uniroyal Optoelectronics Inc. subsidiary that manufactured HB-LEDs at its plant in Tampa, FL. This subsidiary has been selling its assets piecemeal since August 2003 (Compound Semiconductor, 2003h).

Prices

Since 2002, producer prices for gallium have not been quoted in trade journals. Data for 2002 and 2003 in table 4 represent the average customs value of gallium imported into the United States. Reports in Mining Journal indicated that gallium prices rose slightly during 2003. At the beginning of the year, low-grade gallium prices were reported to be about $200 to $250 per kilogram. By March, the price increased to about $250 to $300 per kilogram, where it remained until yearend.

From U.S. Census Bureau import data, the average value for low-grade gallium was estimated to be $225 per kilogram, about the same as the 2002 average value. For high-grade gallium, the average estimated value fell to $411 per kilogram from $530 per kilogram. Import data, reported by the U.S. Census Bureau, do not specify purity, so the values listed in table 4 are estimated based on the average value of the material imported and the country of origin.

Foreign Trade

In 2003, U.S. gallium imports were higher than those in 2002 but had not reached the levels of the previous 10 years (table 5). China (39%), Ukraine (19%), and Russia (13%) were the leading sources of imported gallium. U.S. consumption of gallium metal has diminished mainly because a significant portion of the GaAs manufacturing capacity has moved to other countries, such as China and Taiwan. Gallium metal consumption, therefore, is not expected to be as large as it has been in the past several years.

In addition to gallium metal, GaAs wafers were imported into the United States (table 6). In 2003, 15,400 kilograms (kg) of undoped GaAs wafers and 127,000 kg of doped GaAs wafers were imported. Japan was the leading source of both types of wafers. The data listed in table 6 may include some packaging material and, as a result, may be higher than the actual total weight of imported wafers.

World Review

Imports of gallium into Japan and the United States, the two leading consuming countries, have been used as the basis for estimating world gallium production in past years. But beginning in 2001, Japan has not separately reported its gallium imports, instead including some other metals in the total reported. These may be small compared with the total gallium imported but may overstate Japan's gallium imports. Estimated crude gallium production was 70 t in 2003. Principal world producers were China, Germany, Japan, and Russia. Gallium also was recovered in Hungary, Kazakhstan, Slovakia, and Ukraine. Refined gallium production was estimated to be about 98 t; this included some new scrap refining. France was the largest producer of refined gallium using gallium produced in Germany as feed material. Japan and the United States also refined gallium. Gallium was recycled from new scrap in Germany, Japan, the United Kingdom, and the United States.

France.—Soitec SA, a French manufacturer of silicon-on-insulator wafers, purchased selected assets from French epitaxial wafer supplier Picogiga SA. Picogiga declared bankruptcy at the end of November 2002. The acquisition by Soitec followed a court decision, announced on March 31, 2003, to dissolve Picogiga. Soitec paid $2.5 million for the assets; although the company had not announced exactly what these assets were, they likely included some or all of Picogiga's MBE growth systems. Picogiga supplied GaAs epitaxial wafers (Compound Semiconductor, 2003m).

Germany.—In April, Osram Opto Semiconductors opened a new LED production plant in Regensburg that will enable the company to double its production by 2005. The company already operated one LED plant in Regensburg, which will continue to operate until all the production is transferred to the new plant. This is expected to take 2 years (Compound Semiconductor, 2003e§).

A wafer manufacturing company called NSC Nanosemiconductor GmbH was spun out of the Ioffe Institute in St. Petersburg, Russia, and the Technical University of Berlin in Germany. NSC operates a cleanroom facility in Dortmund with one MBE reactor and can grow onto 2- to 6-inch GaAs and silicon wafers at its facility. It is focusing primarily on InGaAs-base long-wavelength quantum-dot VCSELs. NSC planned to begin shipping wafers to several optoelectronics customers in January 2004 (Hatcher, 2003a).

India.—National Aluminum Co. announced that it would set up a gallium extraction plant using the spent liquor of its alumina refinery and investigate installing subsequent purification facilities. The company intended to prepare a feasibility report for the project after detailed characterization of its Bayer liquor samples and other raw materials was completed. No timetable for the proposed plant was established (Sanyal, 2003§).

Japan.—In 2003, Japan's virgin gallium production was estimated to be 8 t, gallium recovered from scrap was reported to be 70 t, and gallium imports were reported to be 48.4 t, for a total supply of 126 t. Beginning in 2001, Japan began including gallium imports with those of other metals, including columbium (niobium), hafnium, indium, and rhenium, so the import total may be higher than actual gallium imports.

Two companies announced plans to increase production of red laser diodes used in DVDs. In January, Sharp Corp. announced that it would increase production to between 4.5 million and 6 million units per month from about 3 million red lasers per month. Production of high-quality lasers suitable for DVD recorders would total more than 1 million per month. However, as infrared laser production declined, Sharp's total production of semiconductor lasers remained at about 11 million to 12 million units per month during 2003. Sharp planned to shift all production of red semiconductor lasers to its Mihara plant in Hiroshima Prefecture, which opened in May 2002. Mitsubishi Electric Corp. planned to increase red laser diode production by 40% to 5 million units per month by March 2004. Although the company had increased production to 3.5 million units per month in 2003 from 1 million units per month, this supply was insufficient to meet the demand created by the rapid adoption of recordable DVD drives (Compound Semiconductor, 2003f, k).

In September, Toyoda Gosei Co. Ltd. increased its capacity to produce nitride-base LEDs by about 70% to 150 million units per month. The cost of the expansion was estimated to be about $13 million to increase the monthly capacity of its plant in Aichi Prefecture to 120 million units per month by March and then to 150 million units per month by September. Toyoda Gosei (affiliated with Toyota Motor Corp.) produces blue, green, and white LEDs. The strongest demand for the company's products was in the mobile telephone market, where LEDs were used as backlights for keypads and LCD screens (Compound Semiconductor, 2003s).

Showa Denko K.K. developed aluminum indium gallium phosphide (AlInGaP) red and orange LEDs that are three times as bright as existing ones. The new product was expected to fulfill a growing demand for use in automotive devices, mobile telephones, outdoor displays, and traffic signals. Showa Denko planned to begin commercial production of the product by 2005 and to increase the LED's brightness further (Japan Corporate News Network, 2003§).

Hitachi Cable Ltd. was building a production line at an existing plant in Ibaraki Prefecture to produce 2-inch-diameter GaN substrates that would be used in blue laser diodes. During 2004, the company planned to complete construction of a line that could produce 300 substrates per month. Hitachi Cable uses a new method called void-assisted separation that allows it to mass-produce GaN substrates in 2-inch diameters with high uniformity. According to Hitachi Cable, its technique yields GaN substrates that exhibit 10,000 times fewer crystal defects than other methods. In the new technique, a thin film of perforated titanium nitride is grown on the sapphire base before the crystal GaN is grown on top. When cooled, the GaN layer is easily removed from the template (Compound Semiconductor, 2003d).

In April, Sumitomo Electric Industries Ltd. announced that it began volume production of GaN substrates for the fabrication of GaN-base violet lasers. The use of GaN as a substrate instead of sapphire or SiC was expected to significantly reduce defect formation during epitaxial growth. In turn, this would improve the performance and manufacturability of violet lasers, which would be used in next-generation optical disk drives. Initially, Sumitomo Electric expected to produce 200 substrates per month and then, by October 2003, to increase production to 500 substrates per month and to market the substrates to laser manufacturers. The company was using its own crystal growth process, dislocation elimination by epitaxial growth with inverse-pyramidal pits (DEEP). This technique reduces dislocations by forming inverse-pyramidal pits on the surface of the grown crystal. When a pit grows while keeping its inverse-pyramidal shape, as facets grow, dislocations within the pit region propagate in horizontal direction and concentrate at the pit's bottom, thus reducing dislocations around the pit (Compound Semiconductor, 2003q).

Taiwan.—Visual Photonics Epitaxy Co. Ltd. (VPEC), an epitaxial wafer supplier, began shipping high-brightness aluminum gallium indium phosphide LEDs wafer-bonded to a silicon substrate, marking the first time that company had shipped this type of chip to its customers. Potential applications for the new LEDs included automotive lighting, camera flashes, LCD panel backlights, outdoor displays, and traffic signals. VPEC also was selected to be a second supplier of GaAs HBTs to Skyworks Solutions, a U.S.-based manufacturer of components for wireless communications applications (Compound Semiconductor, 2003u, v).

The German firm Infineon Technologies AG signed an agreement with Taiwanese epitaxial wafer and device manufacturer United Epitaxy Co. (UEC) to set up a joint venture that would manufacture and develop optoelectronic devices for use in the fiber-optics market. The joint venture, to be housed within UEC's existing facility at Hsinchu Science-Based Industrial Park in Taiwan, was inaugurated in October 2003. Mass production was expected to start in the fourth quarter of 2004. The new company will manufacture optoelectronic chips for Infineon and UEC. Both partners will assemble and package the optoelectronic devices into components and modules for the telecommunication and data communication markets (Whitaker, 2003a).

United Kingdom.—In late 2003, Bookham Technology plc, a supplier of GaAs MMICs, began a commercial foundry service at its 6-inch-GaAs-wafer facility in Caswell. The company claimed that the new 6-inch-wafer technology would significantly reduce MMIC costs compared to those of the standard 3- and 4-inch-wafer processes by increasing per-wafer device volumes by up to a factor of four (Compound Semiconductor, 2003b§).

Current Research and Technology

Researchers at the University of Illinois at Urbana-Champaign have broken their own record for the world's fastest transistor. Their latest device, which is made from GaAs and indium phosphide (InP), has a frequency of 509 gigahertz (GHz), which is 57 GHz faster than their previous record. The new transistors could be used in such applications as consumer electronics, electronic combat systems, and high-speed communications products. In addition to using smaller device components, the researchers used a narrow metal bridge to separate the base terminal from the device connector post, which provided increased speed. The Defense Advanced Research Projects Agency (DARPA) funded the work (University of Illinois at Urbana-Champaign, 2003§).

Researchers at Michigan State University have developed a noncomposite material made of gallium, germanium, and ytterbium that exhibits zero-expansion behavior from 100 K to 400 K but also conducts electricity. Previously developed zero-expansion materials were insulators. Most materials expand when heated, although a small number contract instead. When combined, these two types of material can form a composite that does not expand at all as the temperature is changed, so it can withstand rapid changes in temperature. The composite material could have applications in components that encounter large temperature fluctuations, such as motors and actuators and also in space (PhysicsWeb, 2003§)

By introducing arsenic antisite deep levels into a GaAs lattice, researchers at Yale University have generated 1,550-nm radiation from a GaAs LED. The work potentially could aid in developing advanced devices for telecommunications applications. Although GaAs is the most established technology for the production of inexpensive integrated optoelectronics, its bandgap wavelength of 850 nm makes it unsuitable for use with long-distance fiber-optic communications. The researchers created artificial deep-level energy bands in GaAs that would lead the material to emit radiation at a more suitable wavelength. The researchers used low-temperature MBE to grow a 400-nm-thick layer of GaAs with arsenic antisites (defects in which an arsenic atom replaces a gallium atom in the crystal lattice) between layers of doped and undoped GaAs. Additional engineering will be needed to commercialize the device (Photonics Spectra, 2003b).

Researchers at Sandia National Laboratories developed a process for depositing layers of GaN that span etched trenches in sapphire substrates. The process, which the researchers call cantilever epitaxy, may improve the performance of LEDs by reducing the number of dislocations by an order of magnitude compared with material grown on planar sapphire substrates. The researchers began by etching a pattern of posts and trenches in the sapphire and then depositing GaN on the substrate at 500º to 600º C, which creates nucleation sites on top of the posts for subsequent deposition. Further GaN growth at 950º C produces facets over the posts that turn vertical dislocations to horizontal dislocations. When lateral growth continues at 1,100º C, the layers coalesce over the trenches forming a uniform GaN layer with low vertical dislocation density (Photonics Spectra, 2003a).

Also at Sandia National Laboratories, researchers developed two deep-ultraviolet (less-than-300-nm) semiconductor optical devices that set records for wavelength emission and power output. One emitted at a wavelength of 290 nm and produced 1.3 milliwatts of output power, and the other emitted at a wavelength of 275 nm and produced 0.4 milliwatt of power. The devices have a sapphire substrate with conductive layers of aluminum gallium nitride (AlGaN). Operating at the shorter ultraviolet wavelengths makes it possible to build miniaturized devices that can cure polymers and other chemicals, decontaminate equipment, detect biological agents, perform non-line-of-sight covert communications, and purify water. The Sandia team is part of the DARPA project Semiconductor Ultraviolet Optical Source (SUVOS) that funds various research groups around the country to develop deep-ultraviolet compact semiconductor optical sources. The new LED devices have been supplied to DARPA SUVOS program participants that manufacture non-line-of-sight covert communication systems and biosensor test beds (Sandia National Laboratories, 2003§).

Ultraviolet radiation has numerous applications in the decontamination of a variety of materials. It has been used effectively for cleaning semiconductors, filtering of ground water, and sterilizing foodstuffs. Ultraviolet decontamination systems typically employ mercury, quartz, or xenon flashlamps, but Toyoda Gosei developed a compact air purifier based on its TG Purple Hi LED. The primary difference between this system and an active-carbon air purifier is that the organic materials are decomposed rather than adsorbed. The TG Purple Hi LED consists of GaN on a sapphire substrate. The 385-nm LED irradiates titanium oxides that are on grains of carbon within the purifier to produce hydroxide radicals and oxygen ions that can break down the organic materials into carbon dioxide and water. Toyota Motor Corp. incorporated the ultraviolet system into the passenger compartment of its Mark II and Premio vehicles. Daikin Industries Ltd. and Mitsubishi Electric Corp. also use it in home air-conditioning units and refrigerators, respectively (Johnson, 2003).

Sensors Unlimited Inc., a manufacturer of short-wave infrared cameras based on InGaAs, received a follow-on $2 million contract from the U.S. Department of the Air Force (USAF) to develop the industry's first high-frame-rate camera for combined imaging and ranging, using a focal plane array. Commercial applications of the technology include collision avoidance and automatic surveying. If the contract is extended through Phase 3 of the program, it will result in the delivery of two advanced cameras to the USAF. The company also received a contract from DARPA to develop the industry's first all-solid-state, night-vision, room-temperature InGaAs camera that will allow imaging under moonless night conditions with no perceptible image lag (Sensors Unlimited Inc., 2003a§, b§). Sensors Unlimited also won four small business innovation research contracts aimed at exploring new imaging opportunities using InGaAs-base photodiodes. The contracts were awarded from several different Government agencies, including the U.S.

Department of the Navy, the Missile Defense Agency (MDA), and the National Science Foundation.

Kyma Technologies Inc. was awarded four government contracts totaling $1 million. The U.S. Department of Defense and the U.S. Department of Energy awarded Kyma the contracts to support microelectronic and optoelectronic applications of GaN substrates. Such applications range from new solid-state lighting to advanced transmit-and-receive modules for radar applications (Kyma Technologies Inc., 2003§). Kyma Technologies (established in 1998 as a spinoff from North Carolina State University's Department of Materials Science and Engineering) is developing GaN substrates to be used instead of traditional substrates, such as sapphire and SiC.

EpiWorks Inc., a developer and manufacturer of compound semiconductor epitaxial wafers, completed a collaborative research project with Epichem Inc. and InPact Inc. to develop carbon-doped gallium arsenide antimonide (GaAsSb). GaAsSb HBTs are an important potential technology for high-speed digital and military applications and could be used in high-speed wireless applications. The GaAsSb was produced on 3-inch wafers using MOCVD, and the company claimed that the uniformity of GaAsSb was comparable to carbon-doped InGaAs, which is critical for HBTs (EpiWorks Inc., 2003§).

Sensor Electronic Technology, Inc. (SET) has demonstrated III-nitride-base HFET wafers grown on 4-inch-diameter sapphire substrates. SET claimed that sheet resistance on the 4-inch wafer was comparable to the best characteristics of currently available 2-inch wafers. The growth of the wafers was demonstrated using a proprietary MOCVD reactor designed and built at SET in combination with a novel hybrid epitaxial growth technology that integrated conventional MOCVD with a process that SET called migration-enhanced MOCVD. This process allows for material deposition at reduced temperatures and at rates comparable to those used in MBE technology. The development of large-diameter III-nitride epitaxial wafers at SET has been supported by DARPA (Compound Semiconductor, 2003g§). In 2003, SET also received six small business innovative research Phase I contracts from the MDA to develop GaN HFETs for defense applications using the new epitaxial growth technology.

A device using specialized LEDs based on the National Aeronautics and Space Administration's technology for plant growth in space shows promise as a treatment to aid healing of bone marrow transplant patients. Use of the LED apparatus has advanced to the second phase of clinical trials in U.S. and foreign hospitals. Results from the first round of tests were highly encouraging, prompting researchers to expand the trials as they seek approval for the treatment as a standard of care for oral mucositis, a common side effect of chemotherapy and radiation treatments. Quantum Devices Inc., Barneveld, WI, manufactures the LED device (National Aeronautics and Space Administration, 2003§).

Engineers at The Ohio State University created special hybrid materials that were virtually defect-free. Key to the researchers' strategy was the idea of a virtual substrate—a generic chip-like surface that would be compatible with many different kinds of technologies and could easily be tailored to suit different applications. The materials design consisted of a substrate of silicon topped with GaAs with hybrid silicon-germanium layers sandwiched in between. The substrate was 0.7 millimeter thick, and the GaAs layer was 3 micrometers thick. The engineers formed the hybrid material into 1-square-inch versions of solar cells in the laboratory and achieved 17% efficiency at converting light to electricity. Other experimental III-V materials grown on silicon have achieved carrier lifetimes of about 2 nanoseconds, but the new material reached a carrier lifetime greater than 10 nanoseconds. The researchers also manufactured LEDs on silicon substrates that had a display quality comparable to that of traditional LEDs (Ohio State University, 2003§).

Outlook

A report from Communications Industry Researchers Inc. predicted that the global LED market would grow to $5.6 billion in 2008 from $3.2 billion in 2004. According to the report, by 2008 the HB-LED market will be worth $2.64 billion, while ultrahigh-brightness LEDs will have gained a 22% share of the global LED market. Rapid cost reduction is expected to begin in 2004, which would allow unit volumes to increase rapidly. Standard and indicator LEDs will make up the bulk of shipments initially, but HB-LEDs and ultrahigh-brightness LEDs will account for a significant majority of the revenues by 2008. Automotive, backlighting, and signage applications will compose more than 60% of the market during the 2004-08 period (Communications Industry Researchers Inc., 2003§). In a separate report from Strategies Unlimited (a research unit of PennWell Corp.), the market for HB-LEDs grew by 47% in 2003 to reach $2.7 billion, and the HB-LED market has grown by 350% since 1995, which represents a compound annual growth rate of 47%. Mobile appliances accounted for 50% of the HB-LED market in 2003. Signage was the next largest segment with 18%, followed by automotive applications at 15%, and illumination with 5%. All these segments enjoyed solid growth, with a minimum 21% market increase in 2003. The company expected the mobile market to start leveling out, reducing overall market growth to 17% from 2004 to 2008 (Hatcher, 2004).

According to a report by Strategies Unlimited, the market for GaN devices (primarily blue, green, and white high-brightness LEDs) has grown by 221% to $1.35 billion since 1999. The company predicted that the market for GaN devices of all types would grow to $4.5 billion by 2007. Since the beginning of the first significant commercial shipments of GaN LEDs in 1995, the market has grown at an average annual rate of 64.5%. Shipments of blue-violet laser diodes based on GaN devices began in 1999 and grew moderately through 2002. However, in 2003, a new market for blue-violet (405-nm) laser diodes in optical storage opened, as several companies announced the first shipments of the next generation of high-density DVD recorders. GaN-base electronic devices are still under development, but the first significant commercial shipments are expected to begin in 2004 (Compound Semiconductor, 2003d§).

A report from Strategy Analytics predicted that the GaN laser diode market would reach $272 million by 2008 compared with $9 million in 2003, which would be a compound annual growth rate of 195%. Although established markets for GaN lasers currently include biological agent detection, laser projectors, printing, and spectroscopy, the emergence of blue-violet-laser-based DVD recorders and increased demand for HDTVs were expected to boost GaN laser diode consumption. Strategy Analytics projected that blue-violet DVD applications would account for 97% of the total market by 2008. Currently, the market is much more divided, with 43% of sales listed under other applications, which include biodetection, machine vision, metrology, microlithography, projection displays, and underwater communication. In order for this to happen, the blue-violet DVD platform needs to be standardized. The existence of two competing standards for blue-violet DVD—Blu-ray and high-density—will mean that the GaN laser diode market will still be at an early stage of development in 2008 (Compound Semiconductor, 2004§).

References Cited

Compound Semiconductor, 2003a, Agilent to close UK fiber-optic component manufacturing plant: Compound Semiconductor, v. 9, no. 7, August, p. 5.
Compound Semiconductor, 2003b, ATMI reduces GaN wafer defect density: Compound Semiconductor, v. 9, no. 11, December, p. 10.
Compound Semiconductor, 2003c, AXT sells opto business, reports flat revenue: Compound Semiconductor, v. 9, no. 10, November, p. 6.
Compound Semiconductor, 2003d, Hitachi Cable to mass-produce GaN substrates using VAS: Compound Semiconductor, v. 9, no. 3, April, p. 14.
Compound Semiconductor, 2003e, IXYS acquires GaAs IC manufacturer: Compound Semiconductor, v. 9, no. 9, October, p. 6.
Compound Semiconductor, 2003f, Mitsubishi ramps up DVD laser diode production: Compound Semiconductor, v. 9, no. 11, December, p. 16.
Compound Semiconductor, 2003g, Motorola to spin off semiconductor unit: Compound Semiconductor, v. 9, no. 10, November, p. 8.
Compound Semiconductor, 2003h, Norlux emerges from Uniroyal's shadow: Compound Semiconductor, v. 9, no. 10, November, p. 13.
Compound Semiconductor, 2003i, RFMD achieves 6 inch customer qualification: Compound Semiconductor, v. 9, no. 8, September p. 14.
Compound Semiconductor, 2003j, Seiwa Electric ramps up LED capacity to 10 million per month: Compound Semiconductor, v. 9, no. 7, August, p. 9.
Compound Semiconductor, 2003k, Sharp increases red DVD laser production: Compound Semiconductor, v. 9, no. 1, January-February, p. 15.
Compound Semiconductor, 2003l, Skyworks launches dime-sized complete handset radio system: Compound Semiconductor, v. 9, no. 2, March, p. 9.
Compound Semiconductor, 2003m, Soitec buys Picogiga growth assets: Compound Semiconductor, v. 9, no. 4, May, p. 5.
Compound Semiconductor, 2003n, Sony unveils first violet-laser DVD recorder: Compound Semiconductor, v. 9, no. 3, April, p. 6.
Compound Semiconductor, 2003o, Spire buys back Bandwidth Semiconductor: Compound Semiconductor, v. 9, no. 5, June, p. 6.
Compound Semiconductor, 2003p, Sumitomo Chemical buys ATMI's GaAs business: Compound Semiconductor, v. 9, no. 4, May, p. 6.
Compound Semiconductor, 2003q, Sumitomo Electric produces GaN wafers in volume: Compound Semiconductor, v. 9, no. 4, May, p. 13.
Compound Semiconductor, 2003r, Toshiba adapts white LEDs to yield new colors: Compound Semiconductor, v. 9, no. 5, June, p. 11.
Compound Semiconductor, 2003s, Toyoda Gosei to boost LED capacity by 70% this year: Compound Semiconductor, v. 9, no. 3, April, p. 13.
Compound Semiconductor, 2003t, Vitesse sells modules, closes GaAs fab: Compound Semiconductor, v. 9, no. 8, September, p. 6.
Compound Semiconductor, 2003u, VPEC ships first WB-LED chips: Compound Semiconductor, v. 9, no. 11, December, p. 9.
Compound Semiconductor, 2003v, VPEC to supply HBT epiwafers to Skyworks: Compound Semiconductor, v. 9, no. 4, May, p. 6.
Evans, Chris, 2003, Newly formed Gallium Compounds picks up where Eagle-Picher left off: American Metal Market, v. 111, no. 12-5, March 28, p. 8.
Hatcher, Michael, 2003a, Russo-German spin-out focuses on reducing wafer defects: Compound Semiconductor, v. 9, no. 10, November, p. 6.
Hatcher, Michael, 2003b, Solar cell manufacturers come back down to Earth: Compound Semiconductor, v. 9, no. 10, November, p. 25-27.
Hatcher, Michael, 2004, HB-LED market grew by 47% in 2003: Compound Semiconductor, v. 10, no. 2, March, p. 18.
Johnson, B.D., 2003, High-power, short-wave LED purifies air: Photonics Spectra, v. 37, no. 12, December, p. 111.
Photonics Spectra, 2003a, Cantilever epitaxy may improve LEDs: Photonics Spectra, v. 37, no. 5, May, p. 20.
Photonics Spectra, 2003b, Low temperature-grown GaAs LED emits at 1550 nm: Photonics Spectra, v. 37, no. 6, June, p. 18.
Whitaker, Tim, 2003a, Fiber market sees more consolidation: Compound Semiconductor, v. 9, no. 8, September, p. 5.
Whitaker, Tim, 2003b, GCS and GCTC form III-V foundry giant: Compound Semiconductor, v. 9, no. 11, December, p. 5.

Internet References Cited

Celeritek, Inc., 2003 (September 29), Celeritek realigns business to focus on higher profit potential market segments, accessed October 1, 2003, at URL http://www.corporate-ir.net/ireye/ir_site.zhtml?ticker=cltk&script=410&layout=9&item_id=453391.
Communications Industry Researchers Inc., 2003 (December 15), CIR report states that worldwide LED market will surpass $5.6 billion in 2008, accessed March 22, 2004, at URL http://www.cir-inc.com/news/pr_detail.cfm?PRID=142.
Compound Semiconductor, 2003a (November 21), APA Optics looks to commercialize GaN devices, accessed November 25, 2003, at URL http://www.compoundsemiconductor.net/articles/news/7/11/23/1.
Compound Semiconductor, 2003b (June 6), Bookham launches GaAs MMIC foundry service, accessed June 11, 2003, at URL http://compoundsemiconductor.net/press/4974.
Compound Semiconductor, 2003c (September 26), Feature—TriQuint integrates to boost margins, accessed October 1, 2003, at URL http://www.compoundsemiconductor.net/articles/news/7/9/29/1.
Compound Semiconductor, 2003d (June 6), Gallium nitride activity continues to thrive, accessed June 13, 2003, at URL http://www.compoundsemiconductor.net/articles/news/7/6/8/1.
Compound Semiconductor, 2003e (April 14), Osram opens new optoelectronics chip factory, accessed April 21, 2003, at URL http://www.compoundsemiconductor.net/articles/news/7/4/10/1.
Compound Semiconductor, 2003f (September 4), Osram Opto develops blue thin-film InGaN LEDs, accessed September 8, 2003, at URL http://www.compoundsemiconductor.net/articles/news/7/9/4/1.
Compound Semiconductor, 2003g (July 22), SET demonstrates 4 inch GaN HFET epiwafers, accessed July 30, 2003, at URL http://www.compoundsemiconductor.net/articles/news/7/7/27/1.
Compound Semiconductor, 2003h (May 13), Spectrolab's new solar cells have 28% efficiency, accessed March 22, 2004, at URL http://www.compoundsemiconductor.net/articles/news/7/5/25/1.
Compound Semiconductor, 2004 (March 15), GaN laser diode market set for explosive growth, accessed March 15, 2004, at URL http://www.compoundsemiconductor.net/articles/news/8/3/13/1.
Cree Inc., 2003 (September 23), Cree expands product line with introduction of XThin™ LED products, accessed September 23, 2003, at URL http://www.cree.com/News/news175.asp.
EMCORE Corp., 2003 (November 3), Emcore sells TurboDisc® business to Veeco Instruments, accessed November 5, 2003, at URL http://www.emcore.com/news/release.php?id=78.
EpiWorks Inc., 2003 (June 4), EpiWorks, Inc. completes GaAsSb development project with supply partners Epichem, Inc. and InPact, Inc., accessed June 11, 2003, at URL http://www.epiworks.com/news/PR_05302003.php.
Fairchild Semiconductor International Inc., 2003 (October 20), Fairchild Semiconductor purchases the RF Components Division commercial business unit of Raytheon Company, accessed October 21, 2003, at URL http://www.fairchildsemi.com/news/2003/0310/PR_RF_Raytheon_acquisition.html.
Indigo Systems Corp., 2003 (September 23), Indigo Systems introduces VisGaAs, accessed March 29, 2004, at URL http://www.indigosystems.com/company/PR/pr_030923.html.
Japan Corporate News Network, 2003 (December 8), Showa Denko K.K. (SDK) develops four-element LEDs with exceptional brightness, accessed December 12, 2003, at URL http://www.japancorp.net/Article.Asp?Art_ID=6082.

Kyma Technologies Inc., 2003 (July 15), Semiconductor industry leader Kyma Technologies awarded $1 million in govt contracts, accessed March 22, 2004, at URL http://www.kymatech.com/media/archives/pressarchive/press071503.html.
National Aeronautics and Space Administration, 2003 (November 5), Light emitting diodes bring relief to young cancer patients; NASA technology used for plant growth now in clinical trials, accessed November 19, 2003, at URL http://www1.msfc.nasa.gov/news/news/releases/2003/03-199.html.
Navigant Consulting Inc., 2003a (November), Energy savings estimates of light emitting diodes in niche lighting applications, accessed November 19, 2003, at URL http://www.netl.doe.gov/ssl/PDFs/Niche%20Final%20Report.pdf.
Navigant Consulting Inc., 2003b (November), Energy savings potential of solid state lighting in general illumination applications, accessed November 19, 2003, at URL http://www.netl.doe.gov/ssl/PDFs/SSL%20Energy%20Savi_ntial%20Final.pdf.
Ohio State University, The, 2003 (December 2), Materials could make for super LEDs, solar cells, computer chips, accessed December 8, 2003, at URL http://researchnews.osu.edu/archive/35led.htm.
Osram GmbH, 2003 (October 16), Osram grants license to Everlight, accessed October 21, 2003, at URL http://www.osram-os.com/download_protected/press/rtf/PR_Everlight_licence.rtf.
PhysicsWeb, 2003 (October 15), New conductor stands the heat, accessed March 15, 2004, at URL http://physicsweb.org/article/news/7/10/8.
Sandia National Laboratories, 2003 (November 18), New Sandia UV LEDs emit short-wavelength, high-power output, accessed November 25, 2003, at URL http://www.sandia.gov/news-center/news-releases/2003/elect-semi-sensors/uvleds.html.
Sanyal, Badal, 2003 (July 29), Nalco to set up gallium extraction facilities, accessed March 15, 2004, at URL http://www.blonnet.com/2003/07/30/stories/2003073000661200.htm.
Sensors Unlimited Inc., 2003a (December 8), DOD extends Sensors Unlimited's contract to develop industry's first imaging/rangefinding camera, accessed December 9, 2003, at URL http://www.sensorsinc.com/pdfs/PR_120803.pdf.
Sensors Unlimited Inc., 2003b (July 14), Sensors Unlimited, Inc. wins military contract for high resolution InGaAs shortwave infrared night vision imaging system, accessed March 17, 2004, at URL http://www.sensorsinc.com/pdfs/PressRelease640NightVisionFinal32.pdf.
University of Illinois at Urbana-Champaign, 2003 (November 6), Illinois researchers create world's fastest transistor…again, accessed November 12, 2003, at URL http://www.news.uiuc.edu/scitips/03/1106feng.html.

GENERAL SOURCES OF INFORMATION

U.S. Geological Survey Publications

Gallium. Ch. in Mineral Commodity Summaries, annual.
Gallium, Germanium, and Indium. Ch. in United States Mineral Resources, Professional Paper 820, 1973.
Historical Statistics for Mineral and Material Commodities in the United States. Open File Report OF-01-006, 2001.

Other

Compound Semiconductor.
Economics of Gallium, The (7th ed.). Roskill Information Services Ltd., 2002.
Gallium. Ch. in Mineral Facts and Problems, U.S. Bureau of Mines Bulletin 675, 1985.
Gallium and Gallium Arsenide—Supply, Technology, and Uses. U.S. Bureau of Mines Information Circular 9208, 1988.
Mining Journal.
Minor Metals in the CIS. Roskill Information Services Ltd., 1997.
Roskill's Letter from Japan.

TABLE 1
SALIENT U.S. GALLIUM STATISTICS[1]

(Kilograms unless otherwise specified)

		1999	2000	2001	2002	2003
Production		--	--	--	--	--
Imports for consumption		24,100	39,400	27,100	13,100	14,300
Consumption		29,800	39,900	27,700	18,600	20,100
Price	dollars per kilogram	640 [2]	640 [2]	640 [2]	530 [3]	411 [3]

-- Zero.
[1]Data are rounded to no more than three significant digits.
[2]Source: American Metal Market.
[3]Estimate based on average value of U.S. imports of high-purity gallium.

TABLE 2
U.S. CONSUMPTION OF GALLIUM, BY END USE[1, 2]

(Kilograms)

End use	2002	2003
Optoelectronic devices:		
Laser diodes and light-emitting diodes	7,430	7,630
Photodetectors and solar cells	386	524
Integrated circuits:		
Analog	8,600	8,090
Digital	560	51
Research and development	1,630	3,720
Other	10	94
Total	18,600	20,100

[1]Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Includes gallium metal and gallium compounds.

TABLE 3
STOCKS, RECEIPTS, AND CONSUMPTION OF GALLIUM, BY GRADE[1, 2]

(Kilograms)

Purity	Beginning stocks	Receipts	Consumption	Ending stocks
2002:				
99.99% to 99.999%	288	67	--	355
99.999%	154	4,820	4,750	224
99.99999% to 99.999999%	136	1,350	1,240	245
Total	578	6,240	5,990	824
2003:				
99.99% to 99.999%	355	17	32	340
99.999%	224	5,600	5,090	729
99.99999% to 99.999999%	245	530	649	126
Total	824	6,140	5,770	1,200

-- Zero.

[1]Consumers only.

[2]Data are rounded to no more than three significant digits; may not add to totals shown.

TABLE 4
ESTIMATED YEAREND GALLIUM PRICES

(Dollars per kilogram)

Gallium metal	2002	2003
99.9999%-pure, average value of U.S. imports	530	411
99.99%-pure, average value of U.S. imports	229	225

TABLE 5
U.S. IMPORTS FOR CONSUMPTION OF GALLIUM (UNWROUGHT, WASTE, AND SCRAP), BY COUNTRY[1]

Country	2002 Quantity (kilograms)	2002 Value[2]	2003 Quantity (kilograms)	2003 Value[2]
China	11,000	$2,520,000	5,540	$1,220,000
France	937	502,000	936	440,000
Germany	185	104,000	--	--
Hungary	--	--	1,300	371,000
Japan	263	118,000	634	181,000
Russia	299	72,200	1,800	362,000
Ukraine	--	--	2,720	597,000
United Kingdom	414	231,000	348	109,000
Other	10	2,600	974	240,000
Total	13,100	3,550,000	14,300	3,520,000

-- Zero.
[1]Data are rounded to no more than three significant digits; may not add to totals shown.
[2]Customs value.

Source: U.S. Census Bureau.

TABLE 6
U.S. IMPORTS FOR CONSUMPTION OF GALLIUM ARSENIDE WAFERS, BY COUNTRY[1]

	Gallium arsenide wafers, undoped				Gallium arsenide wafers, doped			
	2002		2003		2002		2003	
Country	Quantity (kilograms)	Value[2]	Quantity (kilograms)	Value[2]	Quantity (kilograms)	Value[2]	Quantity (kilograms)	Value[2]
China	15	$11,300	15	$9,450	759	$1,140,000	24,800	$23,500,000
Finland	--	--	--	--	12,000	20,000,000	11,200	12,700,000
France	--	--	1	18,000	6,060	15,200,000	4,440	9,790,000
Germany	211	31,400	--	--	18,900	14,700,000	22,200	22,700,000
Italy	--	--	--	--	14,900	154,000	80	15,800
Japan	7,830	201,000	14,000	341,000	49,500	30,800,000	36,700	30,900,000
Korea, Republic of	9	9,750	--	--	335	336,000	14,500	6,930,000
Taiwan	--	--	36	167,000	7,410	5,600,000	8,980	8,390,000
United Kingdom	47	101,000	1,320	26,500	467	774,000	1,600	304,000
Other	53	61,600	107	244,000	1,980	4,910,000	2,890	1,880,000
Total	8,160	416,000	15,400	806,000	112,000	93,500,000	127,000	117,000,000

-- Zero.
[1]Data are rounded to no more than three significant digits; may not add to totals shown.
[2]Customs value.

Source: U.S. Census Bureau.

TABLE 7
ESTIMATED WORLD ANNUAL PRIMARY GALLIUM
PRODUCTION CAPACITY, DECEMBER 31, 2003[1]

(Metric tons)

Country	Capacity
Australia[2]	50
China	40
Germany	35
Hungary	8
Japan	20
Kazakhstan	20
Russia	19
Slovakia	8
Ukraine	3
Total	203

[1]Includes capacity at operating plants as well as at plants on standby basis.

[2]Standby capacity as of December 31, 2003.